EUROPEAN PARLIAMENT

Science and Technology Options Assessment

S T O A

MAKING *PERFECT* LIFE
BIO-ENGINEERING (IN) THE 21st CENTURY

INTERIM STUDY

(IP/A/STOA/FWC-2008-96/LOT6/SC1)

PE 438.829

EUROPEAN PARLIAMENT

DIRECTORATE GENERAL FOR INTERNAL POLICIES

POLICY DEPARTMENT A: ECONOMIC AND SCIENTIFIC POLICIES

SCIENCE AND TECHNOLOGY OPTIONS ASSESSMENT

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Abstract

This document is the result of the preparatory phase of the STOA-project "Making *perfect* life", that defined the project focus. This resulted in the study document *Making Perfect Life: Bio-engineering (in) the 21st century*.

A project plan for the next two phases was developed and a project team was set up. A kick-off meeting with potential project partners was instrumental in discussing and prioritising research themes and issues. This meeting took place on 6 October 2009 at the Royal Academy of Arts and Sciences in Amsterdam.

"Making *perfect* life" refers to a new set of engineering capabilities and ambitions that have developed at the beginning of this century. This study explains and illustrates this by looking at four different domains of bio-engineering:

- engineering of the body;
- engineering of living artefacts;
- engineering of the brain;
- engineering of intelligent artefacts.

There is a need to reflect from a societal point of view on the new developments in these engineering fields within the life sciences and info-cogno sciences.

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Contents

GENERAL INFORMATION

This document is the end result of the preparatory phase of the STOA-project "Making *perfect* life". This phase ran from September to November 2009. During this preparatory phase the research focus of the STOA-project "Making *perfect* life" was defined. This resulted in the study document *Making Perfect Life : Bio-engineering (in) the 21st century*.

Also a project plan for the next two phases of the project was developed and a project team was set up. A kick-off meeting with potential project partners was very instrumental in discussing and prioritising research themes and issues. This meeting took place on 6 October 2009 at the Trippenhuis of the Royal Netherlands Academy of Arts and Sciences in Amsterdam. The resulting project plan is discussed in a separate document.

This study document deals with the framing of the project "Making *perfect* life". This title refers to a new set of engineering capabilities and ambitions that have developed at the beginning of this century. This study explains and illustrates this by looking at four different domains of bio-engineering:

- engineering of the body;
- engineering of living artefacts;
- engineering of the brain;
- engineering of intelligent artefacts.

We argue that there is a need to reflect from a societal point of view on the new developments in these engineering fields within the life sciences and info-cogno sciences.

ACKNOWLEDGEMENTS

The project "Making *perfect* life" continues our intellectual search for the societal meaning of NBIC convergence, the powerful combination of nanotechnology, biotechnology, information technology and cognitive sciences (cf. van Est et al. 2006, 2008). Many people have inspired us. In particular, this study builds on day to day conversations with our colleagues Jan Staman and Bart Walhout at the Rathenau Institute, and also on long discussions with Tsjalling Swierstra and Marianne Boenink at Twente University in preparing for the book *Life as a construction kit* (in Dutch: *Leven als bouwpakket*) (Swierstra et al. 2009a, 2009b). Moreover, participation and interesting discussions within ISSP's project on *Living technologies*, led by Mark Bedau, has stimulated our work very much (cf. Bedau et al. 2009). Next, Brian Arthur's (2009) book *The nature of technology*, an insightful analysis of how technology develops and evolves, has helped us a lot in conceptualising this preparatory study. Last but not least, we would like to thank our ETAG colleagues Leonhard Hennen from ITAS, Helge Torgesen and Karen Kastenhofer from ITA, and Thomas Reiss from ISI for their critical but always constructive comments on earlier draft versions.

1. INTRODUCTION TO "MAKING PERFECT LIFE"

> "We are at an inflection point in time. For all previous millennia, our technologies have been aimed outward, to control our environment. … Now, however, we have started a wholesale process of aiming technologies inward." (Joel Garreau, 2004: 6)
>
> "We are moving from an era where machines enhanced the natural – speeded our movements, saved our sweat, stitched our clothing – to one that brings in technologies that resemble or replace the natural – genetic engineering, artificial intelligence, medical devices implanted in our bodies. As we learn to use these technologies, we are moving from using nature to intervening directly within nature." (Brian Arthur, 2009: 11-12)

The first decade of the 21st century saw the arrival of a new engineering approach towards life. For the first time in history the organic world appears to become moldable in the sense that it can be controlled, designed and built. This new engineering approach goes hand in hand with NBIC convergence. NBIC convergence or converging technologies refer to a mutually empowering set of research areas and key technologies, including nanotechnology, biotechnology, information technology, and neurosciences. Technological convergence is assumed to strongly increase our engineering capabilities with respect to biological and cognitive processes, and delivers provoking prospects on human enhancement, creating synthetic life and making smart artefacts. With the dawn of these converging technologies, "a form of making that has so far been limited to our interventions in the domain of non-living nature, is now expanding into the domain of living nature, ourselves included" (Swierstra et al. 2009a: 185-211). At the beginning of the 21st century we are thus experiencing a radical expansion of the building logic of non-living nature in the direction of living nature. It is this fundamental shift that the above insightful quotes of Joel Garreau and Brian Arthur point at. The project title "Making *perfect* life" refers exactly to this new set of bio-engineering capabilities and ambitions. This project aims to reflect from a societal point of view on this development.

1.1. Bio-engineering in the 21st century

Bio-engineering refers to two interconnected trends. First, bio-engineering refers to the set of engineering tools to intervene in living organisms. This first bio-engineering trend promises to repair, redesign, reconstruct or enhance biological and cognitive processes. Think for example of tissue engineering and deep brain stimulation.

Second, it refers to the engineering capacity to create technology with the specific life-like characteristics of living organisms, like intelligent behaviour or reproduction. This second trend promises to design and construct living and thinking artefacts from the bottom up. For example, constructing artificial protocells from scratch. Arthur (2009: 206-208) refers to these two trends as "biology is becoming technology" and "technology is becoming biology", respectively. NBIC convergence drives these two trends, but is also causing them to close on each other and intermingle.

1.1.1. Biology is becoming technology

Technological convergence can take place in completely different domains, sharing two dominant characteristics: informatisation and miniaturisation. Informatisation refers to understanding and controlling processes in terms of information, while miniaturisation implies studying and manipulating (both non-living and living) matter on ever smaller scales. As our understanding of biological and cognitive processes increases, we are steadily seeing these life processes as more mechanistic. Of course, the idea that living organisms can be seen as machines dates back to the seventeenth century, the times of Descartes. Brian Arthur claims that: "What *is* new is that we now understand the working details of much of the machinery." (Arthur 2009: 208) This increased understanding promises new ways to intervene in biological and cognitive processes. Examples include regenerative medicine, gene therapy and brain implants.

1.1.2. Technology is becoming biology

Technologies are becoming more biological in the sense that they are acquiring properties we used to associate with living organisms (cf. Bedau et al. 2009). Sophisticated "smart" technological systems in the future are expected to have characteristics such as being self-organising, self-optimizing, self-assembling, self-healing, and cognitive. Synthetic biology and research on protocells present visions of the future that go beyond alternating life by creating living systems from scratch, that is, from non-living materials. Moreover, nowadays we are confronted with more and more artefacts being developed that display certain forms of 'intelligent' behaviour. Think for instance of smart cameras that can detect aggressive behaviour, and robots that can display 'emotions' or even autonomous decision making capabilities.

1.2. Need for social reflection and debate

The two bio-engineering trends need social reflection and debate. With regards to "biology is becoming technology" we have seen many debates on the use of recombinant-DNA technology to create new kinds of plant and animal life forms by modifying existing ones. Over the last decade, this genetics debate has broadened towards human beings. Besides genetics, other types of biotechnologies, information technologies and cognitive technologies can be used to improve human performance. As a result NBIC convergence has led to a growing international debate on human enhancement, that is, the promises and perils of engineering the human body and mind (cf. Van Est et al. 2006, 2008).

The public debate on the second trend "technology is becoming biology" is really in its very early stage. In April 2000, computer scientist Bill Joy was one of the first scientists to raise concerns by publication of the pamphlet *Why the future doesn't need us*. He argues that converging technologies are "threatening to make humans an endangered species," because they bring the processes of self-reproduction and evolution within the realm of human intervention. He is worried about their impact on human nature and humanity, and calls for a "period of reflection". Joy's appeal gave impetus to the debate in the United States about nanotechnology, but his main argument that "technology was becoming biological" was overshadowed by discussion of a doom scenario in which self-replicating nano-robots destroy the world. This so-called Grey Goo scenario dominated the early stages of the debate, but was rapidly removed from the agenda as being unrealistic.

Developments in the field of synthetic biology and robotics, however, are currently breathing new life in the discussion theme that Joy signalled. For example, a recent analysis of the nano-debate in Europe is echoing Joy's call:

> "So far, engineering has always been based on the technician's ability to control nature, but now bottom-up engineering seek to harness processes of self-organization that are autonomous, out of immediate control of the engineer, and yet to advance design goals. … It is this unfamiliar conception of engineering that requires close scrutiny and ethical inquiry." (Ferrari and Nordmann 2009: 52)

This objective is shared by the "Living Technology Project", which is set up by Odense University and part of the Initiative for Science, Society and Policy (ISSP) in Denmark to stimulate public debate (Bedau et al. 2009). The term "living technology" catches the trend "technology becomes biology" in an accurate way. The fundamental properties of living technologies, like growth, evolution and intelligence, are very powerful. As a result they can be very useful, but also very risky. For that reason, the Living Technology Project aims to discuss how the future impact of living technology can be addressed in a responsible manner.

1.3. Content

The title "Making *perfect* life" refers to the emergence, at the dawn of this 21st century, of a new engineering approach towards life, which holds the promise of a 'mouldable' organic world that can be (re)designed and (re)built. This preparatory study aims to substantiate that such a development towards bio-engineering is indeed taking place, and that it is important and timely to reflect on this new set of bio-engineering capabilities and ambitions from a societal and policy point of view. We will distinguish between four fields of bio-engineering:

- Engineering of the body
- Engineering of living artefacts
- Engineering of the brain
- Engineering of intelligent artefacts.

For each of these four fields of bio-engineering we will shortly introduce the new developments within science and technology that are currently taking place. We will furthermore describe some of the social issues these new developments are likely to raise. In particular, we will reflect on the type of issues involved in the engineering of the body, brain, and living and intelligent artefacts. Do we indeed witness that "biology is becoming technology" or "technology is becoming biology"? Or perhaps both? And what does that mean for our understanding of life and living systems, and for our concept of making *perfect* life? We will conclude this report with some final reflections and remarks about these two trends and their broader implications.

2. ENGINEERING OF THE BODY

> "The practice of medicine in the 21st century will be very different from how it is today. We are on the brink of a paradigm shift both in medical technology and in its therapeutic applications and effects. (...) Mere stargazing? It need not be. Molecular medicine holds the promise to realize this paradigm shift!" (Website CTMM)

> "Biomedical research today is on the verge of a new revolution, one in which the tissue damage caused by disease and injury will be reversed to restore the body to its healthy and functional state. This new revolution is termed "Regenerative Medicine" and, as this name implies, it will deliver new technologies to rebuild and restore the body." (website US Center for Stem Cell and Regenerative Medicine CSCRM)

Technological innovation is often described in terms of revolutions. Bio-engineering, more specific of the human body, is no exception to this rule. Following this rhetoric, the first technological revolution in modern biology started when James Watson and Francis Crick described the structure of DNA half a century ago. That established the fields of molecular and cell biology, and the initial basis of the biotechnology industry. The sequencing of the human genome nearly a decade ago set off a second revolution which has started to illuminate the origins of diseases. Now many critics are convinced that a third revolution is under way: the convergence of biology and engineering. Human biological functions can increasingly be controlled, and parts of the human body can be engineered, modelled, and directed for different (therapeutic) purposes. Sociologist Nikolas Rose talks of 'politics of life' in this respect, which is concerned with "our growing capacities to control, manage, engineer, reshape, and modulate the very vital capacities of human beings as living creatures." (Nikolas Rose, 2006: 3).

As discussed in the introduction, bio-engineering refers to trends of both the biological becoming technological, and vice versa how technology is becoming biology. This section further explores these trends by analysing the ways in which engineering tools are being put forward in order to intervene in living organisms with the aim to repair, redesign, reconstruct or enhance biological processes. This is best illustrated by focusing on two fields of human biological intervention: regenerative medicine and molecular medicine.

The first is based on regenerating biological functions via stem cell therapies or tissue engineering, where interventions are based on manipulation of cells, molecules, tissues, or whole organs. The biomedical paradigm considers the patient as its main focus of intervention. This paradigm has more recently been joined by genomics and molecular interventions in order to understand and correct disease. This second development has been described as molecular medicine. Rather than taking the patient as starting point, in molecular medicine the biological and medical techniques are joined by chemical and physical ones in order to identify molecular structures and mechanisms, to learn about their cause and interactions and to intervene at this molecular and cellular level to improve or correct functions. Predictive, preventive and personalised medicine are the key aims here. These two emerging fields represent the therapeutic spectrum of bioengineering possibilities, and as such two broad understandings of making biological life *perfect*.

2.1. Regenerative medicine

> "Tissue engineering / regenerative medicine is an emerging multidisciplinary field involving biology, medicine, and engineering that is likely to revolutionize the ways we improve the health and quality of life for millions of people worldwide by restoring, maintaining, or enhancing tissue and organ function." (opening line http://www.tissue-engineering.net/)

Regenerative medicine is a broad definition for innovative medical therapies that will enable the body to repair, replace, restore and regenerate damaged or diseased cells, tissues and organs. We briefly discuss two specific technologies: tissue engineering and stem cell science, as these aptly demonstrate the engineering approach to regenerating life, and the ways in which the biological and technological merge.

2.1.1. Tissue engineering

Tissue engineering combines cells, synthetic materials, and biological factors to make functional substitutes for tissue. As a therapeutic application the tissue is either grown in a patient or outside the patient and transplanted. The idea is to regenerate new tissue, not just restore function, as organ transplants and mechanical devices have done. As such it adds the engineering perspective to medicine, transforming the field and its professional actors. This requires an interdisciplinary approach, bringing together wound healing and developmental processes with chemical and biomedical engineering. For example, some approaches embed cells into a structural matrix which is cultured three-dimensionally in a bioreactor before being implanted. Others use the host's body as the bioreactor, delivering organic molecules to a specific site on 'smart' biomaterials to stimulate tissue growth. But manufacturing processes are complex, combining cell culture with a wide-ranging set of (computer) techniques, and adding new insights and tools to the mix such as nanoscale molecular self-assembly techniques and nano-medical approaches (Hogle 2009; see also Riehemann et al 2009).

While engineering and culture techniques in biology have been around for over a century, the first tissue engineering applications only hit the market in the late 1990s. The most advanced products currently available in the clinic include wound management applications such as living skin (for burns or ulcers, with product names such as Apligraf or Dermagraft, based on cultured human skin derived from newborn's foreskin or patient-own dermal cells), cartilage products (such as Carticel, generally based on patient-own cells that are multiplied in the lab and then injected back into the site of disease, often for knee or sports injuries), and several cardio-applications such as hybrid heart valves. Many other tissue engineering applications are still in (early) development. While expectations are high, especially in combination with nano-medical approaches to regenerating tissues or cells, the applications currently available have only seen limited commercial success so far. The quest for the best business models for the many start-up companies in this field continues, regulatory regimes are complicated, reimbursement of the products is limited or non-existing and the clinical uptake of these applications does not reflect the tremendous potential with which they entered the public arena (see Faulkner et al 2006, 2008). While some argue that these factors have all hampered innovation in one sense, the moral and ethical debate around tissue and cell technologies was yet to come. In tissue engineering the cell source used is often human adult, rather than foetal or embryonic (or animal, for that matter). This is not the case with stem cell science more broadly, as discussed next.

2.1.2. Stem cell technology

Stem cells are considered the ideal 'building blocks' to modify, manipulate, multiply and otherwise apply in order to restore or repair certain bodily functions. It is still early days for the stem cell 'as we know it', though, and stem cell lines are lab inventions rather than biological phenomena found in nature. Moreover, scientists do not agree on what a cell makes a stem cell, or when a cell line really is a stem cell line. However, the isolation of the first human stem cells in 1998 is widely regarded as a breakthrough for modern biomedicine – not just because of its therapeutic promise or potential, but also for the basic scientific understandings of biology and for figuring out 'how life works' from its early beginnings.

In 1998, biologist James Thomson and his team at the University of Wisconsin published long-awaited results in the journal *Science*: the first successful isolation of stem cells from human embryos to grow in immortal cell lines. The research team had managed to isolate so-called human blastocyst-derived, pluripotent cell lines. These cell lines, the authors claimed, 'should be useful in human developmental biology, drug discovery, and transplantation medicine' (Thomson et al 1998: 1145).

The discovery by these stem cell pioneers was perceived, by some, as the logical next step in a long tradition of basic scientific research. After all, existing therapeutic applications of stem cells, especially regarding those obtained from bone marrow, had been a standard treatment course for cancer since 1968. Furthermore, the successful derivation of embryonic stem cells from mice had already been reported in 1981 by Nobel laureate Sir Martin Evans and his team (Evans and Kaufman 1981) and by another group of researchers (Martin 1981). In 1995, Thomson et al celebrated the successful isolation of an embryonic stem cell line in primates. While for some the 1998 discovery did not come as a surprise, then, it did kick off a heated scientific and public debate. Some claim it marked the birth of Regenerative Medicine, often described as 'a new era of medicine' and a 'paradigm shift' in research.

So what's special about these cells? The scientific and therapeutic potential of the stem cells has been heralded in many subsequent publications and presentations. According to these accounts, stem cells are able to develop into many different cell types in the body. With the theoretical potential to divide without limit, these cells are seen to offer a means for renewing tissue throughout an individual's life. The potentially most powerful stem cells are found in the early stage embryo and are believed to possess very specific capacities, especially pluripotency or the ability to develop into many different cell types. In addition, human embryonic stem cells (hESCs) are thought to be immortal (capable of dividing indefinitely without losing their genetic structure) and malleable (with the potential to be manipulated without losing cell function).

These three attributes have stimulated the imagination of patients, politicians, and media consumers alike (see also Geesink et al, 2008 and Prainsack et al, 2008). If we find out how to stimulate hESCs to differentiate into the 'right' kind of tissue, we will be able to alleviate, or even cure, injuries or diseases as diverse as Alzheimer's and Parkinson's disease, heart and kidney failure, diabetes, traumatic spinal cord injury, vision loss and hearing loss. To date, though, not a single embryonic stem cell therapy has entered the clinic -- the first human trials have only been approved early 2009 by the US regulatory body FDA. But scientific insight and innovation is not the only factor at work.

Scientific reports of scientists in Japan and the US reprogramming adult skin cells 'back' into the stem cell stage claim that those (iPS) cells possess similar pluripotent functions as their embryonic counterparts (Yu et al 2007; Takahashi et al 2007; Vogel and Holden 2007). Apart from another scientific breakthrough, one could argue this was exactly the kind of finding that was needed in order to counterbalance the numerous ethical arguments against embryonic stem cell research. With the moral status of the embryo as seemingly most dominant organising principle, regulations and administrations have stumbled over the dilemma whether it was morally acceptable to 'destroy life in order to create life', as the United States Bush administration presented it some years ago, when prohibiting public funds to be spent on human embryonic stem cell research. We will return to these ethical and social dilemmas later.

2.2. Molecular medicine

Breakthroughs in bio-engineering the body also came from a different direction, as a product of synthesis of the current notions on genetics and biochemistry of human diseases. What has now been dubbed 'molecular medicine' is the application of molecular biology (in particular genetics, genomics and proteomics) to medicine, or simply 'DNA in medicine'. An important feature is that the molecular medicine perspective emphasises cellular and molecular phenomena and interventions rather than the previous conceptual and observational focus on patients and their organs. Approaches include molecular diagnostics, pharmacogenetics, gene therapy and preventive medicine more broadly.

The basic premise of molecular medicine is that disease is targeted where it is caused: at the level of the gene product in the critical cell. This approach would enable earlier and more precise detection of diseases and even predisposition, but also personalised treatments that are more effective, that cause fewer side effects, and are more cost-effective due to stratification of specific patient risk and prediction of response to therapy (CTMM, see Boenink 2009).

The emergence of molecular medicine, and its bumpy trajectory on the way to successful clinical application, can be traced back to the famous 1953 papers by Watson and Crick in Nature. From understanding the principles of DNA replication (and translation and regulation of gene expression) the field transgressed to techniques to manipulate genetic material into the 1970s, with the in vitro production of therapeutic proteins by recombinant DNA technology. The start of the Human Genome Project in 1989, if not its finalisation some fifteen years later (the 'book of life' listing all human genes), spurred all kind of visions about not just understanding biological systems, but also designing and constructing living systems more broadly. The next section on the engineering of living artefacts will discuss these developments in more detail, most notably in relation to the emergence of digital biology and synthetic biology. With respect to applications in human biology and medicine, the road ahead contained a few more potholes. Already in the 1980s expectations were high in terms of understanding the basis of disease and the potential for rapid and precise diagnosis, repair or replacement of defective genes – or if all these failed at least the development of rationally designed, powerful and specific drugs. Personalised medicine, then, is exactly about targeting individual disease and predisposition, by focussing on factors specific to an individual patient (information about a patient's protein, gene or metabolite profile) to provide individualised, tailored, or custom-made medical care.

At least, in theory. Some critics argue that molecular biology in medicine leads to disillusionment rather than treatment or cure, as 'for the most part we are still waiting' (Steel 2005). Furthermore, controversy over applications has hindered progress in the field. Gene therapy, or gene delivery in order to target defects in the human body, has resulted in more ethical dilemmas, than actual cure – also because only very rare genetic disorders have been capable of treatment so far, at a high cost, and not the more common single gene disorders such as cystic fibrosis or haemophilia A. Because of the potential hazards of gene therapy, many countries developed very strict regulations - which have not prevented unfortunate deaths arising from the therapy. In the meantime more successes were noticeable from diagnostics and drug design approaches in molecular medicine, for example in molecular profiling for cancer. It is thus in these areas where molecular medicine may prove the way forward in the bio-engineering age.

2.3. Social and ethical issues

As with many breakthrough technologies, biomedical innovation is surrounded by potentiality and risk. Regenerative medicine and molecular medicine so far have raised scientific hope, but also many social, ethical, legal and regulatory questions. With tissue engineering these questions include whether the technology is cost-effective and affordable for larger parts of the population, given the high development costs and price of the tissue products and the lack of reimbursement by most national healthcare systems. Because of the complex and hybrid character of many of these products, also regulatory pathways have been unclear (for more on risk and regulation see also Faulkner et al 2008). The use of specific cell sources has also guaranteed heated scientific and public debate. The moral status of the embryo, as we have discussed in relation to stem cell research, came to dominate the scene, thereby dictating investment strategies (spending tax payer's money on controversial research?) and extrapolating party politics alike. In other words: the successful isolation of human embryonic stem cells represented not just a new scientific chapter, but may have been a 'breakthrough' in terms of new ethical, social, and regulatory challenges too. Some have analysed this in terms of a shift in the promissory economies aligned with a new understanding of biological development (Thompson 2005; see also Brown et al 2000 and Franklin & Lock 2001).

Equally, 'gene talk' (Keller 2000) has been coined to refer to strategies of reporting and argumentation to keep up future hopes and expectations in genomics, however (un)realistic. What connects the technologies described in this section, then, is the risk of overselling science and a potential lack of ability in managing expectations of what technology has on offer – whether it's a cure for disease or better care, and whether it's to restore injury and illness or to improve the overall human condition. Future projected technological hopes also include visions of immortality and eternal life, of anti-ageing or at least extending the lifespan without loss of function. Transhumanist dreams and fears of 'design on demand' in reshaping the human body are part of a discussion on normative limits of techno-scientific development, and the technologies discussed in this section are no exception. There is already a backlash against DNA in medicine and genomics more broadly, which has been oversold to consumers as a deterministic science. In addition, and increasingly, also the financial side is taken into the equation, with rising healthcare costs and unwilling insurance payers as one exponent. Another exponent becomes visible in debates around 'patenting life' and the notion of property in/of the body. The possibility of an international property right regime in human biology is one consequence of engineering the human body – and not the least controversial one.

2.3.1. Technology is becoming biology, and vice versa

Regenerative medicine and molecular medicine represent a crucial turning point in scientific understandings of human biology and of 'making life'. Yet the more significant implications are perhaps better understood as social, ethical and political. How can we begin to understand the effects of converging technologies and biologies for modern medicine if not society at large?

This section discussed the ways in which technology and the engineering toolbox provided, at least in potential, the possibility of transforming human biological life in terms of understanding underlying disease processes and targeting these mechanisms at the level where it matters: engineering of tissues, reproduction of cells, targeting of genes, manipulation of molecular processes... yes even predicting and preventing injury or illness. The biological in technology and the technological in biology are two sides of the same coin in this respect, mutually constituting ways in which human biology (and medicine in particular) affects society by questioning and challenging the very basic understanding and methodology of health and illness. In other words: the envisaged transformation of bio-engineering in medicine may have real effects for the social and symbolic order in society (see also Boenink 2009), questioning our concepts of improvement and enhancement, of health and illness, of injury and disease, and with that the dynamics of making life *perfect*.

3. ENGINEERING OF LIVING ARTEFACTS

> "Once we understand the powers of creation in nature, the result will be very, very, very much more powerful than the discovery of the bomb and it will have much wider consequences." Artificial life researcher Steen Rasmussen (quoted in Noble 1997: 169)

This century has witnessed the coming of age of synthetic biology, which promises to robustly re-engineer existing biological systems and make living systems from non-living material, from scratch so to say. This section will briefly consider the emergence of synthetic biology in an historical perspective. Next it will describe the ambitions of synthetic biology with respect to the engineering of living artefacts. At the end of this section some social and ethical issues raised by synthetic biology will be addressed. In particular, we will reflect on the type of bio-engineering that is related to synthetic biology. Does synthetic biology refer to "biology is becoming technology" or "technology is becoming biology", or perhaps both?

3.1. The emergence of digital biology

During the first half of the 20th century a whole new endeavour grew in the minds of various scientists. For example, the German-American physiologist Jacques Loeb (1859-1924) wanted to develop a chemical theory of life (cf. Campos 2009). He had a strong engineering approach to life, and was interested in having full physiological and developmental control over life, developing new forms at will and as needed. Loeb dreamed of "a technology of the living substance" and his ultimate goal was to create life from scratch in the laboratory.

Also physicist became interested in studying biological processes. During the 1930s, the belief grew among physicists that it should be possible to build a new biology on the basis of the physical sciences; an effort which was later called "molecular biology". One of the promoters of this vision was Erwin Schrödinger, one of the founding fathers of quantum physics. In 1944 he published the book *What is life? The physical aspects of the living cell* in 1944, which became the "ideological manifesto of the new biology." Schrödinger put forward the question: how can the events in space and time which take place within the spatial boundary of a living organism can be accounted for by physics and chemistry? Inspired by this research program many physicists entered the field of biology. Amongst others, this inspired Francis Crick and James Watson, to search for the molecular basis of life.

On 28 February 1953, the biologists Francis Crick and James Watson unravelled the double-helix structure of DNA, proclaiming to have found "The secret of Life". This date is often seen as the birth of molecular biology. Discovering the molecular basis of life, thus, was not an isolated development, but the result of the convergence between biology and the physical and chemical sciences in the two decades before. After the chemical code of DNA was unravelled – DNA consisted only of four types of base pairs - molecular biology really took off. This new field revealed all kind of molecular mechanisms, such as the information flow from genes to proteins to larger cell structures.

In 1973 genetic engineering was accomplished in micro-organisms. Recombinant-DNA technology enabled scientists to cut specific parts of the DNA, and paste them into other cells. Scientists could suddenly combine the genes of two separate species of living beings, and thus consciously and purposefully create new forms of life. This first generation gene technology enabled the genetic modification of an E-coli bacteria in order to produce human insulin for diabetics.

Another type of convergence can be signalled in the 1980s: the influx of informatics in the field of biology in two ways, bioinformatics and artificial life. Again a new type of biology has developed: digital biology. The potential that lies in the merger of biotechnology and information technology was captured in the 1980s by various scientists. Two strands can be distinguished. The first vision relies on information technology to study and model biological systems. This has led to research branches like genomics, proteomics and systems biology. A second vision, Artificial Life (A-Life), developed within the computer sciences. The A-Life community worked towards creating artificial systems that exhibit behaviour characteristic of natural living systems. Both strands have enabled and constitute the arrival of the field of synthetic biology at the beginning of this century.

3.1.1. Genomics, proteomics and systems biology

This bioinformatics vision was pioneered by Leroy Hood at CalTech biology department in the early 1980s (Silver 2006: 271-277). It was already understood that the information contained within DNA and proteins molecules is written down with a limited number of chemical building blocks: four bases in DNA and 21 amino acids in proteins. Hood imagined that in theory a machine could be built to read the information, and store it in an electronic memory. Moreover, he thought DNA and protein writing machines could be designed that would read digital information and automatically piece together building blocks in the right order to synthesize DNA molecules and proteins. In 1982, Hood imagined a future in which a complete "parts list" of a biological organism could be read by machines into electronic memory. Moreover, he foresaw a future in which a computer program could be designed as a model of a living system, based on the knowledge of an organism's components and their interactions. Hood's ideas have been very influential. One of the central techniques for making his vision materialize was the polymerase chain reaction (PCR), which was matured by biochemist Kary Mullis in 1984. PCR is now a technique to create thousands to a million copies of specific DNA sequences. This new tool enabled the merger of the digital and biological worlds. In the 1990s this was best illustrated by the success of the Human Genome project, which depended heavily on bio-informatics. Hood's vision of digitizing biological processes in the cell has nowadays become the central tenet of systems biology.

3.1.2. Artificial Life (A-Life)

Long before Hood discovered the power of computing, computer researchers had become intrigued by the concept of life and evolution. As part of the AI community, an Artificial Life community developed during the 1980s. The father of A-Life was the mathematician John von Neumann (1903 – 1957), who at the end of his life, began to ponder the fundamental logical similarities between life and machines. He developed the theory of self-reproducing cellular automata upon which A-Life came to be based. The 1970s had already shown some forms of artificial life, namely the Creeper computer virus, a self-replicating program on ARPANET, which distributed the message "I'm the creeper, catch me if you can!" By the 1980s, AI scientists found they could simulate life and evolution as well as intelligence and experience. This new research branch was called Artificial Life. In the mid-1980s, Los Alamos became the centre of the A-Life community. During the first conference in Los Alamos in 1987, Artificial Life research was defined as "the study of artificial systems that exhibit behaviour characteristic of natural living systems." While it was subsequently claimed that "Microelectronic technology and genetic engineering will soon give us the capability to create new life forms in silico as well as in vitro." (Noble 1997: 167) The A-Life community thus underlines that "life is not to be judged as a quality of a particular substance (the hegemony of a carbon-based understanding of life) but as a model of the interconnectedness, emergence and behaviour of the constituent components of a(ny) living system." (Parikka 2005)

3.2. Synthetic biology

The Human Genome Project stimulated scientists and visionaries to think further into the future. At the end of the 20th century it created legitimacy for a new type of bio-futurism, aiming no longer solely on mapping and understanding biological systems, but more and more on designing and constructing living systems (cf. Van Est et al. 2006). The overall name given to that new research paradigm is synthetic biology, which is commonly defined as the attempt to "engineer complex artificial biological systems to investigate natural biological phenomena and for a variety of applications" (cf. Bedau et al. 2009: 65). This rapidly evolving research field builds on the idea of convergence among biotechnology, information technology and nanotechnology. Synthetic biology is "an assembly of different approaches unified by a similar goal, namely the construction of new forms of life." (Deplazes and Huppenbauer 2009: 58) We may distinguish between a "top-down" and "bottom-up" approach to synthetic biology. The "top-down" approach starts with a pre-existing living system and then re-engineers it for some purpose. The "bottom-up" approach attempts to make new simple kinds of minimal chemical cellular life, using non-living materials. This is also called the protocell approach (cf. Deplazes and Huppenbauer 2009) or 'synthetic protocell biology' (Solé et al. 2007). Under the heading "bottom-up" synthetic biology, we will also describe the new field of artificial genetics, which attempts to develop an alternative genetic alphabet.

3.2.1. "Top-down" synthetic biology

"Top-down" synthetic biology builds on insights from genomics, proteomics and systems biology, and aims to radicalize genetic engineering. Inspired by the ultimate goal of nanotechnology – to control matter on the atomic scale – the aim is to design and build new biological parts and organisms or modify existing ones to carry out novel tasks. Within "top-down" synthetic biology two cultures in molecular biology meet: 'deconstructing life' and 'constructing life' (cf. de Lorenzo 2006; De Vriend 2006: 16-20). Deplazes and Huppenbauer (2009) talk about the synthetic genomics approach and the bioengineering approach, respectively.

Synthetic genomics approach

The first culture dissects biological systems in the search for simplified and minimal forms that will help to understand the adaptation and evolution of biological systems. This approach is illustrated by Craig Venter's minimal genome project, which aims to produce a minimal organism based on a chemically produced minimal genome. The basic research questions are: "Can you define a minimal genetic operating system for life? Could we define life at a genetic level?" (Brockman 2008: 43) At this moment, the Craig Venter Institute claims that it is about to build the first synthetic minimal genome bacteria Mycoplasma genitalium. Analogous to Dolly, the cloned sheep that led to a worldwide debate on human cloning at the end of the 1990s, the environmental movement has already nicknamed this first synthetic life form Synthia. Such a minimal genome could then serve as a "chassis-genome" that can be expanded by additional genes for specific functions that the organism is supposed to fulfil. This brings us to the second strand.

Bioengineering approach

The 'constructing life' or bioengineering approach aims at producing programmable bacteria or eukaryotic cells. In this approach biological phenomena are compared to computer systems. Electronic circuits can be designed in a modular way by using standard components. Bioengineers believe biological systems can be designed in a similar fashion, using standardized genetic elements that code for certain metabolic functions. Here, synthetic biology builds on systems biology. Systems biology tries to come to a comprehensive view on organisms as living systems. Based on these insights, synthetic biology wants to bioengineer cells with predictable behaviour. Such a bioengineered cells could well be described as a new type of machine, a living machine (Deplazes and Huppenbauer 2009). One of the first big successes of this approach was the creation of E. coli bacteria that synthesise large quantities of the precursor of the anti-malaria drug artemisin by combining metabolic pathways from bacteria, yeast and the plant Artemisia annua. Currently a lot of research money is spent on developing the microbial production of bio-fuels.

3.2.2. "Bottom-up" synthetic biology

In this section, we biefly describe developments within synthetic protocell biology and artificial genetics.

Synthetic protocell biology

According to Solé et al. (2007) synthetic protocell biology "aims at the construction of a chemical life-like ensemble in the form of an artificial cell system able to maintain, self-reproduce and potentially evolve". Such minimal chemical cellular life forms are often called "protocells" (Rasmussen et al. 2009). This research endeavour builds on insights from the artificial life community, (macro-molecular) chemistry and biology. One of its basic questions is: how could complex chemical living systems evolve from a formless, unorganized soup of primordial molecules? Or: how did life spontaneously generate from lifeless materials? Chemists now think that some form of molecular evolution preceded the formation of life. There is some consensus that protocells need to integrate three main components: 1. containment via an artificial cellular structure, 2. metabolism to absorb and utilize energy, and 3. information, a kind of molecular memory is needed in order to reproduce itself along with all its functional components (Rasmussen et al. 2009). Such protocells have not yet been developed. The replication mechanism is the main technical hurdle. Bedau et al. (2009: 66) state, however, that "many expect that the first ones could exist in the laboratory within the next five to ten years and could survive in the natural environment outside of the laboratory within the next ten to twenty years." If scientists succeed, it would show that lifeless material can be designed to have a life-like character. According to Van Santen (2009: 28-29): "This is not only of philosophical importance. When we master some of the processes that underlie life, it may enable us to make materials much more efficiently and sustainable. Many chemists are inspired by the complexity of nature and the evolution of life. It offers them possibilities to extend the reach of their efforts to adapt chemistry to the needs of mankind."

Artificial genetics

Information storage and propagation in biological systems is based on just two types of nucleic acids. Natural DNA consists of only four bases, namely A(denosine), T(hymine), C(ytosine) and G(uanine), often described as the "letters" of the genetic code. Watson and Crick's discovery of the DNA structure in 1953 established how these four chemical "letters" pair up. DNA and RNA are currently being used for many purposes, like producing proteins, peptides, and building complex nanostructures, like molecular electronic wires. Scientists expect that the development and use of unnatural DNA bases (in combination with natural DNA bases) could enable widely different kinds of genetic engineering. Since 1990 attempts have been made to create and use an alternative genetic alphabet based on unnatural DNA bases (De Vriend 2006:15). One way to do this is to extend the number of DNA bases by creating unnatural DNA bases, or new "letters". At the moment, various research groups have succeeded in creating and replicating artificial DNA "letters". Diagnostic tests for viral diseases seems to be a promising field of application for unnatural DNA (American Chemical Society 2009). Namely, natural DNA unnatural often binds with non-disease DNA and thus generates confusing false positive and negative result. Artifical genetic systems, also named orthogonal systems, do not have these problems since they do not operate under the Watson-Crick pairing rules.

Such systems are already on the market for testing people who are infected with hepatitis B and C, and HIV (*ibid.*). The creation of such so-called orthogonal biological systems presents one of the most significant alterations from life as we know it today. It promises to lay the foundation for an unprecedented parallel biological world that cannot exchange genetic information with the natural world. As a result, some claim that synthetic biology might make biotechnology safer (Marliere 2009, Herdewijn and Marliere 2009).

3.3. Social and ethical issues

The social, ethical and legal challenges of top-down synthetic biology have received a growing attention over the last decade (Cho et al. 1999; De Vriend 2006; Schmidt et al. 2009a). Reflection on bottom-up synthetic biology is still in its infancy. Reflection on synthetic protocell biology has only just begun (Bedau and Parke 2009; Bedau et al. 2009), while there is barely any reflection on artificial genetics so far. Four major societal topics in synthetic biology are: safety, security, intellectual property rights, ethics and the science-society interface (cf. Schmidt et al. 2009b). We will not discuss all these topics in detail here, but focus on the issue of engineering living artefacts. Typical ethical and cultural themes that arise with respect to modifying or creating new life include the "patenting of life", "messing with nature" and "playing God" (cf. Ferrari and Nordmann 2009).

3.3.1. Technology is becoming biology, and vice versa

The final goal of all approaches within synthetic biology is to engineer a microscopic factory that delivers the desired chemical products and is self-sustaining and duplicates itself. With respect to the type of engineering, there seems to be a marked difference between the top-down bio-engineering approach and bottom-up protocell approach (cf. Deplazes and Huppenbauer (2009); Bedau et al. (2009)). The aspiration of the bioengineering approach is to make the engineering of living systems as predictable and reliable as the engineering of nonliving systems, like electronic circuits. In the words of Brian Arthur, here "biology is becoming technology", or as Deplazes and Huppenbauer (2009: 59) aptly conclude: "We are thus confronted with a form of living machine." Creating a protocell would mean the creation of life from non-living matter. Artificial genetics promises to create a parallel artificial biological world. In both these cases "technology is becoming biology." Artificial genetics promises a safer biotechnology. In contrast, Bedau et al. (2009: 67) argue that protocell engineering will be less predictable, because of the fact that protocell research emphasises the biological synergies and other unpredictable emergent properties found in even the simplest forms of life. Consequently, they emphasise that this unpredictability raises special regulatory, but also ethical and cultural concerns. Bedau et al. (2009) belief that in particular concerns about violating nature and "playing God" apply more significantly in the case of bottom-up protocells.

4. ENGINEERING OF THE BRAIN

> "This is the first model of the brain that has been built from the bottom-up. There are lots of models out there, but this is the only one that is totally biologically accurate. We began with the most basic facts about the brain and just worked from there. The best way to figure out how something works is to try to build it from scratch." Henry Markram, director of the Blue Brain Project (2009)
>
> "We couldn't have had neurotechnology without the development of information technology – and without its continued development. These are enabling technologies that will continue to develop, and that will support the evolution of more sophisticated neurotechnologies." Zack Lynch, futurist and founder of the Neurotechnology Industry Organization (2009)

The brain is the most complex system known to mankind. From the late nineteenth century onwards, scientists were able – because of the invention of better microscopes and a staining procedure to reveal the intricate structures of single neurons – to strive for a 'cognitive revolution': a scientific description of the brain and the mind. Since then, neurobiologists and neurophysiologists have studied the mechanisms of the brain of animals and humans through many different methods like histology, patch clamp technology and more recently modern neuro-imaging techniques like functional Magnetic Resonance Imaging (fMRI) and magnetoencephalography (MER).

The field of the brain sciences have so far been a reductionist science, describing the brain in all of its physical details on different levels: molecules (e.g. genes), cells (e.g. neurons and glial cells), neuronal networks (e.g. cortical columns), brain regions (e.g. prefrontal cortex or amygdala), etc. The question still unanswered though is how all these details come together, and how it connects to our behaviour. Neuroscientists try to address this question through a large-scale reverse *engineering* project called the Blue Brain project. The first subsection will briefly describe the progress in the neurosciences so far and explain the engineering approach that underlies the Blue Brain project.

Understanding the methods of the brain, although still in its infancy, has resulted in another engineering approach to the brain, namely to intervene in our brain with engineering tools in order to repair, reconstruct or enhance cognitive processes. The second subsection will describe this particular neuro-engineering perspective where we try to interface our brains with electrodes or influence brainactivity through magnetic stimulation and neurofeedback.[1]

At the end of the section some social and ethical issues are raised concerning the introduction of the engineering paradigm into the neurosciences.

[1] We will concentrate on neurotechnologies in this preparatory study, excluding novel psychopharmacology approaches based on nanotechnology which try to influence neural activity more directly by overcoming the blood-brain barrier.

4.1. Understanding the brain

Neuroscientists have tremendous knowledge of the anatomy of the brain, about the way individual neurons process information and communicate with each other, how the major sensory input systems collect and represent information and how output systems (such as muscles, glands, etc.) are addressed. There is still a lot they do not know, though.

Neuroscience has been an experimental, technology-driven science. Every new (research) technology pushed forward the field with a large step. For example, the path-clamp technology in neurophysiology allowed researchers to record the activity from identified individual neurons in the central nervous system. The multitude of tools provided by genetics made it possible to link function to molecules at all possible levels of brain functioning. The inventions that allowed non-invasive imaging of activity in the functioning brain finally opened up the possibility to couple higher functions in the brain with activity in the underlying neural substrate. A consequence of neuroscience still being mainly technology driven, is that the field is data rich but theory poor. Or as British neuroscientist Steven Rose (2005: 4) worries: "The rapid expansion of the neurosciences has produced an almost unimaginable wealth of data, facts, experimental findings, at every level from the submolecular to that of the brain as a whole. The problem which concerns me greatly, is how to weld together this mass into a coherent brain theory."

To eventually understand the brain as a natural cognitive system, some major breakthroughs are needed (Wadman, 2008). The key to progress in understanding the brain will be a parallel development of new concepts on how to integrate the knowledge coming from all the disciplines involved in the neurosciences, from molecular, cell to system level. So far there has been a lack of concepts on how to analyse such a huge complex system.[2] Or as neurobiologist Wadman sighs: "We sometimes feel like chemists in the age before the periodic system was understood" (Wadman, 2008: 53). The introduction of the engineering perspective – as a result of the convergence between neuroscience and information technology – might be able to change that feeling.

4.1.1. Bottom-up approach: reverse engineering of the brain

One particular approach can be extremely helpful in understanding neural mechanisms: reverse engineering of the brain. This approach might even achieve insights into the nature of intelligence or consciousness. This computational approach to the understanding of brain function is embodied in the Blue Brain project.

Inspired by the Blue Gene project which helped out genetics in studying the molecular functioning of genes, the Blue Brain project was started in 2005 by IBM together with *Ecole Polytechnique Federale de Lausanne* in Switzerland. The main purpose is to build a physiological simulation of the mammalian brain. The first phase focused on reconstructing a single neocortical column, an elementary unit of the neocortex[3], at the cellular level.

[2] Systems biology may come up with a solution using a new perspective (i.e. integration in stead of reduction).

[3] The neocortex is the outer layer of the brain and makes up of 90% of the cerebral cortex. It is involved in higher brain functions like language, sensory perception, conscious thought, etc.

To achieve this, an IBM supercomputer was used, consisting of 2000 programmed microchips,[4] that each act like a real single neuron. Like genetics used information technology in the 1980s and 90s to study and model the human genome, neuroscience is employing IT as a tool to make sense of all the brain data. This first phase has been successful. The behaviour of the computer replicates with precision the cellular events in a neocortical column. The researchers are now planning to use more powerful computers to link such simulated columns together into something that mimics a brain. The Blue Brain project has delivered the first bottom-up model of the brain grounded in empirical data.[5] To chief scientist Markram, however, the project is not just a model of a neural circuit. For him, this neuro-engineering project represents a whole new kind of neuroscience which – contrary to cognitive psychology - has no history of modeling. The upcoming field of computational neuroscience is trying to change that.

Interestingly, the Blue Brain scientists explicitly state on their website that their project is *not* an artificial intelligence project: they are not trying to create a specific form of intelligence. The project is primarily designed to *understand* the brain and brain disorders. At the same time, it may well be possible that the project may be the first to deliver a true 'artificial intelligence' through this process of reverse engineering. Markram (2008) already has future plans to download the simulation of a complete rat brain into a robotic rat so that the brain has a body. "The only way to really know what the model is capable of is to give it legs. If the robotic rat just bumps into walls, then we've got a problem." This shows that the Blue Brain project – and for that matter other neuroscientific projects as well – will in the end be able to contribute to the field of artificial intelligence (see section 5 on Engineering of Living Artefacts). The brain not only requires novel ideas – like the Blue Brain project – but the brain also suggests novel ideas, like Daniel Andler states in the EU report on the development of cognitive science in Europe (2005). Neuroscience has new insights to offer to computer engineers on how to construct artificial cognitive systems or how to improve human-machine interfaces.

4.1.2. Top-down approach: cultured neuronal networks

There have been other engineering perspectives on how to understand the mechanisms underlying the brain. It concerns top-down[6] approaches to study neural networks: so-called *cultured* neuronal networks (or neuro-chips or neuroelectronics). These are cell cultures of neurons – usually harvested as neural stem cells from an embryo – that are used as a model to study the brain. Often, cultured neuronal networks are connected to an input or output device such as a multi-electrode array (MEA), thus allowing two-way communication between the researcher and the network (Fromherz, 2003). Such neuroelectronic systems have proved to be a very valuable tool to study the underlying principles behind neuronal learning, memory, plasticity and connectivity.

[4] The programming is based on existing ion channeling data: the basis of the way real neurons electronically communicate with each other. These data are derived from a robot that makes multiple recordings from different genetically engineered hamster cells under different physiological conditions.

[5] Contrary to the new field of computational neuroscience that also uses computers to build functional models of the brain and the mind. Their models are not necessary modelled on reality.

[6] Top-down here means that the starting point of the approach is existing ('real life') neurons (instead of the bottom-up approach of the Blue Brain project where the starting point is artificially modelled neurons).

Some researchers connect these cultured neuronal networks to virtual bodies of animals ('animat'), robotic components ('hybrot') or real bodies of insects or mammals like rats. In 2004 such a neuro-chip has been used to even fly a F-22 fighter jet aircraft simulator. The patterns of neuronal activity of the cultured networks are used to control the virtual or real body or the jet. Main purpose of this research is to study neuronal activity and plasticity while the cultured neuronal network is receiving at least some sensory feedback. In the end, these research tools may also offer application possibilities outside the lab, within the realm of artificial intelligence or man-machine interfaces. For example, the above neuro-chips nowadays function as a prototype within the development of higher-brain prosthesis (Fromherz, 2003).

4.2. Intervening in the brain

As a result of our increased understanding of the brain, we are more and more seeing the brain and the mind in mechanistic terms. This is nicely illustrated by a quote from Blue Brain scientist Markram (2008): "The power of Blue Brain is that it can transform a metaphysical paradox into a technological problem. […] Once we can model a brain, we should be able to model what every brain makes. We should be able to experience the experiences of another mind."

The demystification of the brain and the mind is rooted in the increasingly popular idea – not only in science but also in society – that the mind[7] can be reduced entirely to brain functions. Or as Nicolas Rose (2007: 192) writes about this contemporary style of thought: "Mind is simply what the brain, does." The brain – and thus the mind – is more and more considered to be an organ like any other organ in the body – although more complex – with its different regions, chemicals, etc.

This popular mechanistic view on the mind encourages an engineering approach to the brain, like trying to interface our brain with electronic devices and computers. Schermer puts it in her article *The Ghost and the Machine* (2009) as follows:

> "The mind is increasingly looked upon as a bodily entity and understood in reductionistic and materialistic terms. Brain-machine interactions are conceptually realized through this vision and the success of these technologies seems to reconfirm the accuracy of that vision. By manipulating the brain, behaviour and personality of people can be changed."

Recently, there has been a overwhelming growth in engineering techniques or therapies that can be used to directly intervene in the brain, like deep brain stimulation, transcranial magnetic stimulation (TMS) or neurostimulators for the central nervous system.[8] These neurotechnologies are currently used to treat several conditions, including: severe depression, epilepsy, gastroparesis, hearing loss, incontinence, chronic pain, Parkinson's disease, essential tremor and dystonia. Experimental research on using deep brain neurostimulation (DBS) is done not only for neurological disorders like Parkinson, but increasingly also for psychiatric disorders like obsessive compulsive disorder and, other large population diseases like Alzheimer, chronic migraine, severe obesity, etc.

[7] Mind collectively refers to the aspects of intelligence and consciousness manifested as combinations of thought, perception, memory, emotion, will and imagination. See http://en.wikipedia.org/wiki/Mind.

[8] Neurostimulation is a way to stimulate the brain and the central nervous system directly with the help of electronic or magnetic devices.

Every year six to seven new indications for DBS are studied. The global market for neurostimulation products is already expected to be worth 3,6 billion US dollars in 2009, growing at a rate of nearly 23%.[9] The reasons behind this rapid growth are both the multi treatment possibilities of neurostimulation as well as the emergence of venture capital in the industry. Beside a change in style of thought in the western culture – mechanization of the mind – there is also a more pragmatic reason for the growth of the neurotech market. It is easier and less expensive to bring a medical device like a neurostimulator to the market than a psychofarmacology product.

Besides neurostimulation, there are many other neurotechnologies through which we are increasingly trying to intervene in the brain and the mind. There is for example neurofeedback based on fMRI or EEG or other more advanced brain computer interfaces (BCI) for deaf patients – over 100.000 deaf people currently have a cochleair implant – or for paralyzed people, enabling them to communicate their intentions directly to the outside world by thinking about moving a cursor for example.

Neurotechnologies concerned with electronic and engineering methods of understanding and controlling nervous system function make up an even bigger market. In 2008 global neurodevices industry revenues rose 18,6% tot 6,1 billion US dollars[10]. These figures show yet another way of how biology becomes technology within the domain of the overarching cognitive sciences[11].

4.3. Social and ethical issues

So far there has been little formal consideration (a European ELSI agenda for example) of the implications of the rapidly growing brain research and neurotech development. At the same time, the field of neuroethics is developing quickly with a substantial amount of scientific literature having already been produced in this area, including specialised academic journals like AJOB/Neuroscience and Neuroethics. In addition, the Neuroethics Society was recently founded and the European Neuroscience and Society Network (ENSN) was set up in Europe.

Neuroethics concerns many issues that are familiar to the traditional field of bio-ethics, like medicalisation, treatment versus enhancement, social justice, safety, privacy issues, man-machine distinction and many more. Maybe one issue stands out and gets special meaning with respect to the brain. That is the existential issue of selfhood and identity. Namely, when we increasingly believe that 'we are our brain' and that the brain is a key and determinative factor of our personality, intervening in the brain by ways of neurotechnologies, raises questions on alterations of 'self' and 'personhood' which many people feel uncomfortable about. Besides the ethics of neuroscience, it is also important to consider the neuroscience of ethics.

[9] See www.marketsandmarkets.com/Market-Reports/neurostimulators-advanced-technologies-and-global-market-102.html

[10] Neurotechnology Industry 2009 Report, see www.neuroinsights.com.

[11] A highly interdisciplinary field (psychology, philosophy, neuroscience, linguistics, anthropology, artificial intelligence, sociology and biology) united in the purpose of studying the nature of intelligence.

Brain research increasingly produces data about the neurobiological underpinnings of what makes us human: these findings are unique and have no precedent in any other science (Levy, 2008; Farah, 2005). There has been already some critical ethical and sociological reflections on the neuroscientific findings and perspective on the existence of free will, human rationality and the nature of morality and spirituality.

4.3.1. Biology becoming technology and vice versa

This section has shown in many ways that within the brain sciences 'biology is becoming technology'. At the technological level, this is due to the convergence of neuroscience with other fields like information technology (e.g. enabling reverse engineering of the brain and connections between neurons and electrodes) and also nanotechnology (e.g. enabling miniaturization of (parts of) brain-machine interfaces). At the cultural level, the shift to a reductionistic and mechanical view of our mind, has encouraged research and development of all different kinds of brain-machine interfaces. Although we are far from understanding our brain completely, the dream and promise of one coherent brain theory has to some extent materialised. That raises the hopes of scientists and engineers that in the end we are and will be able to fully understand, control and enhance our brain and mind.

We may notice that At the same time, the trend of 'biology becoming technology' tends to nearly inconspicuously transforms into the trend of 'technology becoming biology'. The Blue Brain project provides a nice example. AThis is especially true when as a more or less *side-effect* of thise reverse engineering project which aims to understand the brain, an actual novel artificial intelligent platform is created that mimics the human brain. In the next section we will go into these neuro-mimetics developments from the perspective of Artificial Intelligence (AI).

5. ENGINEERING OF INTELLIGENT ARTEFACTS

> "To date, however, most AI research and development has utilized engineering methods that are not necessarily based on how the human brain functions, for the simple reason that we have not had the precise tools needed to develop detailed models of human cognition." Ray Kurzweil (2005: 144)
>
> "We believe that computers can get close to the processing power of our brains if the software architecture is based on our cerebral cortex. In Numenta's opinion, this marks a new beginning for the computer industry, just like the revolution of the microchip 50 years ago." Subutai Ahmad (2008: 1)

Neuroscience is not the only field that has been studying the nature of cognition over the last decades. The scientific community of Artificial Intelligence (AI) has also been trying to understand cognition in order to reproduce intelligence in artefacts that matches and in the end even exceeds human intelligence (i.e. 'strong AI'). Although the understanding of natural and building artificial cognitive systems seem to be two closely related activities, for quite a long time, scientists have been working separately on both scientific endeavours. The above quote by Kurzweil illustrates that. But now neuroscience is making rapid progress in unravelling the mechanisms underlying the brain, more AI scientists are looking into neuroscientific research for inspiration.

Jeff Hawkins for example – the founder of Palm Computing – recently started the company Numenta which is working on developing an intelligent computer that does not need to be programmed but, like the human brain, learns by identifying patterns in complex data. Hawkins calls it a hierarchical temporal memory system (HTM) patterned after the human neocortex. This presents a perfect example of what might be called neuro-mimetics. (Analogous to what engineers call biomimetics: the process of understanding and applying biological principles to human design). Technology is clearly becoming biology here: artificial cognitive systems are functionally designed after the human brain, acquiring properties which we used to think of as uniquely human. Like in the case of Numenta: learning by identifying patterns. Besides quite literally mimicking (parts of) the *brain* like Numenta does, another "technology is becoming biology" route can be signalled. This development is about engineering intelligent artefacts that mimick human *behaviour* as in case of affective computing and human-like robots, so-called humanoids.

In this section we will give a brief history of the field of AI and describe the current trend within AI to bring biology (back) into the machine; both from the brain and behaviour mimicking perspective. The section will point at some ethical and social issues surrounding the bioengineering of intelligent artefacts.

5.1. Short history of Artificial Intelligence

Artificial Intelligence started as a science in 1956 when at Darthmouth College the first meeting was held and the term artificial intelligence was coined. Right from the start the AI movement took on the direction of logic based and symbols manipulating computer programs based on an abstract model of human reasoning. This approach has led to artificial cognitive systems that are very good in performing one specific cognitive task. Many of those tasks, like calculating, formerly required human intelligence but can now be done by an artificial cognitive system at human levels or even better (so called 'narrow AI'). Examples of successful AI research are: character recognition, speech recognition, machine vision, robotics, data mining, medical informatics and automated investing.

Interestingly, the logic and symbol based direction AI took from the beginning, was quite opposite to the more biologically inspired origins of AI: cybernetics. Cybernetics started in the 40s under the guidance of Norbert Wiener with the goal to understand general principles underlying behaviour in animals and machines. Central in their ideas is the concept of self regulation, self organisation and feedback as essential characteristics of cognitive systems since continuous adaption to the environment is the only way for living systems to survive. Consequently, cybernetics had a strong interest in developing brain-like devices. However, with the rise of the more logic based AI movement, the influence of cybernetics mostly fell away (Husbands et al., 2008). Still, the work in adaptive systems did not disappear totally, proven by the success of machine learning and artificial neural networks (ANN). For example, Marvin Minsky, one of the founding fathers of AI, continued to work on the construction of ANNs that were able to perform simple learning tasks. In fact, in 1971 he wrote the book *Perceptrons* which became the foundational work on artificial neural networks.[12]

Nowadays, the work in machine intelligence has become much more aligned with the (neuro)biological sciences. In the former section, we described that computer science and AI are increasingly becoming important for furthering progress in the neurosciences. Neurosciences for its part has become a major source of inspiration for engineers in the field of AI and human machine interfaces. Or as AI scientist and futurist Ray Kurzweil (2005: 265) phrases it: "We already have a set of powerful tools that emerged from AI research and that have been refined and improved over several decades of development. The brain reverse engineering project will greatly augment this toolkit by also providing a panoply of new, biologically inspired, self organizing techniques."

[12] However, some claim that this book has contributed to what is called the 'AI winter' when a lot of the funding to AI research dried up because the field was not living up to the expectations.

5.2. Mimicking the brain: 'neuromimetics'

The European Blue Brain project, as discussed in section 4.1., aims to model the brain virtually, based on data of the communication of neurons in a real mammalian brain. Various current research projects go beyond virtually *modelling* parts of the brain and actually try to *build* chips and computers that mimick certain features of the brain: parallel processing or even neural plasticity.

We will describe three projects that try to poor the brain into silicon. First, in Germany there is a Artificial Intelligence project called FACEST: Fast Analog Computing with Emergent Transient States.[13] The researchers have created a silicon chip designed to function like a human brain "through recreating the neurons and synapses as circuits of transistors and capacitors, designed to produce the same sort of electrical activity as their biological counterparts" (Graham, 2009). The researchers claim that the chip is able to mimic the brain's ability to learn much better than any other artificial cognitive system. In comparison to artificial neuronal networks or other neural simulation applications, FACEST can be described as a hardwired approach. The most interesting part of such a chip is that it is able to operate truly parallel like the brain does, instead of serial like computers usually do. The current prototype can operate even 100,000 times faster than the real human brain. Second, researchers at Stanford University[14] have created a neuromorphic chip that simulates neural plasticity, and thus possesses the ability to form new connections. Moreover, in 2008, the Defense Advanced Research Projects Agency (DARPA) started a research program called Systems of Neuromorphic Adaptive Plastic Scalable Electronics (SyNAPSE) in which amongst others IBM and Hewlett Packard are involved.[15] The rationale behind the program is cited at their website:

> "Today's programmable machines are limited not only by their computational capacity, but also by an architecture requiring human-derived algorithms to both describe and process information from their environment. In contrast, biological neural systems (e.g. brains) autonomously process information in complex environments by automatically learning relevant and probabilistically stable features and associations. Since real world problems generally have many variables and nearly infinite combinatorial complexity, neuromorphic electronic machines would be preferable in a host of applications."

The aim of these three research programs is to build a supercomputer by making use of existing knowledge of brain functions. That is a crucial difference with the reverse engineering project Blue Brain which aim it is to engineer an actual brain and in the end even a mind. The other neuromimetics projects are *not* primarily neuroscientific projects aiming to understand the workings of the brain by emulating it. They are applied physics projects with a main goal to mimic the most useful elements of the brain in order to improve existing artificial cognitive systems. Nevertheless, these augmented systems might also "serve as a tool to investigate brain function", as the Stanford project mentions on its site. Again we see that at the crossing of projects coming from a neuroscientific perspective (reverse engineering) with projects deriving from a AI perspective (neuromimetics), the trend of 'biology becoming technology' starts to intermingle with the trend of 'technology becoming biology'.

[13] http://facets.kip.uni-heidelberg.de/

[14] www.stanford.edu/group/brainsinsilicon/

[15] www.darpa.mil/dso/thrusts/bio/biologically/synapse/

5.3. Understanding and mimicking human behaviour

Improving artificial cognitive systems by mimicking certain characteristics of the brain, might be called the 'hardwired' approach. Besides, there is also a 'softwired' approach to augment current intelligent artefacts by using our growing knowledge of human cognition, including emotion. This approach aims to develop systems that can on the one hand recognize and act upon human behaviour better and on the other hand are able to mimic human behaviour better than before. The upcoming field of social neuroscience – studying how the brain mediates social interactions and emotions – will likely support the further development of the 'softwired' AI approach. In this subsection, we will very briefly touch upon developments in the field of affective computing and robotics.

5.3.1. Affective computing

An upcoming field in AI is affective computing, that concentrates specifically on constructing social intelligence. It deals with the design of systems and devices that can recognize, interpret, and process human emotions. For example in e-learning, affective computing can be used to adapt the presentation of a teacher avatar when the student is frustrated, pleased or bored. Or in a gaming application, where it is already possible to scan the expression of the face of the gamer and transport the same expression real time onto the face of his or her avatar. At MIT, researchers are working on an 'Interactive Social-Emotional Toolkit' (iSET) designed to help children with disorders linked to sensory processing, such as autism, to understand emotions in other people[16]. Affective computing is also applied within the field of persuasive technologies, i.e. technologies that help to change your behaviour based on universal influencing principles like aversion against loss or cognitive dissonance. Detecting a user's emotional state, helps the system to determine the best persuasion strategy. The main rationale behind affective computing is that many technologies would work better if they were 'aware' of their user's feelings.

Most of the affective computing research is based on psychology research, but recently neuroscience is also adding to the field. For example, researchers are currently working on brain computer interfaces that can detect neural signals of pleasure, frustration, etc. At the University of Twente they are already able to change the appearance of an avatar – from a friendly elf into a aggressive bear – based on neural signals of the user. Such emotion detection hardware based on neural measuring methods are considered interesting because it can help to detect subjective judgments that take place on a subconscious level or detect subjective judgements that are not reflected in behaviour. Besides detecting emotions, affective computing aims to bring emotion into the machine. In this case the goal is to develop systems that exhibit emotions or are convincingly able to simulate emotions. The robot Jules, created by David Hanson, presents a conversational character robot, which already is very humanlike in its expressiveness.[17] In the next subsection, we will go into the rapidly expanding field of robotics.

[16] See http://affect.media.mit.edu/projects.php for a list of examples of affective computing projects.

[17] www.youtube.com/watch?v=ysU56JzBjTY&feature=related

5.3.2. Robotics

Besides being better able to detect and show social and emotional behaviour, engineers also try to make artificial cognitive systems more 'human' by giving them a higher degree of autonomy. So far robotic systems – unlike humans – cannot react properly to unexpected commands or situations, since they have only a rigid set of responses within pre-specified conditions. Engineers would like to develop smart robotic systems capable of learning complex skills and performing them autonomously (i.e. without remote control) in novel and unanticipated situations. Designing autonomous cognitive robot system is also one of the two major challenges of European robotics research (EC, 2008): "to design robotic systems able to perform complex tasks with a high degree of autonomy".

The other challenge is more in line with the aims of affective computing, namely to "develop robotic systems that can sense and interact with the human world in useful ways". Therefore they need to be able to assess their environment carefully in order to recognize, interpret, and process human behaviour. The same EU report states that the EU is in need of research "required to give robots perhaps more human-like qualities, including the sense of sight, hearing and touch." So when it comes to social robotics – assistive robots outside the industrial realm and into social domains like health care, military, etc. – the homo sapiens is actually becoming the ideal model for engineers. In order to be able to interact sensibly with humans, robots need to become (exactly) like humans. The ultimate frontier of 'technology becoming biology'.

5.4. Social and ethical issues

There are different social and ethical aspects involved in both 'brainlike' artificial systems (see 5.2) and 'humanlike' artificial systems (see 5.3). Ethical issues involved in more 'humanlike' artificial systems are for example fears of emotion sensing computing and persuasive computing being used in patronising ways. Or emotion sensors undermining personal relationships, leaving for example elderly people more isolated since they are 'already' monitored by technology. Of course privacy issues are also involved here, in particular issues of 'cognitive liberty', for example in case of security services using face and posture reading systems to sense stress from a distance.

When it comes to robotics and neuromimetics there is the hope and fear of developing autonomous and self-optimising supercomputers that will exceed human intelligence . This situation is often referred to as 'AI singularity': a runaway chain reaction of machines capable of building even better machines. Quite recently, for the first time, a panel of eminent AI scientists, roboticists and ethical and legal scholars have addressed this issue[18]. This panel warned that in the near future machines will have a far greater ability to make and execute decisions on their own (instead of being only supportive to human decision-making). What to think of this? The panel decided that singularity is not their biggest worry. Instead they are concerned about 'malware' that can mimic the digital behaviour of humans. Think for example about computer viruses that could impersonate or act as an individual because it is able to monitor silently someone's email, text messages, diary, etc. Peter Szolovits, an AI scientist at MIT, is paraphrased in the *NewScientist* (Campbell, 2009) about this : "Common everyday computer systems such as smartphones have layers of complexity that could lead to unintended consequences or allow malicious exploitation."

[18] www.aaai.org/Organization/presidential-panel.php

Another worry of the panel is "the assignment of liability associated with costly, unforeseen behaviours of autonomous or semi-autonomous decision making systems." Writer and psychologist Susan Blackmore (2009) refers to the internet as a whole, and argues that the internet is also increasingly becoming an autonomously working entity: "Much of the content on the web is now designed automatically by machines rather than people." She calls it: "A new evolutionary process that is greedy, selfish and utterly blind to the consequences of its own expansion".

5.4.1. Technology becoming biology

Clearly also within the field of Artificial Intelligence 'technology is becoming biology'. This happens in two different ways. One is the hardwire approach of literally building artificial cognitive systems mimicking unique characteristics of the (human) *brain*. This endeavour is focused on *exceeding* the *cognitive* abilities of humans: creating super intelligent artefacts, In addition, the softwire approach is focused on matching the *affective* behaviour of humans. Within this line of research, engineers are increasingly better able to understand and mimick human *behaviour*. Interestingly, both approaches give rise to fears about technology becoming 'too much' biology, or maybe better 'superhuman'. Artificial cognitive systems becoming too autonomous, resulting in black scenarios in which humans are no longer in control of the technology they themselves have helped to create (cf. Joy 2000; Arthur 2009).

6. CONCLUSIONS: THE NEED TO REFLECT ON BIO-ENGINEERING (IN) THE 21ST CENTURY

> "Our deepest hope as humans lies in technology; but our deepest trust lies in nature." Brian Arthur (2009: 11)

In the introduction a new engineering approach towards life was signalled, which promises that the organic world is becoming make-able in the sense that it can be (re-)designed and (re-)built. Two interconnected trends were described: "biology is becoming technology" and "technology is becoming biology". The four described fields of bio-engineering – engineering of the body, living artefacts, brain, and intelligent artefacts - clearly substantiate the arrival of such a new engineering approach to life, and confirm the above two trends. It was also found that these two trends start to close on each other, and even start to intermingle. As a result it becomes hard, sometimes, to distinguish between these two trends.

With respect to engineering the body both the field of regenerative medicine and molecular medicine demonstrate such a new engineering approach to life. Within the broad field of regenerative medicine, tissue engineering promises to regenerate new tissue, while stem cell science promises to provide the fundamental 'building blocks' to restore or repair certain bodily functions. Molecular medicine promises earlier and precise detection of diseases and even predisposition, as well as effective personalised treatments. With regards to engineering of living artefacts, synthetic biology promises to produce a completely programmable bacteria, build artificial genetic systems based on alternative nucleic acid architectures, and even build an artificial cell system from scratch.

Also in the field of engineering of the brain many examples of a new bio-engineering approach were found. The Blue Brain project, in particular, clearly demonstrates the trend of biology is becoming technology and vice versa. The project aims to re-engineer the brain by digitally mimicking biological processes in the brain. A future challenge would be to create 'real' artificial intelligence. Finally, some new paths were described within the field of engineering of intelligent artefacts. Research in this field aims to build supercomputers by making use of existing knowledge of brain functions. Besides building better hardware, another type of engineering approach was described aiming at developing machines that can recognise, act upon or mimic human social and emotional behaviour.

At the beginning of the 21st century, thus, a wide variety of bio-engineering fields have emerged that all promise to either repair, redesign, reconstruct or enhance biological and cognitive process or to design and build living and thinking artefacts. NBIC convergence, as an actual and anticipated development, stimulates and substantiates both practically and ideologically the arrival such a new engineering approach to life. Over the last decade, this mega-trend has been signalled by various authors (cf. Merelman 2000, Garreau 2004, Van Est et al. 2006, 2008, Bess 2008, Arthur 2009, Swierstra et al. 2009a, 2009b). They all argue that, while engineering was mainly about manipulating external nature, we are beginning to use technology more and more to manipulate (our) internal nature, i.e. to intervene directly within (our) nature. This fundamental broadening of our engineering perspective and ambitions challenges our deepest moral intuitions (cf. Swierstra et al. 2009b). Techno-optimism and hope for a better future go in hand in hand with fear.

As Arthur (2009: 215) explains: "We fear that technology separates us from nature, destroys nature, destroys *our* nature. We fear this phenomenon of technology that is not in our control. We fear we are unleashing some thing of disembodied action somehow taking on a life of its own and coming somehow to control *us*." It is self-evident that a development – bio-engineering (in) the 21st century – which evokes so much human emotions is in need of social reflection and political and public debate.

The STOA-project "Making *perfect* life" aims to reflect from a social, ethical and policy point of view on new developments within the above four fields of bio-engineering. As such, this project aims to provide Members of the European Parliament information about the future directions of bio-engineering and the ethical and political issues involved. First, there is need for realistic estimations of the speed and direction of scientific progress in these four fields. The project, therefore, wants to carefully look at the spectacular visions, promises and future expectations that surround these developments. Moreover, we would like to study to what extent the European research agenda is driven by these visions. The project proposes to investigate the role and meaning of the four respective bio-engineering fields within the European research area, and to explore why and how these fields are being developed. Thirdly, the project aims to reflect on the social and ethical issues related to the new engineering approach to life. Finally, a key objective of the proposed project is to explore the (European) policy issues related to developments in the field of engineering of the body, brain, living artefacts, and intelligent artefacts.

PROJECT PLAN MAKING *PERFECT* LIFE

The title "Making *perfect* life" refers to the emergence, at the dawn of this 21st century, of a new engineering approach towards life, which holds the promise of a 'mouldable' organic world that can be (re)designed and (re)built. This study aims to substantiate that such a development towards bio-engineering is indeed taking place, and that it is important and timely to reflect on this new set of bio-engineering capabilities and ambitions from a societal and policy point of view.

We will distinguish between four fields of bio-engineering:

- Engineering of the body
- Engineering of living artefacts
- Engineering of the brain
- Engineering of intelligent artefacts

For each of these four fields of bio-engineering we will shortly introduce the new developments within science and technology that are currently taking place. We will furthermore describe some of the social issues these new developments are likely to raise. In particular, we will reflect on the type of issues involved in the engineering of the body, brain, and living and intelligent artefacts. Do we indeed witness that "biology is becoming technology" or "technology is becoming biology"? Or perhaps both? And what does that mean for our understanding of life and living systems, and for our concept of making *perfect* life? We will conclude this report with some final reflections and remarks about these two trends and their broader implications.

This project aims to provide an overview of the scientific and technological state of the art with respect to bio-engineering. It reflects on the social and ethical issues that are involved. What kind of opportunities and risks arise, and what kind of ethical questions are raised? Moreover, this study analyses in what way these developments challenge European policy making. What political implications can be drawn from techno-scientific attempts to make *perfect* life?

As such this STOA-project aims to provide Members of the European Parliament (MEPs) information about the future directions of bio-engineering. The project thus refers to a far broader development than can be studied from a single technology. Rather, the strength of this project is exactly in offering MEPs a 'trans-technological' view. Only in this way, the ethical, legal and social challenges related to bio-engineering can be properly discussed and understood.

More specifically, the project investigates the role and meaning of the four respective bio-engineering fields within the European research area, and explores why and how these fields are being developed. What are the visions, expectations and demands that are driving the different R&D fields? Moreover, the project explores the various social, ethical and legal issues and contexts that are connected to these new technological skills. Of specific concern here are the definition or meaning of life and intelligence, and the boundary between the "natural" and "artificial", and the question to what extent we may intervene in biological and cognitive functions.

A key objective throughout this project is to explore the political and policy relevance of the techno-scientific developments within the four discerned fields of bio-engineering. We propose two distinct phases for this project in which this objective is optimally implemented. In particular, the second phase will focus on the political and policy challenges of the new bio-engineering developments. In the next section, both phases will be explained further.

Phase 1: Monitoring report and setting up the network

During the first phase the four respective fields of bio-engineering will be further explored and discussed. The study document *Making Perfect Life: Bio-engineering (in) the 21st century* will serve a point of departure for this exploration. This phase will start by circulating the study document to selected Members of the European Parliament (MEPs), who have expressed interest in related subjects, and to organise personal meetings with those MEPs. After these meetings, their questions, advice and/or comment can be incorporated in the project to increase political relevance of the project. The MEPs to be briefed about the project include Bart Staes and Jorgo Chatzimarkakis.

In phase 1, a monitoring report will be produced that will be presented and discussed during a conference to be organised in 2010 in Brussels. The following research outputs and deliberation activities are distinguished:

1. A concise monitoring report (maximum 80 pages, including an executive summary), which will provide an initial agenda for policy making at the European level. This report will inlcude:
    a. An overview of the state of the art of the science and technology in the four engineering fields. In addition to technological horizon scanning, research projects within the ongoing European Framework Program are analysed in order to identify comparative issues and ensure political relevance.
    b. An exploration of the relevant ethical, legal, social, and R&D-policy aspects surrounding the new techno-scientific developments within these four engineering fields. Moreover, this project will provide a sketch of the related expert and public debates. Rather than discussing these aspects in detail for each field of R&D, phase 1 of the project will focus on identifying general tendencies and overlapping issues in these four bio-engineering fields.
    c. An analysis of the relevance of these topics for the European Parliament. Relevant debates in the committees of the European Parliament on related issues are explored and put in perspective. Moreover, interviews with interested MEPs will be organised to explore the political relevance of "making *perfect* life".
2. A conference organisation and presentation. The monitoring report will be presented and discussed during a conference, involving MEPs and other members from relevant communities. Specific effort will be put into translating the results from the report and conference into media attention.
3. Preparatory work for phase 2. At the end of phase 1, one specific case will be selected from each of the four explored fields of bio-engineering to be scrutinized further in the next project phase from a policy and political perspective.

Phase 1 runs until November 2010. An overview of the outputs and deliverable as well as they will be delivered, can be found in the section «Overview of outputs and deliverables».

Phase 2: Exploring four specific subject areas from a political and policy perspective

In the first phase of the STOA-project "Making *perfect* life" four bio-engineering fields have been explored. The state of the art of the science and technology has been mapped, as well as the relevant ethical, legal and social issues. The central question in this second phase of the project is: What are the main challenges posed by these new bio-engineering developments from a policy and political perspective?

At the end of phase 1, four specific cases have been selected for further scrutiny in this phase 2 of the project. To address the question of political relevance and policy implications, the second phase concentrates on *specific current developments* and *actual political issues* at the Community level and the level of the Member States, with regards to the four specific selected cases. Each of the four subject areas will be explored in-depth by documentary analysis and involvement of relevant experts and stakeholders in meetings about the project. The most important challenge is to embed the issues in regular parliamentary work and the portfolios of MEPs. From the very beginning STOA should collaborate with EP committees concerned with the issues at stake.

The results of the studies of the four specific cases will be presented in four sub-reports. Each sub-report will be discussed during an expert-stakeholder meeting. The four sub-reports will create the synthesising basis of a final report, which will be presented and discussed during a workshop with MEPs. In this way the project results are directly fed back to the relevant actors (MEPs) while creating sustainable commitment to the issues at stake.

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