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Sustainable development in engineering: a review of principles and  
definition of a conceptual framework

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# Sustainable development in engineering: a review of principles and definition of a conceptual framework

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## Abstract

This paper aims to provide engineers and the engineering community with a conceptual framework setting out the connections between engineering projects and the sustainable development of environmental and social systems. The main principles of sustainable development on the one hand and of sustainable engineering on the other hand are first reviewed and summarized. Particular attention is paid to the principles put forward by international and national engineering organizations. Second, concepts and models originating in natural and social sciences are outlined to shed more light on the ways the various aspects of sustainability are related. The conceptual framework we propose combines the reviewed principles, concepts and models in a relevant manner for engineering projects. Engineering and physical or social systems prove to be related in manifold ways. While the most common relations are exposed in the sustainability framework, others have to be further elaborated in order to fully take into account the specificities of the various fields of engineering. Finally, applications of the sustainability framework in engineering practice and engineering education are discussed.

JEL codes: Q01, Q56, Q57, I31.

Keywords: Engineering; Sustainable development; Sustainability principles; Sustainability framework.

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## **Introduction**

More than 20 years have elapsed since the publication of *Our Common Future*, the United Nations report containing the most widely used definition of sustainable development stated as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). Since then, the notion has often been tentatively redefined and interpreted by individuals and organizations in connection with various fields. This has led to a deeper understanding of the concept and has also helped towards its dissemination to a broader audience; yet divergent viewpoints still hold. Since individuals and organizations have different backgrounds, values, interests and responsibilities, such disagreements on such a multi-faceted subject as sustainability cannot completely vanish. Nevertheless, a number of concurring elements emerge upon closer examination of the various interpretations of sustainable development which have been proposed so far.

The purpose of this paper is to provide the engineering community, and by extension, the business community and policy makers, with a conceptual framework illustrating the relations between technical projects and society as well as environment. In that perspective, general and engineering-specific principles of sustainable development are first reviewed then synthesized. Alternative sustainable development concepts and models which are rooted in natural and social sciences are also reviewed. The dynamics and interrelations between the most relevant issues of sustainability are scrutinized according to a systemic perspective. We then propose a framework that draws on the principles, models and concepts reviewed. Finally, the significance of this framework for engineering practice and for educational purposes is discussed.

### **General principles of sustainable development**

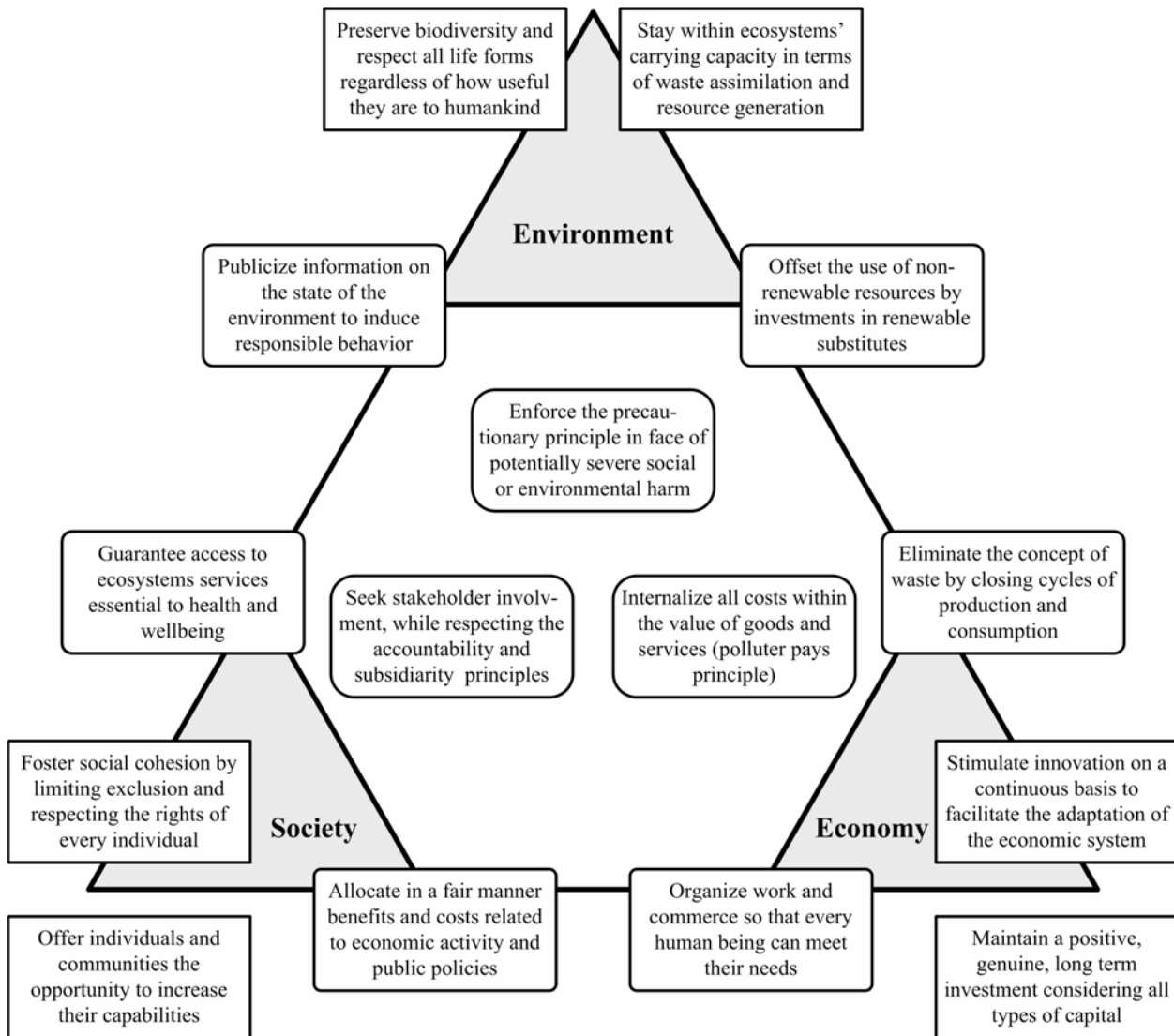
While definitions enable us to grasp the gist of concepts in a nutshell, principles are often needed to provide more precise guidance for action. Not surprisingly, many different sets of principles relating to sustainable development have been proposed over the years. Although all of the principles found in the literature cannot be listed, those reviewed in Table 1 offer a broad overview of the main themes connected with sustainability.

**Table 1. General principles of sustainable development**

Reference	Principles and comments
World Commission on Environment and Development (1987)	<i>Our Common Future</i> marks the emergence of sustainable development as an authorized concept. The report lists seven strategic imperatives encompassing what is now known as the economic, social and environmental dimensions of sustainable development.
Ceres (1989)	The CERES principles are a ten-point code of conduct for companies: Protection of the biosphere, Sustainable use of natural resources, Waste reduction and disposal, Energy conservation, Risk reduction, Safe products and services, Environmental restoration, Information for the public, Management commitment, Audits and reports.
United Nations (1992)	The Rio Declaration on Environment and Development contains 27 principles dealing with: Environmental protection, Poverty alleviation, International collaboration, Production and consumption, Capacity-building, Participation, Precaution, and Peace.
Haughton (1999)	There are five key equity principles to sustainable development: Equity within and between generations, Geographic equity or cross-border responsibility; Procedural equity and Equity between species composing biodiversity.
Earth Charter Initiative (2000)	The Earth Charter is based on four themes : Respect and care for the community of life, Ecological integrity, Social and economic justice, Democracy, nonviolence and peace. These 4 themes are then each broken down into four more detailed principles.
Valentin and Spangenberg (2000)	Principles of sustainable development are structured around 4 thematic imperatives (one for each dimension, i.e., economic, social, environmental and institutional) and 6 inter-thematic links (one for each bi-dimensional interconnection).
Robèrt et al. (2002)	Ten authors present four principles of sustainability making up the Natural Step Framework, as well as 13 principles of sustainable development which can be applied in more practical terms.
Parris and Kates (2003)	Three elements are to be sustained (Nature, Life support and Community) and 3 elements are to be developed (People, Economy and Society). Two or three goals are defined for each element, for a total of 17 sustainable development goals.
Becker (2005)	Sustainable systems are assumed to have three general characteristics (Resilience, Self-sufficiency and Collaboration) which, in turn, are subdivided into three indicators to facilitate their measurement.
Swiss Federal Statistical Office (2005)	Sustainable development is defined by three main elements (Social solidarity; Economic efficiency and Ecological responsibility) and by 45 postulates classified in 20 categories.
United Kingdom Government (2005)	The UK Sustainable development strategy contains five principles: Living within environmental limits, Ensuring a strong, healthy and just society, Achieving a sustainable economy, Promoting good governance and Using sound science responsibly. Many countries (Sweden, France, Columbia, etc.) adopted similar strategies.
Government of Manitoba (1997) and Government of Quebec (2006)	The Government of Manitoba and Quebec adopted Sustainable Development Acts respectively defining 13 and 16 principles. Other governments passed similar legislation: Estonia (1995), Belgium (1997), Oregon (2001), Luxemburg (2004) and Canada (2008).
Villeneuve (2006)	Four dimensions (ecological, economic, social and ethical) are used to define sustainable development and 8 multi-dimensional objectives are derived from these definitions.

A comprehensive list of sustainable development principles is given in Figure 1, based on those general principles reviewed in Table 1. In addition, several sets of principles focusing on a more specific angle (economic, social, human, environmental, institutional and ethical) were also considered. The principles in Figure 1 are structured along the three common dimensions of sustainable development: environment, society

and economy. This representation builds upon the prism of sustainability (Valentin and Spangenberg, 2000) as well as on the fractal triangle of sustainability (McDonough and Braungart, 2002). The principles which are closer to the extremities of the triangle (boxes with sharp corners) are one-dimensional while those on the between angles (boxes with round corners) are bi-dimensional. The latter principles have a stronger connection with the angle they are closer to. We improve upon previous models by providing two detailed principles for every angle and linkage. We also add three-dimensional principles (boxes with rounder corners) in the middle of the triangle, each of them being positioned according to their links with the angles. The entire triangle comprises 15 principles but can also be broken down into pentagons relating to the three dimensions of sustainability, each made of two one-dimensional, two bi-dimensional and one three-dimensional principles.



**Figure 1. Proposed sustainable development principles**

The principles in Figure 1 are wide enough to cover almost every kind of activity. The next section provides additional details on the principles dedicated to engineering.

### **Sustainable development principles dedicated to engineering**

Sustainable engineering principles were proposed by many players, namely international and national engineering organizations, and researchers in the field of engineering. The sets of principles we consider to be most relevant are listed in Table 2.

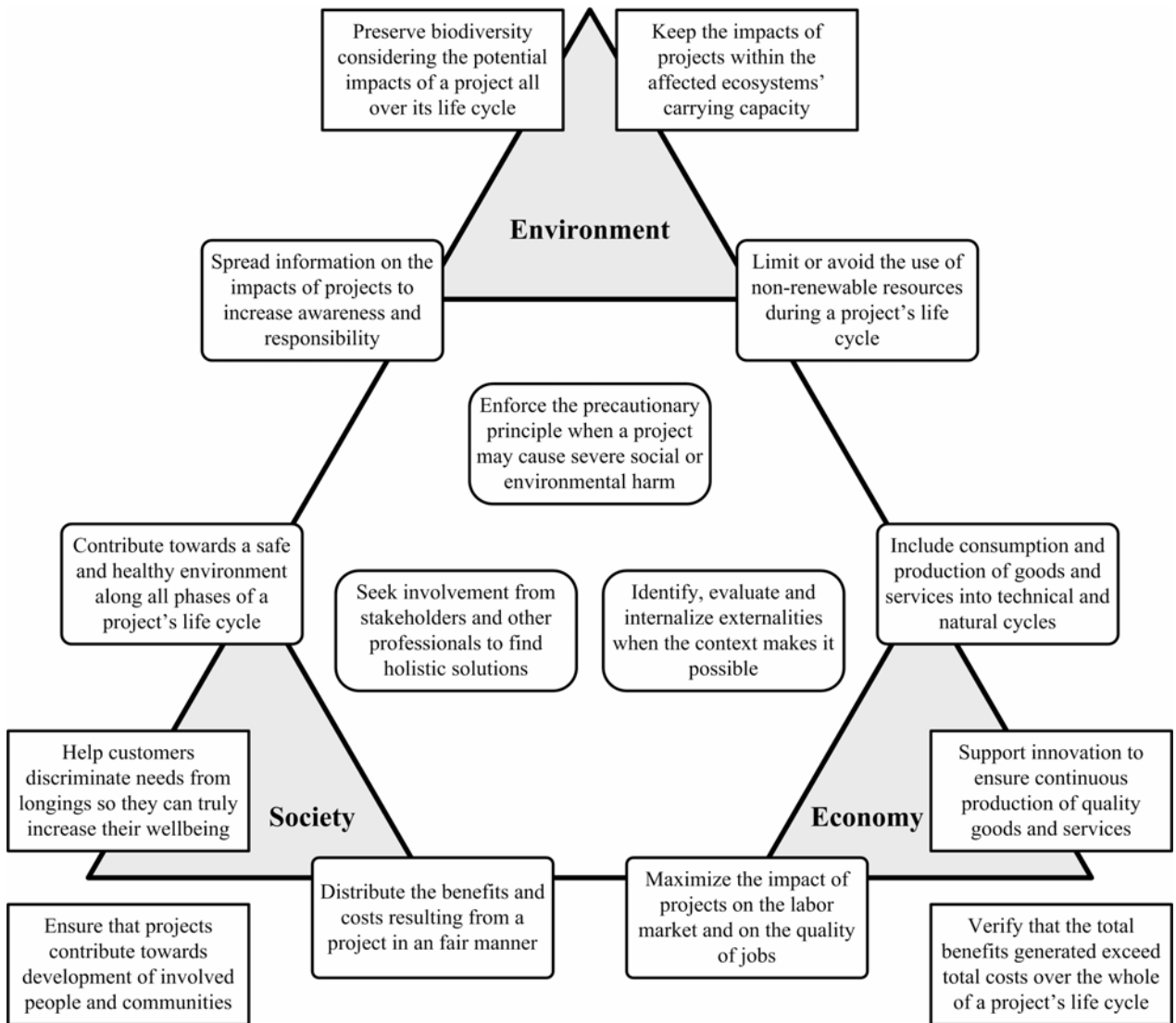
**Table 2. Sustainable engineering principles**

	Reference	Comments
International	International Federation of Consulting Engineers (FIDIC) (2000)	In a strategy paper dedicated to <i>Sustainable Development in the Consulting Engineering Industry</i> , the FIDIC lists 18 objectives categorized along the environmental, economic and social dimensions of sustainable development.
	World Federation of Engineering Organizations (WFEO) (2004)	The WFEO adopted the <i>Shanghai Declaration on Engineering and Sustainable Development</i> , stating that engineers should take greater responsibility for shaping the sustainable future and must thus commit to: Ethics; Interdisciplinarity; Education and capacity building; Women and gender issues; and International cooperation.
National	Institution of Civil Engineers (ICE) (United Kingdom) (2003)	According to ICE, sustainable engineering solutions: strike an informed balance in terms of costs, benefits, sustainability and acceptability; fit within the broader legislative framework; and involve an assessment of whole life cycle costs.
	Institute of Professional Engineers of New Zealand (2004)	Sustainable development focuses on three principles: Maintaining the viability of the planet; Providing equity within and between generations; and Solving problems holistically. Those principles, which prove to be similar to the objectives adopted by Engineers Australia, are detailed in 17 guidelines.
	Engineers Australia (2005)	There are three main objectives to sustainable development: Enhancing well-being while maintaining the viability of the planet, Ensuring equity within the present generation and for future ones, and Solving problems holistically and proactively. Eight principles are also proposed to achieve those objectives.
	Instituto de la Ingeniera de Espana (IIE) (2005)	IIE's <i>Manifesto for Sustainable Development</i> contains 13 principles and explains how the principles can be applied when designing plans, programs, projects and works or when operating systems already in use.
	The Royal Academy of Engineering (United Kingdom) (2005)	Twelve guiding principles are defined on the basis of case studies illustrating the issues connected to sustainable development in engineering. The document also illustrates how the principles can be applied to all the stages of an engineering project.
	Canadian Society for Civil Engineering (CSCE) (2006)	Civil engineering practice should follow nine guidelines: Including sustainability in mission and values; Protecting and enhancing environment; Considering true life cycle costs; Adopting green construction; Keeping informed on environmental issues; Meeting basic human needs; Providing leadership on sustainable development and influencing clients; Including other professionals and stakeholders; Monitoring and continuously improving existing projects.
	Engineers Canada (2006)	Engineers Canada adopted the <i>National Guideline on Environment and Sustainability</i> containing nine guidelines to help engineers fully implement their commitment to environmental protection and safeguarding public well-being.
Researchers	Clift and Morris (2002)	Engineers do not only have to find the best technical solution to a given problem, they should also consider whether: the most appropriate technology is being used; the uncertainty of science is factored in; waste and pollution are avoided all the while preserving resources; and whether social benefits and social acceptance are maximized.
	Abraham (2006)	Generally speaking, sustainable engineering solutions are technologically and economically viable, they promote human welfare and health as well as the biosphere at large. The author proposes nine principles to detail this general definition.
	Fenner et al. (2006)	An eight-point framework complementing the conventional issues of cost, time and quality is proposed: Ethical foundation; Future vision; Interlinking scales; Systems context; Holistic financial accountability; Maintenance of natural capital; Efficient coordinated infrastructure; and Justice through participation.

While a number national engineering organizations have adopted detailed lists of sustainable development principles (Australia, Canada, Spain, New Zealand and United Kingdom), a few others inserted a statement on

sustainable development into their Code of ethics (Finland – TEK, Netherlands – KIVI NIRIA and United States - NSPE).

Based on the general principles presented in Figure 1 and on the engineering-specific ones reviewed in Table 2, we propose a comprehensive set of sustainable engineering principles in Figure 2. They are organized along the same logical structure as the general principles in Figure 1.



**Figure 2. Proposed sustainable engineering principles**



The principles in Figure 2 are phrased in such a way as to fit any engineering project. One practical application of the sustainable engineering principles is the development of question grids. The 15 principles in Figure 2 are included in these grids (they may be slightly adjusted) and rephrased into questions (e.g. How can stakeholders and other professionals be involved in the project if holistic solutions are sought?). The purpose of a question grid is to feed and support the engineers' thinking concerning a project's sustainability from the moment it is initiated. However, the grid is too general to allow for the assessment of technical solutions. The principles must thus be contextualized and broken down into a more fine-grained set of criteria along which design options can be compared. Ultimately, the performance of an engineering system according to each criteria has to be measured with appropriate indicators.

Complying with all of the principles in Figure 2 simultaneously is obviously demanding. The context in which an engineer works will either facilitate or seriously hinder the operational value of sustainability principles. Thus, they must be considered as an ideal to achieve, in the same way as other values put forward in engineering codes of ethics.

Despite their relevance, lists of principles such as the one in Figure 2 only show to a certain extent the wide range of interactions between technology, ecosystems, individuals and society. A more systemic approach is therefore required to improve our understanding of how society and environment are affected by, and, in turn, also impact engineering projects.

### **Concepts and models relevant to environmental and social systems**

This section presents some of the most significant concepts and models proposed in natural or social sciences that help put engineering projects into their broader context. All concepts and models presented in Table 3 share, to some extent, the view that environment and society are complex and broad systems.

### **Table 3. Significant concepts and models relevant to sustainable development, environment and society**

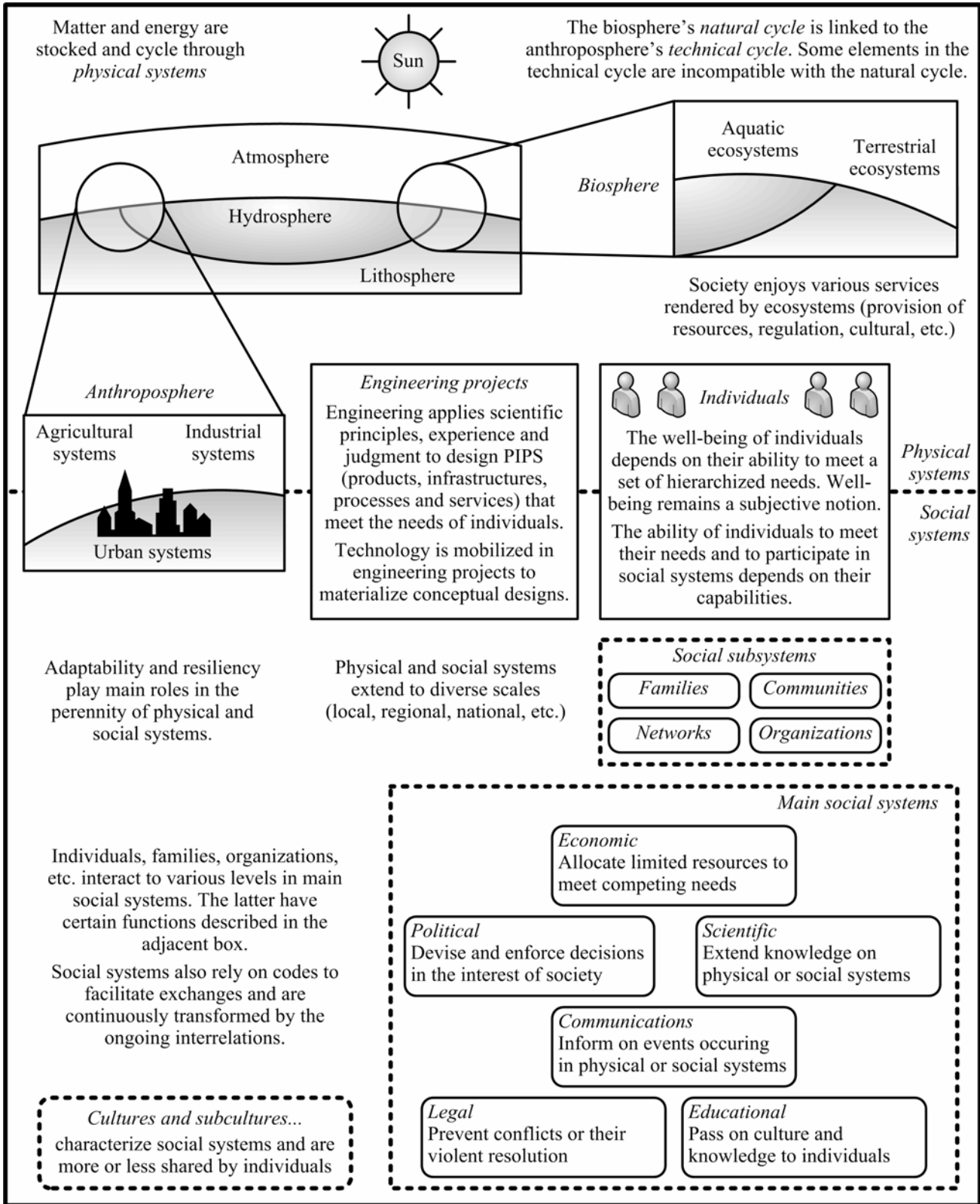
	Concept or model	Description
Sustainable development	Model of economic sustainability (Ikerd, 1997)	The limits of the economic system are expanded to include not only economic, but also ecological and social forms of capital. Sustainability requires that stocks of ecological and social capital be maintained and not depleted by economic activity.
	Model of the sustainable enterprise (Anderson, 1999)	Sustainable enterprises develop on seven fronts: eliminate waste; render emissions benign; use renewable energy; close technical and natural cycles; transport people and products efficiently; sensitize stakeholders; deliver services instead of products.
	Sustainable enterprise (Parrish, 2007)	The enterprise is a system around which individual stakeholders relate and that operates in a broader socio-ecological system. Individuals, companies and the socio-ecological system have survival and purpose needs. The sustainable enterprise organizes its activities so that both types of needs are met simultaneously for stakeholders, the enterprise itself and the socio-ecological system.
Socio-environmental	Industrial ecology (Graedel and Allenby, 1995)	Interactions between the industrial and ecological metabolisms have to become benign to preserve the latter. The changes needed in industrial systems should be inspired by the dynamics observed in natural ecosystems.
	Socio-economic process (Lawn, 2004)	The economy (man-made capital) is part of the sociosphere (social capital) which in turn is part of the ecosphere (natural capital). Well-being (or psychic income, as defined by the author) depends, in different ways, on each one of these systems.
	DPSIR framework (UNEP, 2005)	<i>Driving forces</i> (be they socio-economic or socio-cultural) increase or mitigate <i>Pressures</i> (stresses put on the environment by human activities) and thereby affect the <i>State of the environment</i> . In turn, environmental degradation results in <i>Impacts</i> (upon society or ecosystems) which can trigger <i>Responses</i> enforced by society.
Environmental	Earth's life support systems (Miller, 2005)	The biosphere is the portion of the Earth (atmosphere, hydrosphere and lithosphere) where living organisms exist and interact within ecosystems. The ecological services used by humankind (matter and water cycles, climate regulation, pollution control, etc.) rely on the sound functioning of ecosystems.
	Ecosystems and well-being (Millenium Ecosystem Assessment, 2005)	Ecosystems provide various provisioning, regulating and cultural services to humankind, which are directly linked to one or many constituents of well-being (security, basic material for good life, health and social cohesion).
Economic	Development as freedom (Sen, 1999)	Development can be seen as the expansion of freedoms enjoyed by people. Every person relies on a set of <i>capabilities</i> providing them the freedom to achieve valued lifestyles. <i>Capabilities</i> are materialized into <i>functionnings</i> (actual achievements).
	Needs-opportunity-ability model (OECD, 2002)	Individuals seek to meet their needs to maintain or improve their life standards. Their consumption opportunities are influenced by external factors (availability and accessibility of goods and services), as well as their internal capacities, or abilities (financial, temporal or physical means as well as skills).
	Macroeconomic flows (Parkin et al., 2005)	In a national economy, money circulates between four types of economic agents: households, governments, corporations and foreign countries. In addition to the direct transfers operated by governments, resources are distributed to economic agents via three markets: financial, goods and services, and production factors.
Social	The political system (Easton, 1965)	Society can be perceived as a system interacting with personality, and with biological and ecological systems. It is composed of various subsystems (cultural, political, economic, demographic, etc.). The political system translates inputs (demands and support) from its environment into outputs (decisions and actions).
	Society as a complex adaptive system (Buckley, 1998)	Adaptive systems can be of biological, psychological or socio-cultural nature. Society is a system because it consists in a complex network of interrelationships between multiple individuals and organizations. The current structure of society is the result of past interactions and it influences present interactions. It is also maintained, changed or elaborated upon according to present interactions.
	Social systems (Luhmann, 1998)	Social systems are made up of communications between individuals. Their function is to reduce the inherent complexity of large societies. Individuals, who themselves operate according to a psychic system, interact within small (families, organizations, etc.) or large (economic, legal, etc.) social systems.

The above concepts and models are complementary to a large extent, and we build upon them to construct the sustainability framework exposed in the next section.

### **General sustainability framework and its application to engineering**

The most relevant connections which are characteristic of physical and social systems are included within the framework presented in Figure 3. Physical systems are located in two overlapping spheres: the biosphere (aquatic and terrestrial ecosystems) and the anthroposphere (which encompasses the agricultural, industrial and urban systems). The expansion of the anthroposphere, in which engineering projects (Products, Infrastructures, Processes and Services or PIPS) play a significant part, increases the extent of the technical cycle. It also leads, at least so far, to noticeable disturbances in the natural cycle, which, in turn, can jeopardize the benefits human beings and societies derive from environmental services. In order not to enhance the well-being of some to the expense of others, engineering projects consequently have to maximize positive contributions to their beneficiaries while minimizing negative external impacts. In addition to physical systems, engineering projects are also connected to social systems and therefore stand at the interface between both kinds of systems in Figure 3. Individuals are given a similar place in the framework since physical and social systems both contribute towards their well-being.

The contribution of physical and social systems to life standards is ensured by protecting or enhancing the resilience and adaptability of such systems. These characteristics are expressed in different ways for every system. For example, biodiversity is a factor impacting the ecosystems' resilience and adaptability, while democratic participation might play a similar role in political systems (Buckley, 1998). Extending on Sen's (1999) interpretation of development, this observation also applies to individuals: their ability to operate in changing contexts and adapt depend on their capabilities. Hence, engineering projects undermining the resilience or adaptability of ecosystems, social systems or individuals might bring about benefits in the short term but are likely to have long-term negative outcomes.



**Figure 3. Sustainability framework for engineering**

As noted earlier, social systems (be they economic, political, legal, educational, scientific and communicational) play a key part in meeting the needs of individuals. Conversely, the capacity of social systems to operate adequately relies on the capabilities of individuals and on the ability of social subsystems (i.e. families, communities, networks and organizations) to mobilize such capabilities. Social systems might structure the interactions between individuals, but ultimately, decisions and actions are made by individuals. Therefore, engineering projects contributing towards the development of people and communities also foster sustainable development. In addition, truly sustainable projects tend to simultaneously serve the interests of individuals, organizations and societies (Parrish, 2007).

Engineering projects are generally initiated in specific social subsystems, such as public or private organizations, in order to meet various needs. They also mobilize other social subsystems or individuals for their completion. Since all of those players interact in main social systems, the broader social background inevitably influences a project's outcomes. Traditionally, engineering practice has mostly been concerned with economic and legal aspects, besides obvious technical considerations. Yet, other social systems should also receive proper consideration as they significantly affect the form taken by projects. Let us now explain why this is especially the case for scientific and educational systems.

First, it is much easier for engineers to deal with physical or social phenomena when there is sufficient scientific knowledge about them. Since the objects deemed worthy of scientific scrutiny are typically identified through economic and political systems, it follows that science is, at least partly, a social construction. This, in turn, enables society to select the research activities thought more likely to foster its sustainable development. As a group of professionals applying science to real-world problems, engineers can play a significant part by providing feedback on the scientific knowledge needed to continue the transition towards sustainability.

Second, the complex nature of interactions occurring in physical and social systems should call for a cautious use of technology in engineering projects. Since the scientific understanding of physical and social systems is limited, human interventions almost inevitably have to cause unexpected indirect impacts. Moreover, some decisions or actions taken to solve a problem may worsen the situation in the long run, because of retroactive or rebound effects. Hence, engineering projects should not only be seen as technical challenges, but also as conveyors of social transformation, either positive or negative, acting among many others.

Third, engineers-to-be rely on the educational system to acquire the necessary knowledge and skills. Hence, this system defines the toolbox engineers mobilize as professionals: the strategies for problem resolution, the spectrum of technical solutions considered, the methods of analysis used to assess and compare concepts, the approaches for project management, etc. The impact of the educational system upon engineering sustainability is thus quite significant and will be detailed later on in the discussion.

## **Discussion**

The sustainability framework in Figure 3 helps identify the types of interaction between engineering projects and the physical or social systems associated with them. Since the framework proposed is quite general, we recommend that its elements be expanded to the desired level for every given application. That way, the connections at stake between a project and the related ecosystems, industrial sectors, main social systems or particular stakeholders are more likely to be thoroughly investigated.

The systematic examination of potential interactions is crucial to identify significant issues that require subsequent detailed analysis. As it can be difficult to distinguish what is significant from what is not, engineers should seek the support and opinion of other professionals to make informed decisions. The resulting deliberations will prepare engineers to explain and account for their choices. In the process, engineers should detect factors which may impact the project's sustainability, but for which they lack knowledge or competences. Only then will they be able to determine which professionals or stakeholders are

needed in their (multidisciplinary) design team. The discussions taking place while members of such heterogeneous teams develop a common sustainability framework should be paid attention to, since they reveal some disciplinary biases which influence the different ways they view the world. Once these differences are understood, the design team will be more capable of adopting a shared approach to sustainable development.

This observation illustrates why the framework is not only of interest to engineers, but also to decision makers involved in engineering projects or technological development. The framework could be used, for example, by managers in organizations concerned with social responsibility or by policy makers implementing sustainable development strategies.

The contribution of a project towards sustainable development can be analysed with a wide variety of tools such as life cycle assessment, impact assessment, stakeholder analysis, environmental valuation, etc. (Gagnon and Leduc, 2006). The tools selected to analyze a particular project need to be positioned on the framework to clearly identify which component or interaction they intend to evaluate. Any selected tool should fit in a logical manner within the framework. If it doesn't, it means either that the framework is not complete or that some tools may not be useful. This framework complements the set of principles presented in Figure 2 since elements not mentioned in the former should be included in the latter and conversely.

As mentioned in the previous section, the framework has major implications for engineering education. When presented in introductory courses, it is likely to give students a better understanding of the entire context of engineering practice and of the purpose of engineering projects. In order to offer sufficient content, the framework should be expanded to reflect the distinctive characteristics of each field of engineering and of each area. This is a key step since ecosystems, materials or types of energy, as well as organizations or networks and cultures, as well as interactions in social systems vary with different contexts. The framework would also make it easier for professors to justify the relevance of non-technical courses (ethics, management

and economics, legal issues, environmental management, etc.) since engineers need the related aptitudes to contribute more actively towards sustainable development in the future.

In addition, engineering faculties can build upon the framework to identify and develop new relevant courses, or adapt existing ones, so that future engineers can meet the challenges of sustainability. Organizations accrediting engineering programs, such as ABET and the Canadian Engineering Accreditation Board, now have requirements on that matter. Still, recent surveys show that most U.S. programs do not deal with sustainability issues in an integrated manner (Woodruff, 2006) as is it probably the case in most countries. Additional courses may focus, for instance, on life cycle assessment, environmental economics, sustainable design, society and technology, etc. To make a significant difference, these courses should provide students with the tools to manage effectively emerging environmental or social issues. While it is neither possible nor desirable to turn engineers into experts in every subject, positioning the profession in this broader sustainability framework is, in our view, an essential knowledge future engineers need to acquire. The skills and vocabulary thus developed will increase their ability to take part in decision-making processes and to collaborate efficiently with specialists of other disciplines.

## **Conclusions**

Several lists of sustainable development principles already exist in the literature: some are more general and others are specific to engineering. From the principles reviewed, we proposed comprehensive and coherent sets structured along a novel logical structure in Figure 1 (general principles) and Figure 2 (engineering principles). We then described the various uses engineers could make of sustainable development principles lists. An improved understanding of multiple connections between technology, ecosystems, individuals and society would provide additional guidance. In response to this, we present numerous concepts and models rooted in natural and social sciences in a synthesized conceptual framework (Figure 3). The latter exposes the interrelations between physical and social systems with a particular focus on engineering projects, which relate to both types of systems in various and multi-faceted ways. A glimpse of the potential uses of the



sustainability framework for engineering practice was provided, namely to define problems, but also to set up design teams and to evaluate projects. Educationally-oriented uses were also presented, where it can help introduce the engineering career and also support the adaptation of existing engineering programs to better tackle sustainability issues.

While the framework was developed for engineers, its contents are relevant for decision-makers involved in engineering projects or technological development. Even though the sustainability framework exposed in this paper was developed in a structured manner, only a few of all conceivable interactions between engineering, society and environment could be discussed. The sustainability framework therefore needs to be expanded upon by professional engineers or professors in the field of engineering in order to meet their particular needs. Only then will it capture the entire complexity of every particular situation and truly assist users in their activities. The ultimate step towards an efficient use of the proposed sustainability framework consists in its incorporation into the “sustainable design process”. Such a remodelled design process enables engineers to fully consider sustainability issues along all the phases of a project realization and will be discussed in upcoming publications.

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