The Role of Paradigms in Engineering Education and Practice for Sustainable Development

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Abstract

Engineers have always had to deal with complex challenges. However, a profound change has occurred over the last few decades with a realization of the need to transition from a focus on technical issues to more 'messy' problems that require an integrated, adaptive and participatory approach. Such an engineering approach does not only necessitate new methods and tools, but also the development and teaching of new engineering paradigms. The traditional 'expert' approach in engineering is based on a 'prediction and control' paradigm that aims at the detection of optimal technical solutions to environmental problems such as water pollution or water scarcity. An 'adaptive management' paradigm has been advocated by many scholars and practitioners to deal with high levels of uncertainty. Another paradigm is 'community involvement', which acknowledges the value of local knowledge and involvement of stakeholders in the planning and implementation of engineering projects. A systematic discussion and analysis of paradigms in engineering education and practice is currently lacking in the scientific literature, even though an engineer's awareness of paradigms can be critical for the design and implementation of sustainable solutions. This paper presents a system science approach for the analysis of paradigms for sustainable engineering, and clarifies the factors for their effective application. In addition, the relevance of these paradigms in engineering education and practice is reviewed, and it is determined that the "community involvement" paradigm is particularly important for integrated and adaptive resource management. The article also provides an overview and some reflections on the experiences of the authors in the teaching of these new paradigms at McGill University, Canada, and the University of Osnabrueck, Germany. Through compact lectures, exercises and projects, students learn about multi-causal relationships as well as multiple stakeholder interests that are common with 'messy' problems, and obtain knowledge of hands-on approaches on how to deal with these challenges constructively.

1 Introduction

Engineering practice and education need to be revised continuously to address technical and methodological innovations, and to react to the challenges and demands of changing environments and societies. Engineering is not built upon a specific set of theories, but its concepts, methods and tools are evaluated in terms of their usefulness to solve contemporary engineering problems. In this way, the classical engineering fields of civil and mechanical engineering have been expanded by the fields of electrical, chemical, biological and ecological engineering, amongst others. This practical orientation has made engineering a very effective and flexible problem solving approach. Koen (2003) defines the engineering method as "the use of heuristics to cause the best change in a poorly understood situation within available resources“. This definition highlights that engineers often cannot build upon a complete knowledge of a particular system, and have thus developed heuristics to find the best possible solutions. Heuristics can be understood to be anything that provides a plausible and tested aid or direction in the solution of a problem.

This nature of the engineering method is also reflected in the evolution of engineering curricula. In recent years, traditional engineering courses like material science and construction have been complemented with courses in ecology, economics or stakeholder participation in order to react to new challenges in the engineering profession (cf., Bordogna *et al.*, 1993). One of the more recent challenges in engineering practice and education is the consideration of sustainable development issues that require an integrated and process-based perspective on societal problems (Bagheri & Hjorth, 2007). Sustainability related tasks often have the character of ‘messy’ problems which are indicative of the diverging opinions regarding the definition of the problem and potential solution strategies (cf., Ackoff, 1974; Vennix, 1996).

The mere enlargement of engineering curricula is not sufficient to apply new methods and tools for sustainable engineering. In particular, the engagement of stakeholders challenges the ‘expert’ approach of engineers and demands the rethinking of engineering paradigms (cf., Mulder 2006). This article suggests that the concept of paradigms is an important component of engineering practice and education for sustainable development. Paradigms comprise our basic assumptions about how the world works, including perceived risks, our goals, and the solution strategies we consider. An ignorance of underlying paradigms can lead to miscommunication and subsequent management problems. Thus, an integrated, adaptive and participatory engineering approach does not only necessitate new methods and tools, but also the development and teaching of engineering paradigms.

The relevance of paradigms in engineering education and practice have been explored in some detail by some scholars (e.g., Mulder 2006), but a systematic approach for the comprehensive analysis of paradigms and their interrelatedness is currently lacking. This article presents a definition of paradigms and a methodology for their case-specific elicitation and analysis. A case study on flood management provides an example of the application of the methodology and reveals the interrelatedness of paradigms that often occur in sustainability issues. Further, a literature review examines the prevalence of each of these paradigms in engineering practice and education. Based on the experiences of the authors, a combination of lectures, exercises and projects are proposed to teach these innovative concepts and methods at the university level.

2 Paradigms in Engineering for Sustainable Development

Several new paradigms have been proposed for sustainable engineering. For example, Brandt et al. (2000) highlight the paradigm of clean technology that is aimed at the minimization of resource consumption and wastage during production processes and the product life-cycle. Only technical solutions are not sufficient to solve such ‘messy’ problems since human aspects of engineering systems (e.g., organization of a company, awareness of stakeholders on environmental issues) need to be addressed, too. In addition to the human dimension, the inter-linkages between technical systems and ecosystems are another component of sustainable engineering which has resulted in the development of new methods and tools (cf., Mitsch, 1998; Matlock & Morgan, 2011).

The evolution of engineering approaches from a strong technical focus towards a more integrated perspective requires new approaches in engineering education. This implies changes in the curriculum such as the inclusion of topics like listening and communicating to communities (Lucena *et al.*, 2010) or material and energy flow analysis (Briefs and Brandt, 2002). Mulder (2006) proposes a sustainable technological development paradigm that advocates that engineers should join public debates and closely interact with stakeholders (e.g., customers and politicians, amongst others). Thus, participatory approaches and project-based learning need to be included in engineering curricula (see also Lenschow, 1998).

Paradigms describe the often unconscious assumptions of people about the nature of the world (“worldview”) and potential ways to take action. New paradigms emerge due to the inability of conventional approaches to address contemporary challenges. As shown by the examples above, sustainable engineering requires profound changes in engineering practice and education. However, the meaning of the term ‘paradigm’ is unclear in the literature, and denotes different aspects such as the need for a broader perspective on engineering problems, new skills or methods. In addition, most articles highlight the shortcomings of conventional engineering and advantages of a paradigm change rather than offering a more differentiated picture of the application areas. Therefore, a more systematic analysis of paradigms is helpful to (a) establish a thorough definition of the term and, based upon this, (b) develop a methodology to analyze paradigms that are relevant for case-specific engineering tasks.

According to Kuhn’s work on paradigm changes in science, paradigms are shared by an epistemic community that has a consensus on what is to be observed and analyzed, the kind of questions that are supposed to be asked, how these questions are to be structured, and how the results of investigations should be interpreted (Kuhn, 1962). Pahl-Wostl *et al.* (2011) provide a more practical definition of paradigms for the management of natural resources. A management paradigm is understood as “a set of basic assumptions about the nature of the system to be managed, the goals of managing the system and the ways in which these goals can be achieved” (Pahl-Wostl *et al.*, 2011). Based upon this definition, Halbe *et al.* (2013) present a methodology for the elicitation and analysis of paradigms in resource management using the participatory model building method and institutional analysis. Here, a management paradigm is defined by a specific “system perspective” regarding the management problem, chosen “solution strategies”, as well as “risk and uncertainty management strategies”.

Halbe *et al.* (2013) present a participatory model building approach to analyze paradigms held by stakeholders, as well as an example application on the issue of flood management in Hungary. In a participatory model building process, a stakeholder group built a causal loop model that describes their perspective on flood management in the Tisza Basin in Hungary. The causal loop model comprises system perspectives of stakeholders (i.e., those system elements that are considered to be relevant to the issue), and their proposed solutions as well as risk and uncertainty management strategies. Causal Loop Diagrams (CLDs) are powerful tools for the qualitative analysis of systems (cf., Senge, 1990). In these diagrams, elements of the system are connected by arrows that together form causal chains (see Figure 1). A positive link indicates the parallel behavior of variables: in the case of an increase in the causing variable, the variable that is affected also increases, while a decrease in the causing variable implies a decrease in the affected one. A negative link indicates an inverse linkage between variables.

Figure 1 shows the results of a group model building exercise addressing the issue of flood management in the Hungarian reach of the Tisza River Basin. Since the 19th century, a centralized water management regime has been implemented with a focus on engineered flood protection. The large-scale construction of dikes allowed for intensive agriculture and protection of residential and industrial areas. However, rising flood intensities and frequencies have challenged the existing water management paradigm in the past decade. A bottom-up learning process initiated by activists and academics brought innovative ideas into the flood policy debate (cf., Sendzimir *et al.*, 2007).

The causal loop diagram (CLD) was built around the system's problem variable: "Flood Frequency and Intensity" (red variable). This problem variable is connected to further system elements including technical (e.g., "Dikes"), environmental (e.g., "Soil Quality"), economic (e.g., "Profit/ha"), and social (e.g. "Community Well-Being") variables.

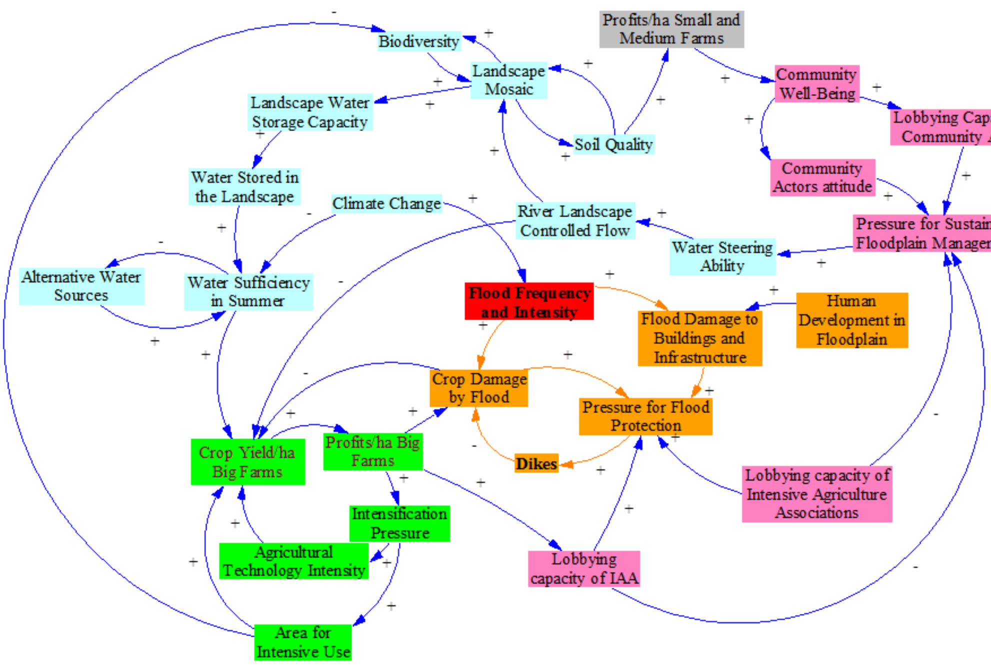

Figure 1: Causal Loop Diagram of the flooding problem in the Tisza River Basin (see extended from Sendzimir *et al.* (2007)).

Table 1: Management paradigms elicited in Figure 1 (Halbe *et al.*, 2013))

	"Economics" Paradigm	**"Predict and Control" Paradigm**	**"Adaptive Management" Paradigm**	**"Community Involvement" Paradigm**	**"Tradition" Paradigm**
System Perspective	Big farms	River and protected values	Floodplain landscape	Flood prone communities	Small farms
Solution Strategies	Economies of scale; rationalization	Build dikes	River-Landscape controlled flows	Community involvement	Traditional farming methods
Risk and Uncertainty Management	Reduce flooding risk and uncertainties	Reduction of uncertainty	Accept flood risk; Adaptive Management (through experimentation)	Uncertainty dialogue	Build on experience from the past

By analyzing the CLD and the risk and uncertainty management strategies of stakeholders, the variables can be related to specific paradigms (see Table 1). The "economics" paradigm has a focus on the economies of scale principle that is applied in large farms in the area by using an industrial farming approach. This paradigm is tightly linked to the "predict and control" paradigm that focuses on the control of river flows and protection of economics goods (e.g., crops) through the construction of dikes. An alternative paradigm is the "adaptive management" paradigm that allows for river-landscape controlled flows through retention areas. Another paradigm is related to "community involvement" that is based upon the discussion of flooding risks and uncertainties in affected communities. Finally, small farms have a separate paradigm called the "tradition" paradigm that comprises the application of traditional farming methods (e.g., planting of native fruit trees that can deal with temporary flooding).

These paradigms reflect diverging perspectives on the same problem (i.e., flooding in the Tisza Basin), as well as different risks and uncertainty management strategies ranging from the reduction of uncertainties and control of risks, towards the acceptance of uncertainties through an adaptive management approach, the discussion of perceptions of uncertainties with communities, and confidence in traditional approaches (see Brugnach *et al.*, 2008 for a thorough discussion of different types of uncertainties).

The messy problems of flood management require careful handling of all these different paradigms. Instead of allowing one specific paradigm to dominate (e.g., the "predict and control" paradigm or "community involvement"), sustainable solutions should acknowledge the value of each paradigm. Sustainable engineering should therefore also include the elicitation and analysis of paradigms, as well as their coordination.

Engineering is often related to a control paradigm that involves the structured analysis of the problem situation, and the prediction of the effectiveness of policies. However, Koen's (2003) definition of the engineering method as the use of heuristics attests that engineering is more than prediction and control, as engineers continuously adapt their practices to contemporary challenges and available knowledge. The following section presents a literature review on the consideration of paradigms in engineering practice and education based upon the following main paradigms discussed in the Tisza Basin flooding case study: "predict and control paradigm", "adaptive management paradigm", "economic paradigm", "tradition paradigm", and "community involvement paradigm". This list of paradigms reflects prevalent paradigms related to sustainable development. However, other topics of engineering for sustainable development (e.g., sustainable construction and energy systems) will have other types and characteristics of paradigms. The next section presents a general overview on the paradigms detected in the flooding case study and the ways in which they are considered in engineering education and practice rather than focusing on the specific implementation of these paradigms in the Tisza example.

3 Consideration of Paradigms in Engineering Practice and Education

This section contains an overview of paradigms that have been defined in the preceding section. Based upon this, potential gaps and challenges in the application of paradigms in engineering practice and education are identified. As this article provides an overview of several paradigms, a more detailed discussion and analysis of each paradigm is beyond the scope of this paper. Where available, references to a more detailed examination of specific paradigms are provided.

3.1 Predict and Control Paradigm

The engineering method is usually associated with a "predict and control" paradigm (cf., Pahl-Wostl, 2011). Engineers are expected to find and implement solutions that work with certainty rather than based upon trial and error. Thus, engineers utilize mathematics, verified physical laws and models as well as empirical knowledge in order to minimize uncertainty. Stochastic methods and safety factors are prevalent approaches to deal with remaining uncertainties. The most appropriate tools and methods for the achievement of best-possible results are specified in the state-of-the-art, which can be defined as the set of heuristics that represent best engineering practice at a specific time (cf., Koen, 2003). These heuristics are first and foremost specified through engineering codes, but also in engineering curricula and contemporary engineering design and practice itself.

An example of the "predict and control" paradigm was already introduced in the flooding example in section 2. By using this paradigm, flood management relies upon the accurate forecasting of flood incidence and amplitude. Today, a variety of physical and data-based modeling approaches are available to predict flooding events (e.g., Razi *et al.*, 2010; Adamowski 2008). Through time, the validity of assumptions like the principle of annuality (i.e., that variables like river water levels can be described by a time-invariant probability density function) are continuously revised in order to improve the evidence of methods and adapt them to contemporary challenges (cf., Milly *et al.*, 2008). Based upon this information, advanced technical measures or warning systems can be designed and applied.

In the Tisza example, the "predict and control" paradigm resulted in the construction of over 4500 km of primary and secondary dikes to protect around 97% of the basin at risk from flooding (Sendzimir *et al.*, 2010). However, an unexpected rise of flooding parameters (i.e., peak elevation, volume, frequency) has resulted in the failure of the defense infrastructure (Sendzimir *et al.*, 2004 and 2010). Another example of the application of the "predict and control" paradigm are the flood management practices implemented in the Netherlands. The Deltaworks is a sophisticated system of dams, sluices, locks, dikes, levees, and storm surge barriers that aim at protecting the Netherlands from storm surges and river floods. Even though the Deltaworks is certainly a remarkable and unique engineering construction, the appropriateness of the underlying assumption is questioned, like future storm wave properties and maximum river discharges (see Bouwer & Vellinga 2007). Thus, there are also signs in Dutch water management that reflect a paradigm shift towards a more adaptive flood management paradigm (cf., Pahl-Wostl, 2011).

3.2 Adaptive Management Paradigm

An "adaptive management" paradigm is based upon experimentation and an iterative refinement of policies and strategies. In this paradigm, "policies are really questions masquerading as answers" (Gundersson 1999). Instead of defining the optimal policy (through prediction), an adaptive management approach can deal with high uncertainties through the continuous monitoring and revision of measures. An adaptive approach is already acknowledged through engineering concepts like "resilience engineering" (Hollnagel *et al.*, 2006), "adaptive engineering" (VanderSteen, 2011) or "ecological engineering" (Diemont *et al.*, 2010). In addition, concepts for sustainable engineering usually include an adaptive management approach as a core requisite to find sustainable solutions in messy problem situations (cf. Dodds & Venables, 2005; Fenner *et al.*, 2006).

Some stakeholders in the Tisza example (see section 2) prefer such an adaptive management approach which would include the reconfiguration or removing of dikes in order to allow more natural river-landscape flow of water. Such a paradigm has been termed "living with floods and giving room to water", which is also emerging in the flood management practices in the Netherlands (Pahl-Wostl, 2006). While a "predict and control" paradigm still dominates in engineering practice and education, there have been various attempts to foster the implementation of an adaptive management paradigm (e.g., Krysanova *et al.*, 2010). Besides the focus on monitoring and experimentation, learning of groups and communities is also a central component of developing adaptive capacity (Folke *et al.*, 2002). Thus, the community involvement paradigm is also closely related to an adaptive management approach, and supports sustainable resource management by addressing diverging stakeholder interests and perceptions (cf., Pahl-Wostl *et al.*, 2010).

3.3 Economic Paradigm

Economic methods and tools like project management or accounting are important in engineering practice. The choice for technological options usually involves the calculation of economic viability, requiring proficiency in both engineering and economics. Engineering curricula generally includes more business economics (comprising, inter alia, statistics, econometrics, as well as decision and risk analysis) than economic theory (cf., Ashford, 2004 and Chinowsky, 2002).

The flooding case study in section 2 highlights the importance of the "economies of scale" principle which is a theoretical concept of microeconomics. Even though not included in the group model, the strengthening of the local economy to deal with the challenges of globalization is also highly relevant to the topic of sustainable development (cf., Bellows & Hamm, 2001). However, micro- and macroeconomics are often not included in engineering curricula (compared to courses in business economics). There are nevertheless examples where micro- and macroeconomics are taught as part of a humanities and social sciences module (see Meyer & Jacobs, 2000).

The Tisza example also shows the relatedness of massive infrastructure for the protection of values (i.e., the predict and control paradigm) and an economies of scale approach. In contrast, more decentralized systems can be more amenable to regional value creation (e.g., local wind parks). Knowledge about fundaments of economics allows engineers to understand and evaluate these connections between technology and economics in sustainable development issues.

3.4 Tradition Paradigm

Traditional knowledge is usually not taught as a separate course in engineering studies. Traditional approaches are sometimes mentioned as historical examples in design courses. For instance, the design of ancient composting toilets in Vietnam can be presented as part of a course about wastewater systems (cf., Mara *et al.*, 2007). Traditional and local knowledge can, however, be a vital part of sustainable solutions as they are adapted to a specific context (cf., Berkes *et al.*, 2000). There are numerous studies that show that local stakeholders can have a deep understanding of environmental or social processes that goes beyond scientific knowledge. For instance, local fishermen on Lake Como, Italy, were able to accurately describe hydrodynamic processes that scientists had been unable to model (Laborde *et al.*, 2011).

The tradition paradigm in the Tisza example (see section 2) also shows the relevance of traditional knowledge for sustainable engineering. There is currently a gap in engineering education regarding the teaching of traditional design and solution strategies. Courses on traditional knowledge could present different cultural approaches for decision making and application of technology, and offer methods to deal with cross-cultural education and projects (cf., Aikenhead, 1997; McCullough & Farahbaksh, 2012). In this respect, community involvement can be an important approach to include local knowledge in engineering projects.

3.5 Community involvement paradigm

Participation of stakeholder groups is considered a key approach for sustainable engineering (see for instance: Ashford, 2004; Dodds & Venables, 2005; Fenner *et al.*, 2006). A community involvement paradigm is tightly linked to an “adaptive management paradigm” (i.e., social learning is a key requisite to the development of adaptive capacity) as well as a “tradition paradigm” (i.e., as an approach to communicate between cultures as well as experts and lay people). Thus, community involvement can also be regarded as a central approach to coordinate the application of paradigms.

Approaches like consensus building exercises (Fenner *et al.*, 2005) and the application of participation methods like backcasting (Quist *et al.*, 2006) or participatory model building are increasingly being embedded into engineering curricula. However, in actual engineering practice, participation often consists of merely information provision or consultation events, which can frustrate stakeholders who expect to be more meaningfully involved (Tippet *et al.*, 2005). Real participation in the design of policies and strategies through a collaborative learning process is rare, as engineers and planning authorities often still operate in a “predict and control” paradigm (cf., Halbe *et al.*, 2013).

The Tisza study serves as an example for a gap between the engineering community and a local bottom-up movement. It seems that both sides cannot acknowledge the value of each other’s paradigm. The teaching of paradigms in engineering education could sensitize engineers to the value of community involvement and diversity in paradigms. This could lead to an “integrated management” paradigm that is based upon the purposeful application and combination of paradigms for certain aspects of the system (social aspects could be coordinated through a “community involvement” paradigm) or different localities (e.g., a “prediction and control” paradigm could be applied for urban areas, while “adaptive management” paradigm could be applied for rural areas) (see Halbe *et al.*, 2013).

3.6 Discussion

The literature review about the relevance of paradigms in engineering education suggests that the “predict and control” paradigm is still dominating with respect to the other paradigms identified in the flooding case study. These preliminary findings are substantiated by a database analysis of Scopus (the academic literature database) that was conducted to assess the evolution and prevalence of these paradigms in engineering practice and education. Search terms were selected as a proxy for each paradigm (see detailed explanations below). Selected key words and the term “engineering” were entered in the search engine of the Scopus database. Table 2a and 2b show the numbers of publications that have the search terms in their title, abstract or key words from 1975 to 2013 (see Table 2a)[1], and

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[1] Search terms in the Scopus database (www.scopus.com): ”engineering“ AND paradigm key words; Data range: years from 1975 to 2013; Document types: All (article, review, conference paper,…); Search related to all subject areas.

The diagram shows corrected publication numbers (C) for each paradigm (i): $\mathbf{C_i = N_{i,j} / c_j}$ where N := number of publications; i := specific paradigm; j := year (j); $\mathbf{c := E_j / E_{1975}}$ where c := conversion factor, E := Number of publications for the search term “engineering”;

their normalized development (Table 2b)[2] (the search procedure is explained in more detail in a footnote below). The graph for each paradigm is colored by using the same colors as in Figure 1: “predict and control” paradigm (orange; search terms: predict and control); “adaptive management” paradigm (light blue; search terms: adaptation or adaptive); “economics” paradigm (green; search term: economics); “tradition” paradigm (grey; search term: traditional or indigenous); “community involvement” paradigm (pink; search terms: stakeholders or participation).

Table 2a: Numbers of publications related to paradigms

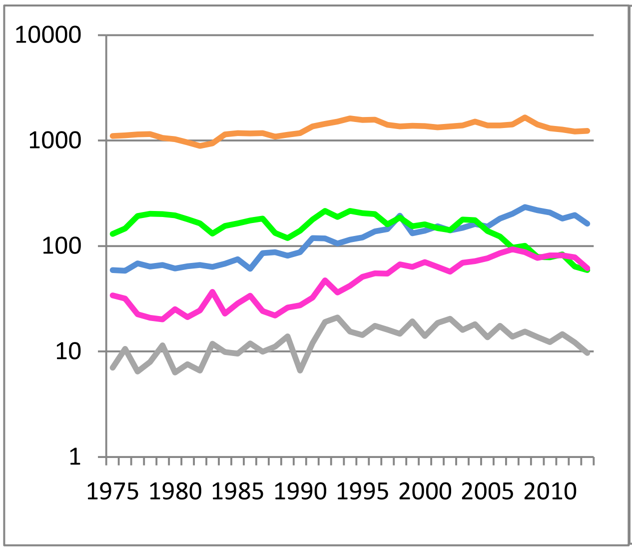
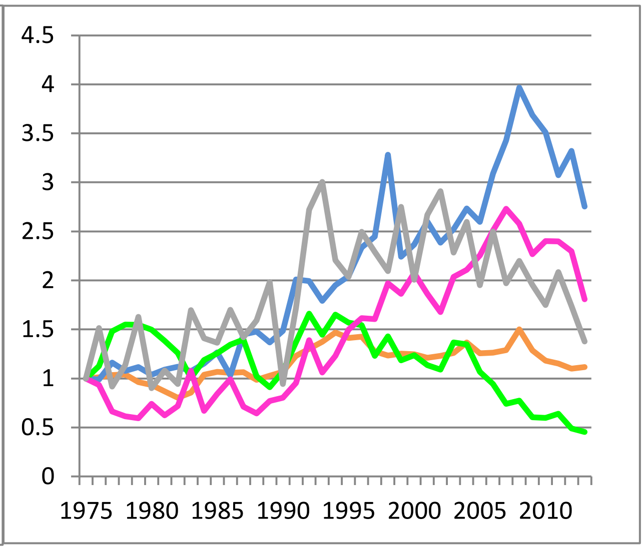


Table 2b: Evolution of paradigms in the engineering literature using 1975 as a reference year



🟧 ‘Predict and control’ paradigm
🟦 ‘Adaptive management’ paradigm
🟩 ‘Economics’ paradigm
🟪 ‘Community involvement’ paradigm
⬜ ‘Tradition’ paradigm

The results of the literature database analysis underlines that the “predict and control” paradigm is the dominating paradigm while the economic, adaptive and community involvement paradigms are represented to a lesser extent. The consideration of traditional or indigenous knowledge in engineering practice and education are at a niche level only (see Table 2a). Adaptive management, economics and community involvement are, however, increasingly being considered in engineering (Table 2b). The

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Explanation of the compilation of data: the numbers are corrected as numbers of publications have increased steadily through time (i.e., in the 1970s, total publication numbers are lower than in the 2010s); however, this might distort the results, as an increase in publications related to a paradigm might not necessarily imply an increase in the relative importance of this paradigm, but might be due to a total increase in publication numbers. Thus, results are corrected by computing the numbers of publications for the term “engineering”, and relating the results to the number of the year 1975 (i.e., correction term of 1975 is “1”; for the year 2000, the correction term is “3.5” – this means that the number of engineering publications in 2000 are higher by a factor of 3.5 compared to publication numbers in 1975; thus, the numbers of publications for paradigm-rated search terms are divided by the annual correction factors)

[2] Search terms in the Scopus database (www.scopus.com): „engineering“ AND paradigm key words; Data range: years from 1975 to 2013; Document types: All (article, review, conference paper,…); Search related to all subject areas.

The diagram shows relative publication numbers (R) for each paradigm (i): $\mathbf{R_i = N_{i,j} / N_{i,1975}}$ where N := number of publications; i := specific paradigm; j := year (j) adaptive management paradigm shows the most significant increase followed by the community involvement and tradition paradigms.

Based on the discussion of the relevance of paradigms in engineering practice, the following section presents experiences in the teaching of paradigms in university courses at McGill University and University of Osnabrück. The focus of the discussion is on the "community involvement" paradigm due to its particular importance for sustainable development issues (i.e., community involvement is a central approach to mediate conflicting perceptions and to help coordinate diverging paradigms) (cf., Lucena *et al.*, 2010).

4 Teaching the Community Involvement Paradigm

Role playing games, backcasting, and participatory model building are effective approaches to teach systems thinking, and the relevance of diverging opinions and interests for the solution of messy problems. In addition, we propose the explicit consideration of paradigms in engineering education in order to sensitize students to differing epistemologies. Students are taught to understand and appreciate the application areas and limitations of a range of paradigms in order to be able to coordinate diverging solution perspectives and find integrated strategies for sustainable development. In addition, students can profit from experiences outside of the classroom (i.e., with real stakeholders) in order to gain confidence in the relevance and applicability of participatory methods. Carefully designed small projects are used as suitable mechanisms to gain practical experiences and strengthen the connection of the university to regional sustainability issues. Table 3 shows a mix of lectures, exercises and projects that were tested at the University of Osnabrueck, Germany, and McGill University Canada to teach the relevance of paradigms and community involvement to undergraduate and graduate students. All three authors have used these different approaches to varying degrees in the two universities. Each of the elements is presented in detail in the following sub-sections.

Table 3: A combination of lectures, exercises and projects to teach community involvement

Teaching Units	**Contents**
Lectures	Paradigms in Sustainable Engineering (2h) Systems Science (2h) Participatory Model Building (2h) Design of Participatory Processes (2h) <u>Supplemental Lectures:</u> *Further Methods for Stakeholder Involvement*
Exercises	Individual Modeling (2h) Group Modeling (3h) <u>Supplemental Exercises:</u> *Role Playing Games; Scenario Analysis; Computer Models as Educational Tools*
Project	Individual Interviews (3 weeks) Merging and Analysis of Models (3 weeks) Presentation of Results (2 weeks)

4.1 Lectures

The lecture on paradigms in sustainable engineering introduces paradigms that are frequently found with the various ‘messy’ problems of sustainable development. Students learn about different paradigms and their epistemological foundations. In addition, advantages and limitations of each paradigm are presented and discussed in this lecture by providing examples from practice (e.g., the Tisza example, see section 2). Systems science is also a core methodology for sustainable engineering; the lecture on systems science comprises the methods of systems thinking and system dynamics (see Sterman, 2000). The application of these methods in a participatory setting is provided subsequently in a lecture on participatory model building (c.f., Vennix, 1996, van den Belt, 2004). Participatory methods cannot be applied in isolation but need to be embedded in a broader design of a participatory process. A related lecture deals with the framing of a ‘messy’ problem, the analysis of stakeholders, the organization of the participatory process, and its embedment in the broader institutional structure (see Halbe *et al.*, submitted).

4.2 Exercises

Individual and group modelling exercises are used to provide students with experiences dealing with the method of participatory modelling in the “safe environment” of the classroom. In the individual modelling exercise, students learn to build a causal loop model of their individual perception regarding a specific environmental issue (e.g. water scarcity). The model is built on a large sheet of paper by the student. Variables are written on sticky notes and connected through causal arrows (see Vennix, 1996 for a detailed description of the methodology). Following the guidelines of Vennix (1996), the problem variable is placed in the middle of the paper. Then, the causes of the problem are placed on the left hand side and causal arrows are drawn. Subsequently, the consequences of the problem are added, and feedback processes are analysed (i.e., the student assesses whether a consequence of the issue can be connected to a cause variable). This exercise results in a comprehensive causal loop diagram that can be interpreted as the mental model of an individual.

In a group modelling exercise with the students, the same method is applied in a group setting, i.e., a group of students (about 4 - 8 students) construct the model jointly. This exercise can be combined with a role playing game. For example, in a group model building exercise on the issue of water scarcity, students assume the roles of farmers, hoteliers, citizens, governmental representatives, and engineers to learn the applicability of the method in stakeholder discussions. In addition, the role of a “facilitator” is represented by a student in each group. This student has the task to moderate the discussion and to help if questions related to the methodology arise. Therefore, facilitators meet once with the lecturers before the actual class exercise for about one hour in order to learn about the application of the method in detail. The group exercise follows the same procedure as the individual modelling exercise (i.e., define the problem variable; add causes, consequences and feedback loops). At the end of the exercise, one or two student groups present their results to the class (see an example of a resulting CLD in Figure 2). Feedback from the students indicates that the students find this exercise very useful in better understanding the concepts of systems thinking and modelling.

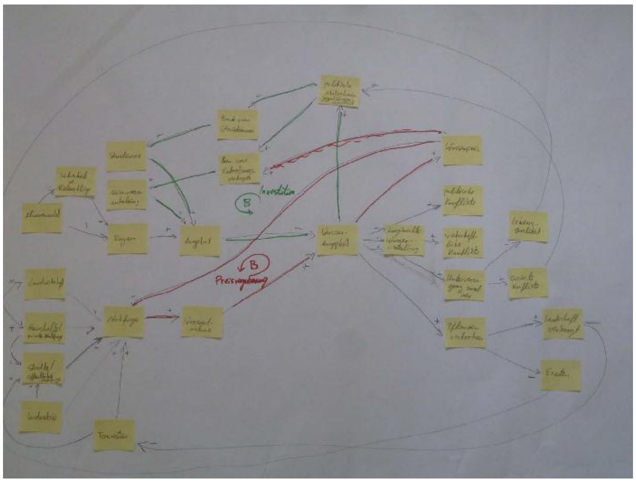

Figure 2: Group model built by students on the issue of water scarcity including causes, consequences, and feedback loops (marked in colour).

4.3 Project

In group projects, students learn to apply participatory modelling with real stakeholders. Locally-relevant and up-to-date topics are chosen that can ideally be related to an on-going participatory process. The list of stakeholders is discussed with students, and potential participants are contacted by the lecturer (via e-mail or regular mail) in order to ensure an effective and immediate start to the student project. However, students are free to contact further stakeholders during the interview process.

After the initial contact with stakeholders is accomplished through the lecturer, students arrange a meeting time with the participants (stakeholders). Each stakeholder interview is conducted by a sub-group of two students, and takes place at the university or the participant's working place. An interview takes around 1.5 h, and proceeds using the same steps that were learned during the exercises (see section 4.1.2). Each sub-group of students has the task to complete at least two interviews. After the interviews, students compare the individual models and analyse diverging points of view as well as complementary aspects. In addition, students develop a holistic model that contains all the perceptions of the stakeholders and highlights the points where opinions differed. Finally, the project results are presented to the stakeholders in a final meeting. In addition to the discussion and presentation of results, students moderate a discussion between different stakeholder groups.

An example is provided of the above with a project focused on the topic of sustainable mobility in Osnabrueck, Germany. In this project, students supported the work of a "bike traffic" round table that had existed for several years. The round table consisted of various stakeholder groups that promoted cycling in the city (for instance, stakeholders included representatives from the City of Osnabrueck, cycling clubs, and the police). The stakeholder group was trying to determine why cycling was not more popular in Osnabrueck despite positive conditions. The student group was asked to analyse the barriers and drivers of cycling in Osnabrueck, and potential feedback processes that inhibited a higher rate of bike-use.

The results of this project revealed the unexpected finding that the anticipated consensus between members of the stakeholder group was not reflected in the individual models. Only five variables and three causal connections were contained in all individual models of the cycling issue. Thus, the interviewees put their focus on different aspects of the issue (of low cycling rates) in Osnabrueck. In light of this, the students analysed certain aspects of the models in detail: "cycling infrastructure", "health", "security", "emissions", and "share of motorized private transport (MPT)". For each of these topics, the students elicited the system structures and feedback processes from the individual models. At the end, the students compiled a holistic model that showed the interrelations and feedbacks of all aspects of the modelled system. Based on this model, potential reasons for the relatively low rates of cycling were analysed. Three main explanations of the phenomena were found. First, two balancing feedback processes were detected that are expected to slow down the growth of the cycling rate: (1) a rising cycling rate was related to a higher prevalence of bike-related accidents which decreases the feeling of security which ultimately lowers the bike share; (2) if more people used their bike, congestions on MPT would decrease which makes the usage of the car more attractive. Secondly, the reinforcing mechanisms for growth in the cycling rate are subject to constraints. For example, the use of cycling infrastructure is constrained by its publicity (i.e., people need to know about the bike system) and the personal travel range of cyclists (i.e., even with a good bike system, people are only willing to bike for a certain distance). Third, students determined external variables that have an impact on the cycling rate such as standard of living, oil price, or environmental consciousness. These aspects cannot be influenced at a local level (e.g. oil price), or require a long time to change (e.g., environmental consciousness).

The stakeholder group approved the holistic model as a comprehensive representation of the cycling issue. The model helped to develop a comprehensive overview of the system and potential policy interventions. The group discussion revealed that subjective perceptions of cyclists (e.g., on security or the quality of the bike system) have a critical influence on the system. It was revealed that most measures in the past have focused on the improvement of biking infrastructure rather than considering the influence of bikers' perceptions. The group concluded that a more concerted effort on raising awareness to increase cycling rates in Osnabrueck would likely be the most effective policy to pursue.

4.4 Experiences

Students acquire various competencies in engineering for sustainable development through a combination of lectures, exercises and projects presented above. First, students learn about the value of different paradigms and are encouraged to review their paradigm as an engineer. The role of a facilitator in particular is an important extension of the prevalent expert approach in engineering. Second, the method of participatory model building is a suitable approach to analyse issues in an integrated manner (as required for sustainability issues) and to involve stakeholders in the analysis and design of sustainable solution strategies. In addition, causal loop diagrams are a helpful method to elicit paradigms and analyse their interrelatedness (see section 2 and Halbe *et al.*, 2013). Third, the group project allows students with the opportunity to test their methods on real world problems. The direct feedback from stakeholders provides opportunities to reflect on the applicability of the method and to get hands-on experience in community involvement. Due to the linkage to an up-to-date and relevant problem, stakeholders are typically willing to devote their time to the interviews. The students generally obtain very positive feedback regarding the value of their work, and the relevance of the results. For example, in another project on the more contested issue of wind energy, stakeholders were impressed that students were able to explain the volatile dynamics of the system due to the dominance of reinforcing loops that can cause a "boom and collapse" dynamic. Students are usually very motivated to produce meaningful results since they feel that their study is relevant for stakeholders. In addition, the moderation of the closing event is a good learning opportunity for students to listen to differing perceptions, and to facilitate a fruitful discussion which is also a critical skill for sustainable engineering.

5 Conclusions

Sustainable development poses particular challenges to engineering. In the past, engineering has applied a more ‘expert’ approach based upon a ‘control and predict’ paradigm. However, sustainability issues require the participation of various stakeholder groups that might have differing perspectives, goals and paradigms. The consideration and management of differing paradigms is thus a critical task in engineering for sustainable development.

This paper presents an analysis of paradigms that are related to flood management in Hungary which includes prevalent features of sustainable development issues. It turns out that the application of a single paradigm is not sufficient to address the multiple aspects of messy problems. The integrated analysis and combination of paradigms is a more promising approach to find sustainable solutions. A literature review examined the prevalence of paradigms related to the flooding example case. The results indicate that the “predict and control” paradigm is still the dominating paradigm in engineering. The “economics”, “adaptive management” and “stakeholder involvement” paradigms are additional paradigms that are increasingly considered in engineering education and practice. A “tradition paradigm” that acknowledges the value of traditional knowledge resides at a much lower niche level. Further analysis revealed the central relevance of the “community involvement” paradigm, as this paradigm is linked to the “adaptive management” as well as the “tradition” paradigms.

Based upon this analysis, some of the authors’experiences are presented to sensitize students to different paradigms and to teach practical approaches for community involvement. A combination of lectures, exercises and projects are proposed to introduce the tool of participatory modelling, and to provide students with experiences in its application in stakeholder processes. In particular, the linking of group projects to on-going local stakeholder processes proved to be a valuable approach for students to gain experience in the implementation and facilitation of meaningful stakeholder participation.

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