Ecological Engineering 73 (2014) 80–91

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Functional organization analysis for the design of sustainable engineering systems

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ARTICLE INFO

Article history:
Received 20 February 2014
Received in revised form 9 July 2014
Accepted 8 August 2014

Keywords:
Ecological engineering
Ecosystem services
Natural infrastructure
Engineering design
Food systems
Agroecology

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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http://dx.doi.org/10.1016/j.ecoleng.2014.08.011
0925-8574/

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

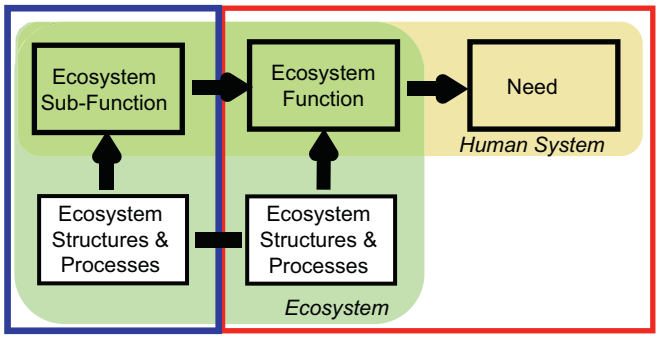

Fig. 1. Conceptualization of Ecosystem Services and Infrastructure, adapted from Termorshuizen and Opdam (2009)—the interpretation of "natural infrastructure" has been added to Termorshuizen's and Opdam's diagram.

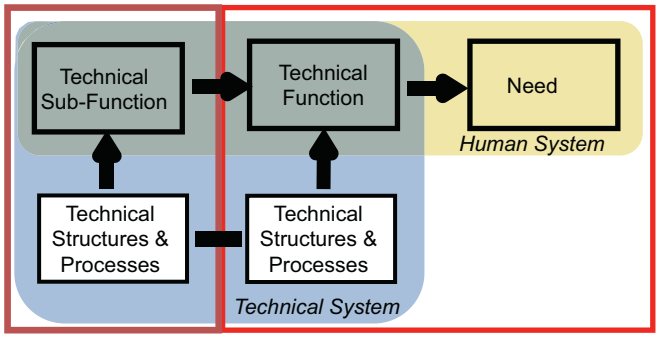

Fig. 2. Conceptualization of Technical Services and Infrastructure as being equivalent to the conceptualization of Ecosystem Services and Infrastructure (see Fig. 1).

coherent and thus can cause confusion and ambiguity. For instance, water supply is a regulating function for De Groot (2006) and a provisioning service in the MA definition (Millennium Ecosystem Assessment, 2005).

Other classifications of ecosystem services exist. Wallace (2007) criticized the Millennium Ecosystem Assessment categories as "not [being] a coherent set of services at the same level that can be explored and traded off in a decision system." For instance, food production (provisioning service) is the end result of an ecosystem management process, whereas pollination (regulating service) is a means of service delivery. The following conceptualization addresses this point of criticism by explicitly differentiating between *Ecosystem Services*, *Ecosystem Function* and *Natural Infrastructure* (Fig. 1).

Ecosystem structures are "the physical organization or pattern of a system" (Noss, 1990), while processes are the "complex interactions (events, reactions or operations) among biotic and abiotic elements of ecosystems that lead to a definite result" (Wallace, 2007). Primary functions are those functions that are directly related to a human need. Thus, the human need, primary functions and underlying ecosystem structures and processes together form an ecosystem service. Sub-functions (e.g., pest management) support the provision of primary functions (e.g., food production) that are directly related to a human need (e.g., food). Thus, natural infrastructure denotes all sub-functions as well as underlying ecosystem structures and processes that together generate primary functions.

System science allows one to use the same conceptualization for both technical and ecosystem solutions (Figs. 1 and 2, respectively), thus rendering feasible a comparison of their respective technical and ecosystem approaches.

Fig. 2 shows the equivalent conceptualization for technical supply systems. A human need (e.g., mobility) is provided through a system of primary technical functions (e.g., provision of vehicles) and underlying technical sub-functions (e.g., a road network). Thus, the human need, related primary technical functions and underlying technical structures and processes form the technical service. Technical sub-functions and related technical structures and processes are understood as technical infrastructure.

Based on these concepts, the proposed FOA method for engineering supply systems (e.g., for water, energy or food) reveals the *system's organization*, comprised of basic needs (the system's purpose) and functions, which, in concert, deliver these needs. In addition, technical/ecosystem structures and the underlying functions of the processes, which represent the *system's structure*, are visualized (i.e., material specification of the respective functions), as outlined in the following section.

2.2. The functional organization analysis (FOA) method

Concepual and preliminary design are important steps in the engineering design process, and have a major influence on the success of engineering projects (e.g., Pahl et al., 2007). Functional analysis as part of the conceptual and preliminary system design steps allows one to develop alternative system designs to fulfil a specific need (i.e., the purpose of the engineering system; cf., Blanchard and Fabrycky, 2006). Functional analysis in engineering design has mainly focused on functional flow analysis (FFA) (Blanchard and Fabrycky, 2006; Woldemichael and Hashim, 2011). While it is a standard method in technical systems engineering and analysis, FFA has yet to be implemented in design processes which include both technical and ecosystem solutions. FFA provides several benefits when employed in engineering design and analysis by: (i) allowing the engineer to approach design in a logical and systematic manner, (ii) helping to reveal relationships between system elements and, (iii) supporting the design of interfaces between sub-systems (Blanchard and Fabrycky, 2006).

The functional *organization* analysis (FOA) method that is proposed for in this study allows one to employ these benefits of FFA in the design of supply systems for basic needs (e.g., water, energy, or food) which requires a broader system boundary (e.g., a regional scale) than regular engineering projects. Instead of analysing the flow of functions, the present method supports the analysis of the organization of alternative supply systems, along with the underlying functions invoked in the realization of the system's purpose. The lack of clarity in existing functions and the structures supporting them, along with the need for stakeholder engagement, make FOA a key preliminary step in envisioning and analyzing technical and ecosystem solutions to broader engineering problems (e.g., the design of food supply systems).

While several computer-aided conceptual design and knowledge management tools exist (for an overview, see Woldemichael and Hashim, 2011), tools for engineering design for broader societal problems that integrate technical and ecological solutions are currently missing. In this paper, Cmaps is applied as a graphical tool for knowledge visualization and management (cf., Novak and Cañas, 2008)[1]. Cmaps are used to visualize and analyze: (i) the system organization, consisting of the purpose and underlying functions, and (ii) underlying technical/ecosystem processes and structures. The relationships between concepts can be further specified by linking words that are added to connecting lines. The tool is based upon the learning psychology of Ausubel (cf., Ausubel et al., 1978)

[1] Software for the construction of Cmaps can be downloaded for free at the following webpage: http://cmap.ihmc.us/download/.

that explains learning as "assimilation of new concepts and propositions into existing concept and propositional frameworks held by the learner". Therefore, Cmaps represents a particularly useful tool in gathering and organizing knowledge about alternative system designs.

The FOA method can be employed for scientific research where it is applied by experts, as well as in the course of participatory processes to discuss alternative system designs with stakeholders. The analysis of alternative system designs and potential synergies via Cmaps occurs in five steps:

1. Defining the purpose of the engineering system, i.e., the service the system is supposed to fulfil (e.g., provision of drinking water).
2. Defining the system's primary and subsidiary functions achievable through technical/ecosystem structures and processes (e.g., water storage).
3. Defining the ecosystem/technical structures and processes underlying the functions determined in Step 2 (e.g., dams or wetlands).
4. Adding available data, information and knowledge to the determined structures and processes.
5. Identifying alternative system designs (i.e., a concerted set of functions and underlying process and structures) and assessing synergies and differences, as well as innovative system designs.

In Step 1, human needs and values expected to be supplied by the engineering system must be specified. From a resilience and sustainability perspective, basic human needs (e.g., for drinking water or energy) are suitable starting points for sustainable engineering system design. The choice of a broad definition of a need (e.g., food, heating, mobility) supports creativity by integrating several perceptions that might be held by stakeholders (cf., Vennix, 1996).

In Step 2, the primary and subsidiary functions required to fulfil the system's purpose, determined in Step 1, are defined. The definition of functions and underlying structures and processes can be based on an analysis of the literature and interviews with experts and other stakeholders. Functions can be ecosystem functions (i.e., functions that are provided by ecosystems) as well as technical functions (i.e., functions that are generated by technical systems). Fig. 3 provides a simplified example for a drinking water supply system: the need (top of graph) is connected to underlying primary functions. Together, the need and primary functions form an ecosystem or technical service, depending on whether the function is provided by an ecosystem or technical structures/processes. Subfunctions and related structures and processes together constitute the underlying technical and natural infrastructure, respectively. The need for drinking water requires inter alia the primary functions of *water generation*, *water storage*, and *water transport*. These functions can be interrelated as shown by the sub-function of *water purification* which increases the primary function of *water generation* when low quality water is rendered useable.

Step 3 involves the addition of structures and processes that provide these functions. Such structures can again be of either a technical or ecological nature and should reflect a diversity of solutions. For instance, water storage can be provided by dams (a technical solution) or constructed wetlands (an ecological solution) (cf., Fig. 3). Of course, the choice of a dam vs. a wetland depends on various context factors, such as the scale of the area to be supplied with water. However, according to the aim of the proposed FOA method to support the analysis of alternative system designs and their synergies, the system diagrams should reflect the diversity of solutions. The choice for specific technical/ecosystem solutions requires the subsequent assessment of alternative system designs.

The Cmaps software allows for the inclusion of expandable/collapsible structure or process details within a structure or process box. Fig. 3 illustrates the structures underlying the technical solution *dam* and the feedback processes at work in the *wetland* solution—other boxes being collapsed for purposes of clarity.

In step 4, relevant data, information, and knowledge are added to structures and concepts. Cmaps allows for adding links to documents, pictures, websites or further Cmaps to each system element. In Fig. 3, links to further information in the form of photos, documents, and a Cmap structure have been added to the *Desalination* structure (marked through icons added to the concept box). Thus, the Cmaps tool allows for the gathering and integration of different pieces of knowledge. Cmaps can also be published online so that stakeholders can add further information.

Step 5 includes the identification of alternative system designs and the assessment of synergies and differences. The functional organization analysis of the (simplified) engineering system for drinking water supply (see Fig. 3) integrates different system designs including a centralized/technical water supply system (that draws on massive infrastructure like dams and a conveyor network) and a more decentralized/ecosystem-based water supply system consisting of wetlands and decentralized water harvesting systems. The visualization of the system organization highlights the complementary functions that need to be realized in order to provide a specific service such as the supply of drinking water. While the system organization is often similar across different designs, a range of underlying system structures exist that can potentially produce the determined functions. A tabular presentation of the functional organization and underlying structures and processes of alternative system design can help to detect synergies (e.g., similar system structures) and differences (see Section 4). Thus, the proposed FOA method helps to analyze alternative system organizations as a part of the preliminary system design step in the engineering process. In this step, multiple alternative solutions are sought through a creative process (cf., Blanchard and Fabrycky, 2006). Such a method supports the design of innovative systems that is based upon a combination of technical and ecosystem approaches.

This kind of integrated illustration of alternative system designs is possible for relatively simple systems that include few functions and technical/ecosystem structures and processes; however, when it comes to more complex engineering systems, the construction of distinct Cmpas for each alternative system configurations has been proven to be more straightforward (see Section 3). A case study on sustainable food supply in Southwestern Ontario, Canada, is presented in the following section that illustrates the use of the FOA method.

3. Case study: Sustainable food supply systems in Southwestern Ontario

Agroecological engineering belongs to the spectrum of ecological engineering practices (Mitsch, 2012) and can be defined as "the science of applying ecological concepts and principles to the design and management of sustainable food systems" (Gliesman, 2007). For Francis et al. (2003), agroecology also includes "the integrative study of the ecology of the entire food system, encompassing ecological, economic and social dimensions". While our analysis focuses on a broader food system scale, agroecology can also be researched at the field, or farm scale (see Wezel et al., 2009). In food systems, technological and ecological processes are intertwined with social and economic aspects (cf., Francis et al., 2003). Several practices of ecological engineering are relevant to sustainable

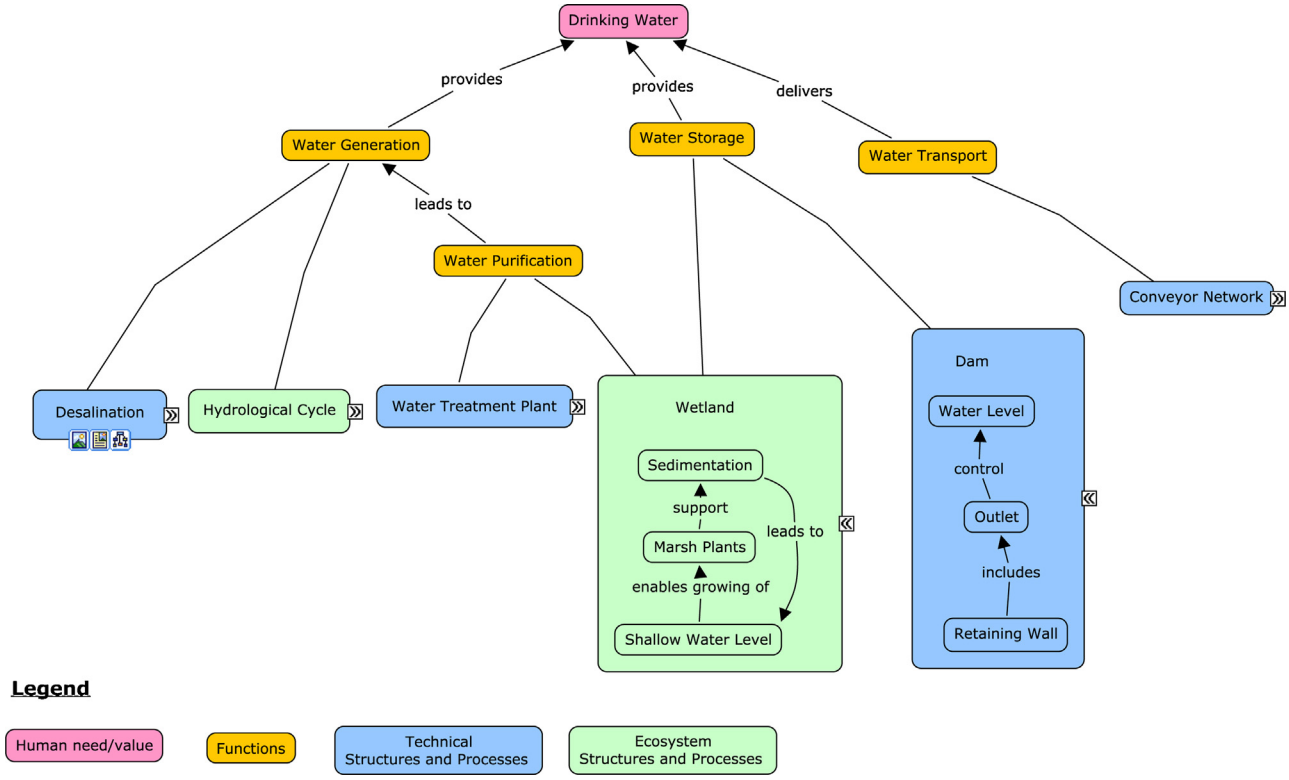

Fig. 3. Organization of a drinking water supply system including alternative technical and ecosystem solutions for the provision of functions. Ecosystem solutions are marked in green, and technical solutions in blue.

agriculture, such as ecohydrology (Zalewski, 2000), biological pest control (Bianchi et al., 2006), or rooftop gardens (Rowe et al., 2014).

Ontario is the province with the highest number of farms in Canada (Statistics Canada, 2011). While agriculture, forestry, fishing, and hunting account for 0.8% of the province's overall economic output in 2012, manufacturing of food, beverage and tobacco products contributes a slightly greater fraction (2.0%) (Ontario Ministry of Finance, 2014). The vast majority of farms in Ontario belong to the large-scale, conventional type of agriculture. Small farms (less than 10 ac/~4 ha) account for only 5% of the total number of farms in Ontario. Certified and non-certified organic farming remains at a niche level, representing roughly 1% and 5% of farms, respectively (Statistics Canada, 2006). Data on the relevance of subsistence agriculture (i.e., farming for personal consumption) is currently unavailable, as official statistics focus on commercial forms of agriculture. However, subsistence farming could become a significant approach for sustainable agriculture, e.g., in the form of community gardens (cf., Wakefield et al., 2007).

A case study addressing sustainable food systems was conducted in southwest Ontario's Bruce and Grey counties, along with the area around the city of Guelph, Ontario, Canada. There are several current challenges (e.g., a changing climate), as well as likely challenges in the future (e.g., depleting resources for fossil fuel and phosphate) that could pose significant challenges to the food system. A sustainable food supply system is viable in ecological, economic and social terms, and has the capacity to adapt to those challenges. An adaptation process can proceed in a reactive fashion (i.e., problems are solved when they appear), or in a proactive manner by anticipating future challenges and taking action based on expectations of future developments (Pahl-Wostl, 2008). The study aimed at supporting such an anticipatory approach by analyzing different perceptions of the term 'sustainable agriculture', and collecting and analysing visions for a sustainable food system in the study area. The proposed FOA method was chosen to *visualize* and *compare* these different system designs in terms of their synergetic potential and usage of ecosystem solutions.

In September 2012, a participatory modelling process was initiated by the authors through individual interviews with farmers, distributors, and other regional stakeholders. Over the course of 1.5 years (until March 2014), 27 stakeholder interviews have been conducted. These interviews aimed at the detection of alternative designs for a sustainable food system and related structural barriers and drivers through the construction of causal loop diagrams (a description of the method can be found in Vennix, 1996).

Further alternative visions were collected through the organization of a visioning exercise at an organic food conference in Guelph.[2] Participants at the conference were asked to complete a FOA showing their personal vision of a sustainable food system, including both the systems' purpose and underlying functions. Cmaps were used to include those technical and natural infrastructures serving to fulfil these functions according to the individual's vision. The interviews and surveys (53 surveys were completed) revealed the existence of multiple alternative visions of a sustainable food system: some participants envisioned a large-scale organic food production system, while others stressed the importance of a localized food system including small-scale organic agriculture and subsistence farming.

A clear delineation of alternative food systems' organization was the goal in implementing a FOA in the case study. Instead of becoming confined to the current problem situation and multiplicity of alternatives, the FOA served as an exercise in enhancing the stakeholders' capacity to envision a range of different system

[2] URL of the conference homepage: http://www.guelphorganicconf.ca/.

design alternatives and the potential synergies existing between them. The following sections present a FOA for the supply of vegetables from each farming system. The presentation is limited to vegetable crops for clarity. The organization of food systems for animal products and field crops would be slightly different, and should therefore be accomplished in a separate functional organization analysis.

Alternative system designs were developed based upon models built through the participatory modelling process and the visioning exercise at the Organic Food Conference in Guelph, Ontario. A supplemental review of the literature was conducted to include ecological engineering approaches relevant for sustainable food systems. System designs for the following alternative food systems are presented: (i) large scale, conventional agriculture (AG^{LS}_{Conv}), (ii) large-scale organic agriculture (AG^{LS}_{Org}), (iii) small-scale, organic agriculture (AG^{SS}_{Org}), and (iv) organic subsistence agriculture (AG^{Subs}_{Org}). While the AG^{LS}_{Conv} system represents the current dominant food supply system in the study area, the AG^{LS}_{Org}, AG^{SS}_{Org}, and AG^{Subs}_{Org} systems reside more at a niche level.

3.1. Large-scale, conventional agriculture

Large scale, conventional agriculture (AG^{LS}_{Conv}) is the most common farm type in Ontario in terms of vegetable production (Statistics Canada, 2006). The AG^{LS}_{Conv} system is based on the utilization of economies of scale effects which arise from the decrease of unit costs through large scale production and automation (cf., Altieri and Rosset, 1996). The diverse primary and secondary functions and underlying technical/ecosystem structures and processes required for large-scale vegetable production are outlined in Fig. 4. This figure shows how all the features of the system come together to provide food.

The primary function of Production is related to the sub-functions Provision of Water, Pollination, Provision of Seeds/Seedlings, Fertilization, Provision of Plots, Provision of Technical Equipment, and Pest Control. Agriculture in Ontario is predominantly rain-fed so irrigation only becomes necessary during dry periods (except for greenhouses) (Statistics Canada, 2013). The Provision of Water thus depends upon ecological and hydrological processes which can be actively managed through an ecohydrological approach (e.g., Zalewski, 2000). Technical approaches for water provision are mainly related to irrigation technologies to overcome dry periods and address recent climate trends (i.e., drier and warmer summers) for Southwestern Ontario (Tan and Reynolds, 2013). Pollination is another crucial function for agricultural production which can be provided through abiotic processes (e.g., wind pollination), natural pollinators (e.g., wild bees) or domesticated pollinators (e.g., honey bees). The demand for pollination services in Eastern Canada is increasing and has caused Ontario's beekeepers in 2012 to export about 26% of their colonies to other provinces in Eastern Canada (Ontario Ministry of Agriculture and Food (OMAF), 2013). The Provision of Seeds and Seedlings is the domain of specialized companies which apply sophisticated technical processes to produce high-yielding seeds (cf., Perez-Prat and van Lookeren Campagne, 2002, on hybrid seed production). Fertilization is mainly provided by the application of mineral fertilizers and requires intensive soil studies to develop an appropriate fertilization programme in terms of fertilizer materials and/or application method. Crop rotation is a more ecological approach applied by farmers to increase or sustain soil fertility and control pests. Nonetheless, the sub-function of Pest Control more generally draws upon the application of pesticides by mechanized methods. Plots are of large scale and require application of high-input technology specific to large-scale farming (cf., Altieri and Rosset, 1996). Greenhouse crops also have a high relevance in Ontario. The greenhouse area roughly doubled from 4.4 km^2 in 2001 to 8.0 km^2 in 2011 (Statistics Canada, 2011).

Another central primary function is the *Storage* function, which is relevant for the generation of all other primary functions (i.e., the storage of products is required during the production process, transport, distribution and preservation before consumption). The storage of products is accomplished by technical approaches along the supply chain including silos, storehouses, and fridges. *Transportation* is another primary function required to distribute products from producers to wholesalers and retailers. This function is mainly accomplished through professional transport companies. Transportation from the market place (e.g., supermarket chain or retailer) to the site of consumption (e.g., home) is usually accomplished through individual transport by the customer (i.e., usage of cars).

3.2. Large-scale, organic agriculture

Compared to conventional agriculture, organic farming is considered to support biodiversity (Topping, 2011) and pollination (Gabriel and Tscharntke, 2007) in agricultural landscapes, and increases soil fertility (Mäder et al., 2002). The organization of the large-scale, organic agriculture system (AG^{LS}_{Org}) is largely the same as that of the large-scale, conventional (AG^{LS}_{Conv}) system, particularly with regard to the underlying structures and processes for the *Storage* and *Transport* primary functions. However, significant differences between the AG^{LS}_{Conv} and AG^{LS}_{Org} do exist with respect to the structures and processes underlying the sub-functions of *Provision of Seeds/Seedlings*, *Fertilization* and *Pest Control*. Organic seeds and seedlings are provided by companies which employ more natural production approaches (i.e., no chemical or genetic modification of seeds) (Forman and Silverstein, 2012). The fertilizer sub-function can also be provided by other organic fertilizers such as manure or nitrogen-fixing green crops) and crop rotation (including winter cover). Pest control is realized through physical and mechanical weed control practices, as well as through natural and biological solutions (e.g., management of natural enemies) (cf., Bianchi et al., 2006). The sub-functions of *Plots* and *Technical Equipment* are again similar to those for AG^{LS}_{Conv} systems. The *Market* function is also similar in that it includes supermarket chains and retailers, but dissimilar in that it also includes specialized organic food stores.

A comparison of Figs. 4 and 5 shows that the functional organization of the AG^{LS}_{Org} food production system is compatible with the dominant AG^{LS}_{Conv} system. The food system designs AG^{LS}_{Conv} and AG^{LS}_{Org} contain the same functions, and the underlying structures and processes are the same for the transport and market functions. Thus, large-scale organic agriculture is supported through existing system elements (e.g., the distribution system) of the prevailing AG^{LS}_{Conv} system. A more detailed analysis of synergies and differences is provided in Section 4.

3.3. Small scale, diversified, organic agriculture

Small scale, diversified, organic agriculture (AG^{SS}_{Org}) is viewed as an important part of a sustainable food system in social and ecological terms (Dalsgaard et al., 1995; De Schutter, 2010). Local food systems are expected to have positive effects on community resilience towards challenges such as globalization or scarcity of fossil fuels. Key concepts related to this approach include organic cultivation of diverse field crops, including vegetables and fruits, on

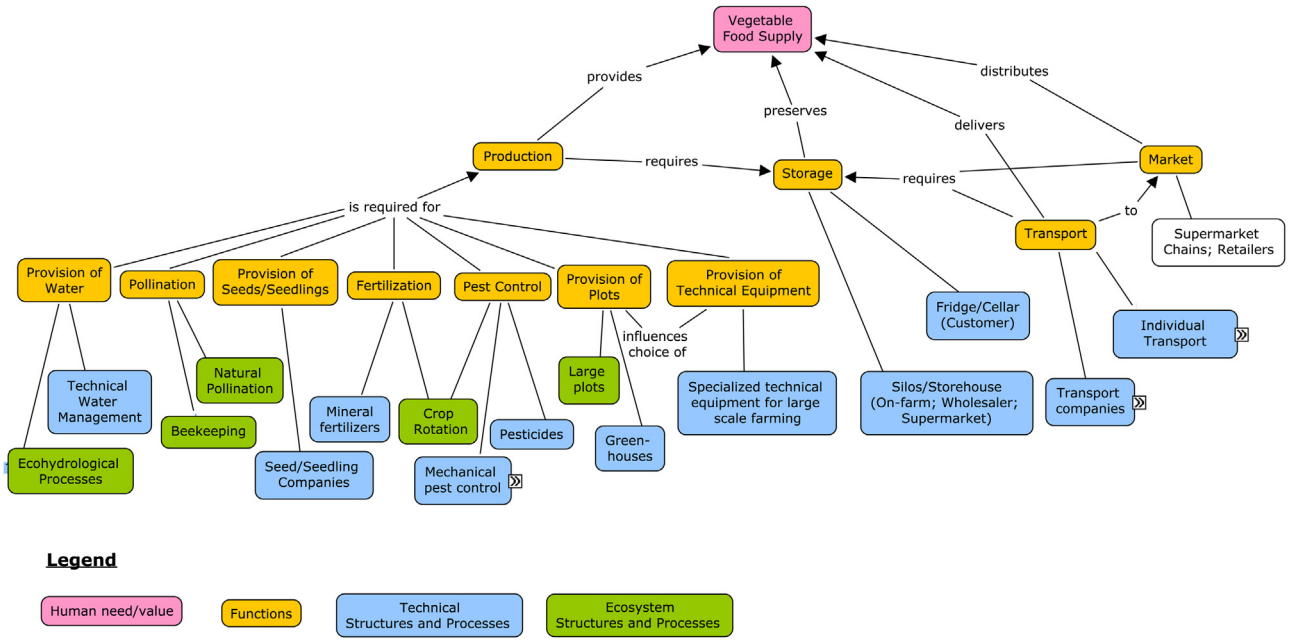

Fig. 4. Functional organization analysis of the large-scale, conventional agriculture system (AG^{LS}_{Conv}) for the production of vegetables.

a small scale in order to minimize ecosystem impacts. Small scale, diversified, organic farming can be done in a rural as well as urban context.

Information regarding the state of local food systems in the case study regions is sparse due to missing consideration by statistical agencies and governmental reports. In Grey/Bruce counties, only 3% of producers and 1% of processors are believed to belong to the local food system (Hammel, 2010). In any case, small scale, diversified organic agriculture in rural and urban areas can be considered as a niche solution. The result of the functional analysis of this food system is depicted in Fig. 6.

The organization of the diversified AG^{SS}_{Org} system resembles that of the AG^{LS}_{Org} and AG^{LS}_{Conv} systems to some extent: the primary and secondary functions are the same; however, the realization of these functions is built upon different structures and processes. The implementation of the secondary function *Provision of Seeds/Seedlings* through the buy-in of seeds/seedlings from companies is complemented by self-production and preservation of seeds and seedlings. The organic orientation of this agricultural approach is reflected in the *Fertilization* function through the abandonment of chemical fertilizers, and use of organic fertilizers instead (e.g., animal manure or compost). For example, worm composting can be an ecologically friendly approach to support seedling germination and growth as well as plant fertilization (Suthar, 2010). Due to the implementation of organic principles, biological/natural and physical/mechanical pest control options are applied that are based upon a higher vegetation diversity (Bianchi et al., 2006; Xu et al., 2011). As only small scale-plots are

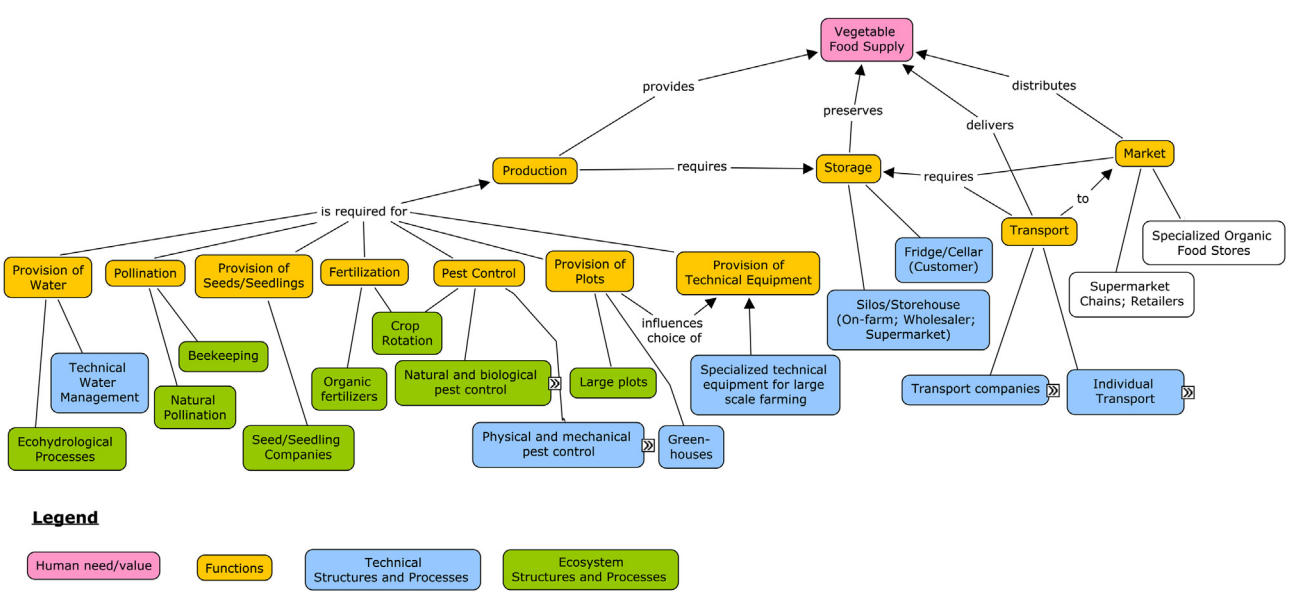

Fig. 5. Functional Organization Analysis for a large-scale, organic agricultural system for the production of vegetables.

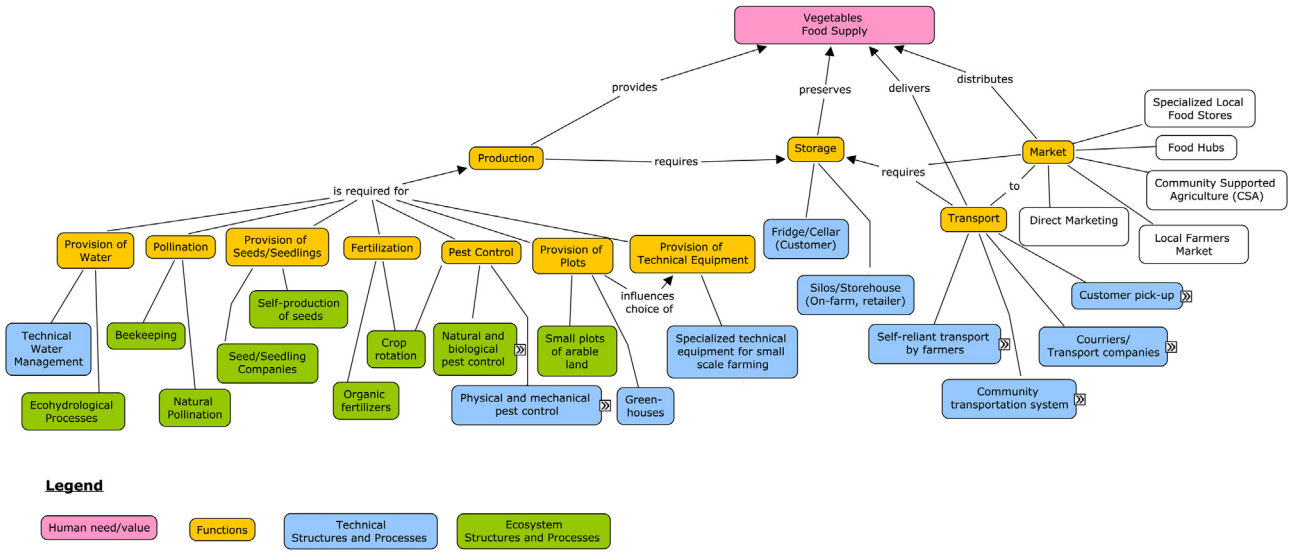

Fig. 6. Functional Organizational Analysis of the small-scale, diversified, organic rural and urban agricultural system for the production of vegetables.

cultivated, the use of large agricultural machinery is not necessary and can be replaced by specialized technical equipment for small-scale farming. In an urban agriculture context, plots can also be artificially developed through the installation of roof gardens (cf., Rowe et al., 2014) which support food production as well as biodiversity (Madre et al., 2013). For the storage of products, smaller technical solutions are chosen on-farm or in the distribution system (i.e., silos, storehouses, fridges) compared to the larger installations associated with large scale agricultural systems. The *Transport* function is usually accomplished by the farmers themselves, who transport their products to the market place or customers directly, or by the customers themselves (e.g., pick-up of food boxes). Other options could be a community transport system (i.e., the farming community could initiate a bottom-up transportation and distribution system) or transport by professional companies that pick-up the products of small-scale farmers collectively. For the *Market* function, community supported agriculture (CSA) systems, direct marketing, specialized local food stores, and local farmers' markets are the most common approaches to distribute food (cf., Brown and Miller, 2008). Food hubs have been mentioned as another option to bring together regional supply and demand using an online marketplace (cf., Mount et al., 2013).

3.4. Organic subsistence agriculture in urban and rural areas

Organic subsistence agriculture AG_{Org}^{Subs} was stated by several stakeholders as an important element of a sustainable food system. Subsistence agriculture denotes an individual or community farming approach in which food is produced for one's own consumption. This design of food supply systems has negative connotations in the scientific literature and is mainly referred to in the context of developing and transition economies (cf., Kostov and Lingard, 2002). For instance, Todaro's definition (Todaro, 1995) highlights the "low productivity, risk and uncertainty" of most subsistence food systems. Data about the scale of this agricultural approach in Southwestern Ontario is currently lacking.

Most stakeholders in our analysis highlight the fact that subsistence agriculture does not necessarily imply the production of all personal food requirements. It is also a means to preserve and distribute farming knowledge and increase awareness of small-scale farming methods in general, and healthy foods in particular. While within the study area subsistence agriculture was performed predominantly in rural communities, there is an accelerating trend to also farm in such a manner in an urban context. The urban farming movement is gaining strength through city dwellers' desire to grow food by and for themselves (cf., Nasr et al., 2010). Fig. 7 shows that the organization of a AG_{Org}^{Subs} system's *Production* and *Storage* functions resemble those of the small-scale system. However, the *Market* and *Transportation* functions are absent since the food is not sold but rather consumed by the subsistence farmers themselves. Thus, the distinction between farmers and consumers no longer exists under this system design.

Community gardens can play an important role in the provision of the *Pollination* function by being a habitat for bees and other insects in urban areas (Matteson et al., 2008; Madre et al., 2013). The functions *Provision of Seeds/Seedlings* and *Fertilization* under AG_{Org}^{Subs} resemble those of the AG_{Org}^{SS} systems, where seedlings can be purchased from companies or grown by the subsistence farmers themselves, and fertilization is provided by organic fertilizers (mainly compost). Several solutions have been mentioned by stakeholders to develop sufficient plot area for subsistence farming. While in more rural areas plots can be provided by small plots of arable land, urban farming builds more on artificially-constructed plots like raised beds, small rooftop gardens, and square foot gardens. Primarily biological solutions were mentioned by the stakeholders for pest control, such as the support of biological controller species like spiders (Chatterjee et al., 2009). Fridge, cellar and traditional conservation methods were mentioned for the storage of products.

4. Discussion

The Functional Organization Analysis of sustainable agriculture in Southwestern Ontario examined the organization of different alternative food supply systems. Only the organization of AG_{Org}^{Subs} systems deviates from AG_{Conv}^{LS}, AG_{Org}^{LS}, AG_{Org}^{SS} systems primarily in terms of the absence of the functions of *Transport* and *Market*. What differs between all designs of food supply systems are the specification of structures and processes that produce functions. Data, information, and knowledge were gathered from various sources including expert and stakeholder interviews, scientific publications, statistical reports, and relevant websites which were

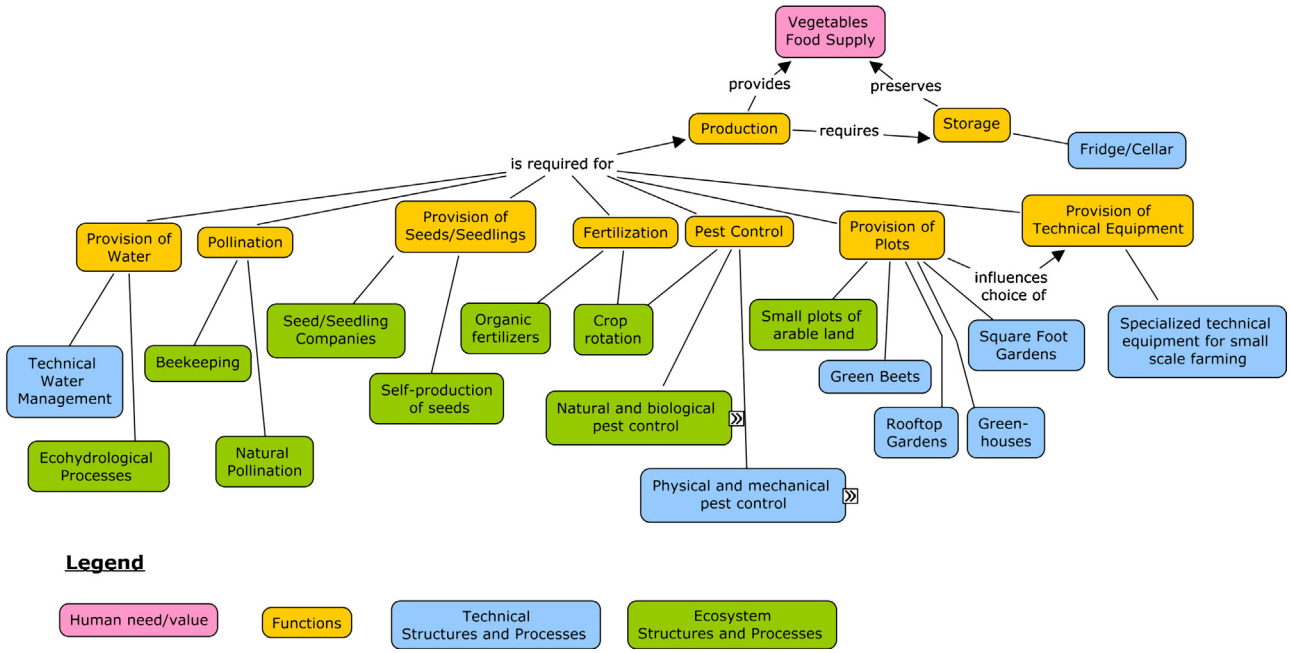

Fig. 7. Functional Organization Analysis of the organic subsistence agriculture (AG_{Org}^{Subs}) system for the production of vegetables.

subsequently linked to associated structures and processes. In this manner, the developed Cmaps helped to integrate different kinds of knowledge.

Visualizing food supply systems' functional organization reframes one's perspective on the associated food system and reveals the interconnectedness of the food system to market processes and transportation. Instead of getting lost in the breadth and detail of structures and processes involved, the FOA reveals alternatives for the provision of needs and functions, thereby allowing the analysis to become more focused on alternative solutions that can potentially be applied in practice. In addition, the commonalities existing between different food supply systems become apparent. For instance, *Transport* and *Market* functions are similar for the AG_{Conv}^{LS} and AG_{Org}^{LS} systems. The identification of similarities can be important in revealing potential areas for cooperation between groups of stakeholders and in developing effective policies.

Table 1 shows an overview of similarities and differences of system designs for the four types of food systems that came out of the FOA. Clearly, all food system designs depend on a combination of technical and ecosystem approaches, in addition to the non-material structures of markets. The effectiveness of each structure and process depends on context-related factors that might vary across the case study area. Thus, the FOA method reveals the diversity of potential system designs (as a part of the preliminary systems design step) rather than determining the 'optimal' system design (cf., Blanchard and Fabrycky, 2006).

The application of FOA to food supply systems revealed large-scale conventional and organic systems to be similar in several respects (in particular related to transport and marketing) (cf., Table 1). Differences between these food systems are merely related to the sub-functions of *Provision of Seeds/Seedlings*, *Fertilization*, and *Pest Control*. Thus, a transition from AG_{Conv}^{LS} towards AG_{Org}^{LS} only requires on-farm changes which can be more easily implemented than off-farm functions like *Transport* and *Market* which require the cooperation of several stakeholders (i.e., distributors, retailers). In contrast, small-scale agriculture faces unique challenges in off-farm functions related to the distribution of food (i.e., *Transport* and *Market*). A system transformation towards small scale agriculture would be challenging, as new structures and processes for transportation and market functions would need to be developed.

The comparison of system designs in Table 1 also revealed synergies between small scale organic farming and subsistence farming. In terms of production, small-scale and subsistence agriculture is based upon similar structures and processes (for instance, comparing production sub-functions of pollination, provision of seeds/seedlings, fertilization and pest control) so that cooperation on several aspects would be possible. As an example, small-scale farmers could support various inputs to subsistence farmers such as seeds, seedlings, or animal fodder. Another potential area of cooperation is the provision of expertise of small-scale farmers to subsistence farmers (for instance in urban areas). Such a close cooperation would support resilient local food systems and can also be an interesting strategy for rural development.

By clearly highlighting the diversity of technical and ecosystem approaches, the FOA method can support the envisioning and analysis of alternative system organizations and structures. For instance, Table 1 shows that the sub-function of pest control can be accomplished by technical approaches (i.e., application of herbicides, pesticides or mechanical pest control) or ecological solutions (i.e., natural and biological pest control, or crop rotation, cf., Bianchi et al., 2006; Chatterjee et al., 2009). Thus, options for a replacement of technical infrastructure (consisting of the pest control sub-function and underlying technical structures and processes) and natural infrastructure (consisting of the pest control sub-function and underlying ecosystem structures and processes) can be analyzed. For the *Provision of Plots* sub-function, Table 1 shows technical alternatives to ecosystem approaches through the construction of artificial plots (e.g., raised beds or rooftop gardens). A comparative analysis of alternative designs (as part of the preliminary system design step) can support communication and learning. For instance, some organic farming approaches could be adopted by conventional agriculture (see Pimentel et al., 2005) rather than fuel ideological disagreements between proponents of different system designs. The explicit consideration of ecosystem

Table 1
Different agricultural system designs obtained by combining technical, natural, and non-material structures and processes for the provision of functions (for details on structures and processes see Section 3).

Functions	Food system design			
	Large scale, conventional agriculture	Large scale, organic agriculture	Small scale, organic urban and rural agriculture	Organic subsistence agriculture
Production *(Primary Function)*				
Provision of Water	Technical water management Ecohydrological processes	Technical water management Ecohydrological processes	Technical water management Ecohydrological processes	Technical water management Ecohydrological processes
Pollination	Natural pollination Beekeeping	Natural pollination Beekeeping	Natural pollination Beekeeping	Natural pollination Beekeeping
Provision of seeds/seedlings	Seed/seedling companies[a]	Seed/seedling companies	Seed/seedling companies Self-production of seeds	Seed/seedling companies Self-production of seeds
Fertilization	Mineral fertilizers Crop rotation	Organic fertilizers Crop rotation	Organic fertilizers Crop rotation	Organic fertilizers Crop rotation
Pest control	Herbicides/pesticides Mechanical pest control Crop rotation	Natural and biological pest control Physical and mechanical pest control Crop rotation	Natural and biological pest control Physical and mechanical pest control Crop rotation	Natural and biological pest control Physical and mechanical pest control Crop rotation
Provision of plots	Large plots Greenhouses	Large plots Greenhouses	Small plots of arable land Greenhouses	Small plots of arable land Raised beds Rooftop gardens Square foot gardens Greenhouses
Provision of technical equipment	Specialized technical equipment for large scale farming	Specialized technical equipment for large scale farming	Specialized technical equipment for small scale farming	Specialized technical equipment for small scale farming
Storage *(Primary Function)*	Silos/storehouse (on-farm; wholesaler; supermarket) Fridge/cellar (customer) Further conservation methods (e.g. making preserves)	Silos/storehouse (on-farm; wholesaler; supermarket) Fridge/cellar (customer) Further conservation methods (e.g. making preserves)	Silos/storehouse (on-farm; wholesaler; supermarket) Fridge/Cellar (Customer) Traditional conservation methods (e.g. making preserves)	Fridge/cellar Traditional conservation methods (e.g. making preserves)
Transport *(Primary Function)*	Transport companies	Transport companies	Self-reliant transport by farmers Community transportation system Couriers/transport companies Customer pick-up	N/A
Market *(Primary Function)*	Supermarket chains; retailers	Supermarket chains; retailers Specialized organic food stores	Community supported agriculture Local farmers market Direct marketing Specialized local food stores	N/A

[a] Seeds and seedlings are heavily modified through technical processes for large-scale conventional agriculture (cf., Perez-Prat and van Lookeren Campagne, 2002). Thus, the provision of seeds and seedlings have been classified as a technical process for the conventional agriculture system while the organic agriculture systems apply more natural approaches for the production of seeds (cf., Forman and Silverstein, 2012).

structures and processes supports the reframing of current system designs and highlights alternatives to technical approaches.

The proposed FOA method can make an important contribution to the conceptual and preliminary design of sustainable engineering systems. The conceptual framework integrates a range of concepts (ecosystem services, natural infrastructure, ecosystem functions, structures and processes) and renders them compatible to engineering design. In order to proceed towards detailed design and quantitative evaluation, the analysis of functional flows can follow such an organizational analysis. The assessment of alternatives and decisions for a favourable system design in a given context would require the use of assessment tools such as system dynamics modelling (Ness et al., 2007). Future research will build upon the FOA method and develop tools allowing for the quantitative simulation and assessment of system designs. Other future application areas are the participatory collection of knowledge and usage as a learning tool. For this purpose, Figs. 4–7 can be presented on a website, with links providing more in-depth information for each structure (e.g., on biological solutions for pest control). Farmer communities could thereby share knowledge and learn from each other's experiences.

5. Conclusions

The proposed FOA method is based upon systems theory and the concepts of ecosystem services and natural infrastructure. The FOA method helps to visualize alternative system organizations

(i.e., the systems of functions that fulfil a specific need) and underlying structures and processes. As part of a preliminary system design step, the method thereby reveals alternative system designs and their potential synergies. In addition, the method supports the gathering and integration of relevant data, information and knowledge on alternative designs.

The case study of Grey and Bruce counties, and the city of Guelph, situated in Southwestern Ontario in Canada, presents an example of the application of the proposed FOA method for the analysis of sustainable food systems. An agroecological perspective was applied by analyzing ecological structures and processes in each food system design. Based upon interviews and surveys we revealed multiple alternative visions of a sustainable food system held by stakeholders, including a large-scale organic food production system, small-scale organic agriculture and subsistence farming. A FOA was undertaken for large scale conventional agriculture (AG^{LS}_{Conv}), the currently dominant agricultural system in the case study area, as well as for alternative designs such as small scale organic agriculture in rural and urban contexts (AG^{SS}_{Org}), large scale organic agriculture (AG^{LS}_{Org}), and organic subsistence farming (AG^{Subs}_{Org}). The system organization for the AG^{LS}_{Conv}, AG^{LS}_{Org}, and AG^{SS}_{Org} agricultural systems was largely the same, whereas that of the AG^{Subs}_{Org} system differed significantly in the functions of *Transport* and *Market* being absent due to the self-consumption of products. The FOA also revealed several similarities between system structures and processes of food supply systems. For instance, AG^{LS}_{Conv} and AG^{LS}_{Org} food systems showed strong similarities in terms of distribution systems, so that a certified organic agriculture producer could draw upon established structures. Similarities also existed between production systems of small-scale and subsistence farming. There is the potential for cooperation between these food supply system designs. For example, small-scale farms can provide different kinds of input to urban farming (e.g., seeds or seedlings) or offer their expertise to urban farmers. The consideration of these similarities and differences support strategic policy making, as commonalities and unique challenges can be addressed directly rather than applying a unilateral approach.

In addition, the FOA clearly highlighted alternative technical and ecological structures and processes for the provision of functions. For instance, agricultural systems applied different technical (e.g., application of herbicides and pesticides) and ecological approaches (e.g., natural and biological pest control) for pest management. The clear identification of these alternatives supports the integrated assessment of agricultural practices. Such an analysis could clarify whether ecological solutions can substitute for technical solutions, or vice versa.

Future research will apply such a method to the design of other engineering systems, e.g., for water or energy supply. While the proposed FOA method reveals a plurality of solutions, approaches are needed to assess different options and support decisions leading to an effective and sustainable system design. The application of integrated assessment approaches will be applied in future research for the assessment of sustainable engineering systems.

Acknowledgements

The case study in Southwestern Ontario was financially supported by a Agriculture and Agri-Food Canada Grant (grant number: 299548-KTT) from the Ontario Ministry for Agriculture, Food and Rural Affairs (OMAFRA) held by Khosrow Farahbakhsh and Jan Adamowski.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.08.011

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