Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0
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Transdisciplinary Engineering Research Challenges

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Abstract. Transdisciplinary research (TDR) has been the subject of discourse in the past few decades, but has bot been studied much in the context of engineering problems. Many engineering problems can be characterized as ill-defined, like open innovation, adoption of new technology, business development, and the adoption of the Industry 4.0 concept. Transdisciplinary engineering research (TDER) is also performed in large projects by multi-disciplinary teams, as in TDR projects, including stakeholders and people from practice. Such projects may last long, often years. In such large projects, the involved disciplines should include both engineering disciplines as well as disciplines from social sciences. In this paper we address the challenges that exist in adopting a TDER approach. Universities need to prepare students to work in TDER projects. We discuss the current situation in transdisciplinary engineering education (TDEE) and identify challenges that need to be addressed for including TDEE in curricula. The paper ends with a summary and ideas for further research.

Keywords. Transdisciplinary engineering research, transdisciplinary engineering education

Introduction

Transdisciplinary research (TDR) has been the subject of discourse in the past few decades in the context of large, complex, ill-defined problems, also called wicked problems. Such problems may also have outcomes that cannot easily be predicted. These problems, like sustainability, environmental problems, or urban planning, can no longer be tackled by means of a disciplinary approach. Knowledge from different scientific communities as well as from practice is needed to reach a solution that is acceptable to the (often many) stakeholders (see e.g., [1]).

TDR is performed by teams and subteams composed from different disciplines from science, technical as well as social, and practice, both from companies and user communities. Managing such teams is not an easy task. Gaziulusoy et al., [2] have

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identified challenges that need to be addressed in managing and participating in TDR project. Moreover, a transdisciplinary research project does not proceed according to preset timelines, budget, and goals. Such a project is characterised by its emergent behaviour an shifting goals. A TDR project needs to be shaped along its course [3] and requires leaders that are visionary and flexible.

In engineering contexts, a transdisciplinary research approach has not been studied much yet. Many engineering problems, however, can be characterized as large, complex, and ill-defined, also with unknown outcomes. Especially new innovations, business development, the adoption of new technology, or the development of a completely new factory, like the smart factory, are examples of such engineering problems.

Transdisciplinary engineering research (TDER) is also performed in large projects by multi-disciplinary teams, including stakeholders and people from practice. Such projects may last long, often years. In such large projects, the involved disciplines should include both engineering disciplines as well as disciplines from social sciences, as indicated above.

In this paper, we address the challenges that exist in adopting a transdisciplinary way of working in TDER projects. In section 1, the challenges that need to be addressed in a TDR project will be briefly discussed. In section 2, challenges in TDER projects will be indicated. In section 3, challenges in transdisciplinary engineering education (TDEE) will be discussed. The paper ends with a discussion section and ideas for further work.

1. Challenges in TDR projects

Collaboration and coordination between researchers from different disciplines is one of the main characteristics of TDR. Problems studied in TDR projects are practical problems. This means that people from practice also need to be involved as well as other stakeholders, like financers and legislators. TDR is similar to other types of collaborative research but differs in three main characteristics [2]:

1. It is agenda-driven.
2. It aims at integration between and alignment of knowledge from different disciplines, as well as theoretical and methodological transformation of each discipline throughout the process of the research.
3. It involves non-academic participants with significant stakes in the research problem and process, as researcher or as informant.

In the literature many challenges haven been described that are faced by TDR teams. Gaziulusoy et al. [2] have grouped challenges in TDR project as reported in the literature into three groups:

1. Inherent challenges: challenges that directly rise from the characteristics inherent to TDR;
2. Institutional challenges: challenges that arise from the current structures and procedures of knowledge generation and performance evaluation in academic institutions;
3. Teamwork challenges: challenges that stem from the requirement of collaboration of researchers from different expertise background and often from different academic institutions with each each other and with non-

academic stakeholders in ways to enable transdisciplinary knowledge generation.

Teamwork challenges, more specifically, have been described in a publication on the longitudinal study of a large transdisciplinary project [4]. Frescoln and Arbuckle have assembled these challenges from the literature on complex projects like TDR projects. These challenges are:

- Communication and language barriers.
- Professional cultures and cognitive cultural differences create subgroups among team members, challenging cross-discipline collaboration.
- Differences in methodologies between disciplines.
- Competition for funds.
- Difficulty in reproducing research.
- Different geographical locations of participants.
- Conflicting goals amont team members.

These challenges are well-known for large distributed projects. Managing such projects is an encompassing task. The Project Management Body of Knowledge (PMBOK) [5] has provided guidelines for managing different kinds of projects, from small to large, in various application domains. These guidelines, however, cannot be considered as recipes. Transdisciplinary projects are complex, goals are shifting during the course of the project, destructive forces may be active, sponsors may loose their interest, etc. [3]. Knowledge of and experience with large, complex problems is needed to manage transdisciplinary projects.

The teamwork challenges listed above have also been identified by Gaziulusoy et al. [2] in a case study of a TDR project. The strict adherence to project deadlines, fixed budgets and reporting requirements does not attend to the evolving characteristics of a TDR project. In addition, an institutional challenge like career development may be hampered, because the development of new scientific knowledge is often not the only priority in a TDR project. Greater emphasis is put on knowledge for practice and targeted on a wider audience. Leaders of TDR projects have to develop adaptive strategies to manage emergent challenges that may compromise scientific validity and social responsibility of the project [2]. The often large scope of TDR projects often have large impacts on project management, expertise management and resource management.

In the following section we will explore some additional challenges in TDER projects

2. Challenges in TDER projects

What is transdisciplinary engineering research and in which circumstances is it needed? Transdisciplinary engineering research (TDER) is especially aimed at solving problems that require a vision beyond the immediate engineering task for their solution. In transdisciplinary engineering research not only technical disciplines need to participate but also disciplines from social sciences. In addition, knowledge is needed from practice and stakeholder communities, including financers, legislators, sponsors, etc. For example, many construction projects can be considered as projects requiring a transdisciplinary approach. Other examples can be found in the medical and in the aeronautics industry.

Miller and Lessard [3] have emphasized that large engineering projects cannot be fully predicted and designed beforehand. A shaping approach is needed depending on task complexity and the degree of development of institutional arrangments. The task complexity requires exploration and testing, while in the development of institutional arrangments strong coalitions need to be formed. The real-options framework is applicable, recognizing that decisions determining project cash flows in conjuction with exogenous events are not all made at the outset of the project [3].

Shaping a transdisciplinary engineering research project requires several management processes [3]:

- Negotiating a project concept or proposition that truly creates value and can be progressively refined in the overarching issue;
- Developing stability for the future of the project;
- Gaining and ensuring legitimacy;
- Achieving shock-absorption capabilities;
- Ensuring capital-cost reduction.

These activities cleary transcend engineering activities. They require the involvement of all relevant actors and disciplines. Below, we explore some projects that require a transdisciplinary engineering research approach.

2.1. Open Innovation

In the past, many companies performed their innovation processes in a closed way. In the research lab of the company, breakthroughs were sought, products were developed in the company, built in its factory and distributed, financed and serviced from within the four walls [6]. Open innovation, on the other hand, requires collaboration with other companies, because not all new technology can be developed in-house or new technology from the own research lab may not be profitable enough for the own company [6]. The former case requires the buy-in of new techology or close cooperation with the inventing company, often a small company. The latter may result in spin-off companies that are required to collaborate with other, often larger companies.

New inventions are not merely given away. Often they are protected by IPR (Intellectual Property Rights), giving a company a means to gain revenues by licensing an invention to other companies to develope and manufacture, or by leasing a name, logo, or slogan to other companies [7]. Companies may also get an equity stake in companies that further develop and produce their invention [6].

Open innovation requires collaboration between different companies, while involvement of legal people and business people is needed to investigate business opportunities and the legal limits and options. In addition, knowledge of potential markets is necessary to build a viable business model. A true transdisciplinary approach is needed, because the process evolves over time and needs to be shaped. A visionary leader is also needed to buy-in commitment and support.

2.2. Business Development

After a new technology has been developed, a new business may need to be set up, involving possibly the company in which the technology has originated, but more often a new start-up company or spin-off company. The new business may be a technology service provider or a manufacturing company that will produce a new product. A whole new socio-technical system has to be set up in developing the new business.

In setting up a new business or changing an existing one, many different aspects need to be investigated, like economic feasibility, patenting, licensing, location demands, waste disposal, etc. In addition, resource demands and availability are important to consider, in particular financial resources, knowledge and experience of the employees, and management capabilities.

Especially with the demands on sustainability, the 3 Ps need to be taken into account as well: people, planet, profit. The new business needs to provide a good environment for its workforce, it needs to care for the environment with respect to its inputs, outputs and waste during and after the process. A trade-off needs to be made between investements on the short term and revenues on the longer term (see e.g., [8]).

It is clear that business development requires a transdisciplinary (research) approach, because the process may take some time, goals may shift as insights grow, stakeholder values are at stake, and investments are large. In addition, the process is multi-dimensional, requiring both people from science and practice as well as people from both technical and social-science disciplines. Knowledge exchange needs to be extensive and lead to new knowledge and insights, academically and practically.

2.3. Adoption of new technology

Disruptive technology like 3-D printing leads to many new business opportunities, but also triggers new legislation and copyright and IP protection measures. Ownership of design, printfile, or final product need to be redefined.

In setting up a new 3-D printing service all that has been indicated in the previous section needs to be taken into account. In addition, new technology is needed to protect products against plagiarism [9]. Although already incorporated in law, e.g., paragraph 54 of the German Copyright Law, counterfeiting and plagiarism are still possible, especially in the B2B area. Holland et al. [9] have defined four categories of conterfeit protection: internal security, external security, product labelling, and legal safeguard. In their paper, they discuss product labelling more extensively, like visible and invisible tagging and the introduction of marker particles.

This example shows that the adoption of new technology is not only an engineering or technical task, but involves other disciplines as well. The process of new technology adoption may also take quit a long time, because new insights and unexpected consumer or client behaviour may trigger the need for additional protective measures and business redesign.

2.4. Towards Industry 4.0

With the development of new technoloy and cloud computing a totally new concept of production facilities has become possible, the so-called smart factory. Smart factories are an instantiation of the Industry 4.0 concept [10]. The concept Industry 4.0 has been introduced by the German government and is targeted on industrial production systems. Industry 4.0 is the name for the current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems (CPS), the Internet of Thing (IoT), cloud computing, and cognitive computing [11]. Data are typically stored in the cloud.

In a smart factory, products, processes, and machines have both a real and a virtual presence. They can be called 'smart', because at any point in time their status, progress, and activities can be identified, monitored and planned. The data are continuously updated and used during a production process and during product and machine life. Factories are becoming 'smart' and 'adaptive', because of the new intelligence that has been embedded in machines and systems. They are able to share data and support enhanced functionalities at a factory level and include collaborative and flexible systems able to autonomously solve problems that arise during the process [11][12].

Smart products, processes, and machines can be considered an instance of the IoT. CPSs monitor physical processes and create a virtual copy of the physical world to make decentralized decisions. Over the IoT, CPSs communicate and cooperate with each other and with humans in real time and via cloud computing [13][14].

Industry 4.0 is radically changing the way people interact with machines, systems, and interfaces. Many different skills will be required in the new context. Lower-skilled repetitive tasks will be replaced by tasks that require competences in software development, and IT technologies. The Boston Consultancy Group recently reported a set of examples to illustrate the possibilities for deployment and the implications for the workforce in Industry 4.0 contexts [15, 16]. For example, companies will need algorithms for analyzing real-time or historical quality control data, identifying quality issues and their causes, and pinpointing ways to minimize product failures and waste. The application of big data analysis will reduce the number of workers specialized in quality control, while increasing the demand for industrial data scientists [17].

Other consequences of adopting Industry 4.0 are:

- Robots will replace humans, because they can be easily trained to take on new tasks, in contrast to humans; A new job may be the robot coordinator;
- Automated transportation systems navigate goods intelligently and independently within the factory; They replace logistics personnel; Increased need will grow for skilled controllers and programmers;
- Production line simulation prior to installation will increase the demand for industrial engineers with production management knowledge and simulation experts;

New jobs will be more cognitive and complex. The business model, in addition, will also change including the markets that can be served, because the range of products and the degree of customization will change. Because production lay-out needs to change frequently, the job floor requires a flexible lay-out. Resource management needs to adapt to the changing situation, because workers need other skills and knowledge. New IT systems, like CPSs, are needed to manage the physical world and interact with the virtual world represented in the cloud. These systems need to be able to cross organizational borders.

Implementing the Industry 4.0 concept in a company clearly requires a TDER approach. Changing the business is not only a technical task, but involves the whole business as well as sponsors, legislators, and financers. The people in the company as well as existing and potential markets play an important role also. The change process may take many years, with a step-by-step approach, in which the goals to be achieved may shift over time.

3. Transdisciplinary engineering education

As described above, solving complex, practical, problems often involves many disciplines, which are not only technical. In addtion, people from practice and from the context involved need to be incorporated. However, universities tend to deliver their programs in discipline-specific courses, like materials, propulsion, dynamics, etc. Although these courses are essential for building the basic knowledge engineering students need, knowledge of other disciplines is needed to learn to solve realistic problems. Some universities have recognized the necessity for transdisciplinarity, for example:

- The University of Technology Sydney (UTS), for example, has a faculty dedicated to transdisciplinary innovation [18];
- The Tokyo Institute of Technology has a Department of Transdisciplinary Science and Engineering in the School of Environment and Society [19].

In engineering curricula it is very essential to create opportunities for students to experience and practice design on a realistic problem. Project-Based Learning (PBL) is an approach for students to acquire deeper knowledge through active involvement in exploring and solving real-world challenges and problems. It involves learning by doing [20]. The outcome of PBL can be a report, a model, or an artifact that defines the proposed solution. People from practice are often involved to provide information and judge the outcome. Some sources of inspiration for PBL are:

- The Warman Design and Build Competition [21];
- Engineers without Borders Challenge [22];
- Global Grand Challenges [23];
- Fly your Ideas [24];
- GoFly [25];
- Telanto [26].

RMIT students have participated in a project established by SpaceX to build a hyperloop pod [27]. The project required a transdisciplinary approach, involving not only engineering, but also media, industry sponsors, business and finance. The team consisted of about 30 students from different schools, like engineering, business, computer science, and media and communication. The team was invited to SpaceX headquarters in LA, where the pod was subjected to safety tests. The students needed to produce technical documentation and answer questions. The project, though, was relatively unique, but does emphasize the complexity of the project and the need to cross domain borders to produce a good solution.

The School of Engineering at Jönköping university became a member of CDIO in 2006 and was the first university in Sweden to include all engineering curricula in first and second cycle level [28]. In 2013, shared courses covered the following modules:

- Off campus integrating theory and practice;
- Leadership and project management;
- Group dynamics;
- Business administration and entrepreneurship;
- Business planning and marketing;
- Presentation and report writing;
- Research methods;
- Sustainable development.

In addition, PBL, internationalization, multidisciplinary projects, and a focus on societal challenges were also part of the shared educational concept.

Different courses have been defined in bachelor and master programmes, including the Product Development Project, which has been given on a yearly basis since 1998. Students appreciate the course, while the companies that have been involved value both the results and the collaboration, as it brings new perspectives and is vitalizing for the organization.

Although initiatives towards transdisciplinary engineering education exist, as can be concluded from the examples above, the focus is still for a large part on technical disciplines mainly. The CDIO example, for instance, does not yet fully embrace all aspects of transdisciplinary engineering. Problem solving is directed towards needs expressed by society as represented by external stakeholders, but the actual involvement of people and knowledge from social sciences is not emphasized. Large projects, focusing on ill-defined society-relevant problems, where students collaborate with practitioners and practitioners are involved in guiding and evaluating the work done, do not seem to be part of a curriculum. They are primarily organised as a one-off exercise, driven by some enthusiast lecturers.

We have identified challenges that need to be met to fully transform education into transdisciplinary education:

- *The organization of faculty*. Research is mainly disciplinary, while also the organization of faculty is based on a disciplinary logic.
- *Mutual responsibility and engagement*. Faculty staff from social sciences as well as faculty staff from engineering need to take equal responsibility, value other iterpretations and knowledge, and be ready to collaborate.
- *Inclusion in curricula*. A question that needs to be answered is, whether all engineering and social science students should be educated in solving society-relevant problems in a transdisciplinary way. Some universities choose to organize special masters courses for bright students only.
- *Finance and time for projects*. Projects tend to be large when it comes to credits to be earned and efforts required from teaching staff. Other expenses include travel costs. Budget planning is difficult because the amount of work ahead cannot be precisely estimated.
- *Preparation and training of students*. Training for collaboration is essential to create openness for knoweldge and thinking of other disciplines.
- *Emphasis on learning of shared processes and methodologies*. Not all projects may reach an acceptable solution, because the problem is ill-defined and insights into the path to follow may grow during the process. The learning and knowledge gained must be assessed and evaluated. The knowledge can be transferred to other projects.
- *Increased involvement of practitioners*. Practitioners from different disciplines should be involved in the project to take part in problem formulation, goals setting, evaluation of progress and final assessment of the result, including the knowledge gained. Practitioners can act as mentors, coaches, and experts continuously during the project and support learning of knowledge and methodologies.

First of all, disciplinary and multi-disciplinary courses are still needed, both in engineering and social sciences disciplines. The process towards transdisciplinary engineering education requires teachers, students, practitioners and knowledge from engineering and social sciences. The motivation, ambition, and effort to solve society-relevant problems should be a mutual effort from the start.

4. Summary and Conclusion

We have discussed transdisciplinary research in the context of engineering research. Several engineering problems have been presented that are deemed to require a TDER approach, like open innovation, the adoption of new technology, business development, and the adoption of the Industry 4.0 concept. Several challenges have been identified that need to be tackled for TDER projects.

We have also discussed the need for including transdisciplinary problem-solving into engineering and social science curricula. Some examples of existing approaches in universities have been presented. TDEE projects are demanding, exhausting university resources and placing heavy demands on companies involved. However, TDEE project, with the new knowledge and methodologies to be developed, are not only expected to benefit students and teachers as well as science, but also practitioners. Many challenges need to be addresses before universities and companies together can engage in real TDEE projects.

Recapitulating, the challenges that need to be addressed are:

- Identification of engineering problems that require a transdisciplinary approach. Problems that can be solved by a disciplinary, inter-disciplinary or multi-disciplinary approach need not be solved in a TDER way.
- Technical disciplines should have an open mind to disciplines from social sciences, and vice versa. Additional training is needed to create such an open mind. The problems to be tackled cannot be solved by a disciplinary approach.
- In each TDER project, both science and practice goals need to be formulated. Proper measurement and assessment systems are needed both for science and practice. In addition, publication in scientific journals must receive special attention, because it may need the formulation of specific disciplinary goals, next to goals aimed at combining knowledge.
- TDEE projects require proper methods and tools to support teachers and practitioners in guiding complex education projects.

TDE research should be aimed at increasing understanding of the nature of transdisciplinary work and support the management of complex teams, measure their progress and output, and manage and support collaboration between people with many different backgrounds.

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