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Functional organization analysis for the design of sustainable engineering systems

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ABSTRACT

Sustainable engineering design requires consideration of technical and ecosystem structures and processes. Even though the concepts of ecosystem services and natural infrastructure are maturing, their application in concrete engineering design is currently lacking due to their ambiguous definitions and a lack of methods that allow for the combined consideration of ecosystem and technical approaches in engineering design. This article proposes and discusses a new functional organization analysis (FOA) method for the comparative analysis and design of supply systems for basic needs (i.e., water, energy or food). This method allows for the analysis of the organization of system functions as well as underlying technical and ecosystem structures and associated processes. On this basis the method allows one to gather data, information, and knowledge about alternative system designs, and analyze their synergies. The theoretical and conceptual background of the proposed FOA method is presented, along with a case study regarding sustainable food supply systems in Southwestern Ontario.

1. Introduction

An integrated and systems approach for the design of human-environment-technology systems is promoted by many scholars (e.g., Checkland, 1981; Pahl-Wost, 2007; Stasinopoulos et al., 2008; Simonović, 2009; Matlock and Morgan, 2011). Sustainable engineering comprises a life-cycle perspective and consideration of ecological, economic, and socio-cultural aspects (Maydl, 2004). Sustainable engineering includes technical approaches from structural and process engineering (e.g., Maydl, 2004), as well as ecosystem approaches from bio- and ecological engineering (e.g., Matlock and Morgan, 2011). Due to the relatively recent development of sustainable engineering, standardized methodologies for the design of sustainable engineering systems comprising both technical and ecological approaches are currently lacking.

Ecological engineering is based upon an ecosystem paradigm and forms a separate field within sustainable engineering (Mitsch, 2012). Defined as the study of "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch, 1998), ecological engineering considers the capacity of ecosystems for self-organization and self-design in engineering problem-solving (Mitsch and Jørgensen, 2004). Ecological engineering can therefore offer ecosystem solutions with the potential to complement or substitute for technical solutions. The Audubon sanctuary at Port Aransas in Texas, where the effluent from a primary and secondary treatment plant (i.e., a technical solution) flows into a freshwater marshland that functions as a tertiary treatment stage (cf., Odum and Odum, 2003), serves as an example of a complementary usage of ecosystem and technical solutions.

The principles of ecological engineering are closely related to the concept of ecosystem services which highlights the close relationship between nature and humanity through the explicit valuation of ecosystem structures and processes based on the

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services they deliver (cf., Millennium Ecosystem Assessment, 2005; Mitsch, 2012). The concept of natural infrastructure has a similar meaning and refers to the indirect services that nature provides for humanity, e.g., flood protection achieved through increasing natural buffering capacity by floodplain restoration (Smith and Barchiesi, 2009; Hey and Vaughn, 2010; Wilson and Browning, 2012). The ecosystem services and natural infrastructure concepts seek to elicit an appreciation of the value of ecosystem structures and processes, while ecological engineering represents the practical implementation facet of ecosystem process and structure design for achieving human well-being and ecological balance at the same time.

The consideration of ecosystem structures and processes in the design of engineering systems is an important field of research. Even though relevant knowledge from systems science, ecology, biology and engineering is available, ambiguous definitions of concepts such as ecosystem services and natural infrastructure (cf., Wallace, 2007) and their relationship to technical approaches is a major barrier against integration of technical and ecosystem design. Other impediments are the traditional engineering paradigm that is aimed at the reduction of uncertainty (Halbe et al., 2013; Mitsch, 2014), and which lacks design methods that allow for the combined consideration of ecosystem and technical approaches. One of the more integrative design methods is the whole system approach (WSA) which offers ten key operational elements to find and exploit synergies between subsystems, and design engineering systems that address multiple problems through a single solution or process (Stasinopoulos et al., 2008). However, the WSA does not consider the use of ecosystem approaches in the design process. In contrast, Matlock and Morgan (2011) provided guidelines for the design of ecosystem services, but did not provide links to technical solutions that could complement or substitute for the provision of ecosystem services, or vice versa.

To directly address the above described issues, this article proposes a new functional organization analysis (FOA) method that supports integrated engineering design of technical and ecosystem structures and processes. The FOA method is part of the preliminary system design step (cf., Blanchard and Fabrycky, 2006), and allows for knowledge integration on alternative system designs and analysis of synergies between alternative system designs, thereby identifying innovative designs as well as new areas for cooperation.

The article is structured as follows. First, the theoretical background of the proposed FOA method is explored, including the concepts of ecosystem function, structure and process, ecosystem services, and natural infrastructure, as well as how, within the conceptual framework, these might be rendered compatible with technical solutions. Based on this theoretical background, the functional organization analysis (FOA) method is proposed as a new approach that allows for the analysis of alternative system designs. A case study is presented which examines various alternatives for a sustainable food supply system in Southwestern Ontario, Canada. An agroecological approach is applied by analyzing ecological structures and processes that form the basis of food systems. Finally, additional steps towards the design, assessment, and implementation of engineering system alternatives, as well as future research needs, are discussed.

2. Functional analysis of sustainable supply systems for basic needs

As discussed earlier, methodologies for an integrated design of ecological and technical structures and processes are currently lacking. This section develops a conceptual framework that provides a clear conceptualization of ecological and technical approaches. The lack of such a conceptual framework is a major impediment to an integrated design method (such as the FOA method). The conceptual framework builds upon system science which provides a common analytical foundation for a combined analysis and design of technical and ecological systems. In order to be classified as a system, an object must (Bossel, 2007): (i) have a special **purpose** that can be perceived by an observer, (ii) consist of a constellation of **system elements** representing the system's structure, and (iii) have a **system identity** that would be lost if elements of the system structure were lost. This definition can be applied to either technical or ecological systems as long as their purpose is to deliver either direct services (e.g., drinking water from rivers), or indirect services (e.g., water purification through a treatment plant). As the identification of a purpose (i.e., a service or function) depends on the perspective of the observer viewing the system, different services and functions within a given system may be prioritized depending on the observer's values or needs. The system structure refers to the actual relations between system elements. As system identity demands simplicity of the structure describing system organization, redundant elements should be eliminated and only essential elements and their relationships should be included. The choice for relevant system elements is not necessarily a trivial task, and is based on systems analysis. Varela (1979) points to the distinction between the organization of a system and its structure: the **structure** specifies the properties and relationships between *specific system elements*, whereas the **organization** only specifies the *general system elements* along with the relationships that make up the system. The organization is "independent of the materiality that embodies it; not the nature of the components, but their interrelations" (Varela and Maturana, 1972). Based upon systems theory, a novel conceptual framework is developed in the following section which forms the foundation for integrated ecological/technical analysis and design using the FOA method (which will be presented in Section 2.2).

2.1. *Conceptual framework for integrated ecological and technical engineering design*

The '**ecosystem service'** and '**ecosystem function'** concepts address the relationship between ecological systems and human values. Ecosystem functions (e.g., soil retention) are ecosystem structures and processes that are used and valued by people (e.g., prevention of damage from erosion), and thereby become ecosystem services (cf. De Groot, 2006; Termorshuizen and Opdam, 2009). The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) placed ecosystem services into four categories: *provisioning, regulating, cultural*, and *supporting services*. Provisioning services are the most clearly recognizable services, with direct products people can physically use (e.g., clean drinking water, food). Regulating services, such as natural water purification in wetlands and river ecosystems are often less obvious. For instance, the natural flow regime of rivers supports a variety of regulating ecosystem services, such as erosion control, pollution management, and flood and pest control (Poff et al., 1997). Recreational, spiritual, and aesthetic services are examples of cultural services of natural bodies of water. Water in general, and rivers in particular, have a special value in certain cultural and spiritual traditions (Craig, 2007). Supporting services are those ecosystem processes or structures necessary for the provision of other ecosystem services. Their impacts on people are indirect or occur over longer time frames than other types of services. Examples include soil formation, nutrient cycling, or climate regulation (Millennium Ecosystem Assessment, 2005). The classifications provided by De Groot (2006) and the Millennium Ecosystem Assessment (2005) are not