Transdisciplinary systems engineering: implications, challenges and research agenda

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Abstract: Transdisciplinary processes have been the subject of research since several decades already. Transdisciplinary processes are aimed at solving ill-defined and socially relevant problems. Many researchers have studied transdisciplinary processes and have tried to understand the essentials of transdisciplinarity. Many engineering problems can be characterised as ill-defined and socially relevant, too. Although transdisciplinary engineering cannot widely be found in the literature yet, a transdisciplinary approach is deemed relevant for many engineering problems. With this paper we aim to present an overview of the literature on research into transdisciplinary processes and investigate the relevance of a transdisciplinary approach in engineering domains. After a brief description of past research on transdisciplinarity, implications for engineering research, engineering practice, and engineering education are identified. In all three areas, the current situation is described, while challenges are identified that still exist. The paper ends with a research agenda for transdisciplinary engineering.

Keywords: transdisciplinary systems; transdisciplinary processes; transdisciplinary engineering; transdisciplinary research; engineering education; project-based learning; Industry 4.0; transdisciplinary collaboration; social relevance.

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1 Introduction

Transdisciplinary processes have been the subject of research since several decades already. Much research can be found in the literature on the subject. The emphasis of transdisciplinary approaches is on surpassing inter- and multidisciplinarity by integrating and relating natural and technical sciences with social sciences and practice. Transdisciplinary processes are focused on solving ill-defined and society-relevant problems, like sustainability and environmental problems. The idea is that these problems cannot be solved by any discipline alone, even not by one person with knowledge of many different disciplines. Collaboration between and knowledge from different disciplines is needed for solving these problems.

Engineering design is a domain in which technical solutions are sought for many different problems. Not all problems in this domain can be characterised as ill-defined, or even society-relevant, but many do. An example is the adoption of a new technology that impacts the way of working and society, like 3-D printing. The question is whether a transdisciplinary approach applies to an engineering domain like that.

In this paper, we will investigate the applicability of a transdisciplinary approach to engineering problems that can be characterised as ill-defined and society-relevant. We start with presenting current insights into transdisciplinarity. We list some characterisations found in the literature on research of transdisciplinary processes. This list is then matched with engineering research processes that require collaboration between different disciplines and with practice. Such engineering research processes are often part of a larger project aimed at solving the complex problems that require a transdisciplinary approach. Challenges are identified that need to be addressed in transdisciplinary engineering research.

Secondly, transdisciplinary engineering requires extensive IT support to manage and control the vast amount of data and knowledge produces and used in TE processes. As an example, the concept of the smart factory is briefly discussed in the context of Industry 4.0. We will argue that the development and implementation of a smart factory requires a transdisciplinary approach.

Thirdly, transdisciplinary engineering requires the involvement of people with an open mind to other disciplines. Engineering education should incorporate courses aimed at equipping students with knowledge and skills needed to understand and be able to collaborate with people from other disciplines. In this paper we discuss some courses that have been designed to achieve this goal. Especially project-based learning (PBL) will be described with examples from education practice. In addition, challenges are identified that still exist for achieving TE education.

The paper is organised as follows. Section 2 is a brief literature review with current insight into transdisciplinarity. Some implications for research, IT support and education are presented as well as a brief characterisation of a transdisciplinary approach. Section 3 contains an introduction into TE research with a list of challenges that need to be addressed. In Section 4, the concept of the smart factory is presented. An introduction to the context of Industry 4.0 is discussed as well as some current technological developments. It is emphasised that development, implementation and management of a smart factory requires a transdisciplinary approach. In Section 5, approaches to and examples of TE education are presented. Challenges are identified that need to be tackled before PBL can truly be called TE education. The paper ends with a brief discussion of the current state-of-the-art in TE research, processes and education as well as a research agenda for the domain of transdisciplinary engineering.

2 Transdisciplinarity and engineering

Much can be found in the literature on the concept of transdisciplinarity, transdisciplinary research and transdisciplinary processes. Space limitation in this paper prohibits an extensive essay on these concepts. The reader is referred to the literature for a more extensive study of the concepts. In this section, a brief history of research of transdisciplinarity is sketched, followed by a brief discussion on some consequences of adopting a transdisciplinary way of working in engineering. This section ends with some implications for education in transdisciplinary engineering.

2.1 Transdisciplinarity

In the past century, many new disciplines have emerged (Scholz and Steiner, 2015c), leading to a fragmentation of the body of sciences. Each discipline has developed its own methods, qualitative or quantitative, for validation. Examples are deductive and inductive reasoning, probabilistic and deterministic models, or other forms of reasoning (Scholz and Steiner, 2015c).

Transdisciplinarity has been subject of discourse in the 70s of the previous century, when it was realised by Piaget that interdisciplinarity is only possible between neighboring disciplines, like physics and chemistry (Scholz and Steiner, 2015c). Mode 1 transdisciplinarity [see Scholz and Steiner (2015c)], including General Systems Theory (Von Bertalanffy, 1951), then emerged in search of a meta-structure for integration of disciplines and a unity of knowledge. However, natural sciences have been dominant in this approach.

In the 90's of the previous century it was realised that societal needs should shape research and education. Klein (2004) argues that the problems of society are increasingly complex and interdependent. Not one single sector or discipline can tackle such problems. Each problem is multidimensional. Tackling complex problems requires mode 2 knowledge creation, which is meant to overcome the reductionist view of science [see Scholz and Steiner (2015c)]. In a Mode 2 knowledge creation, older hierarchical and homogenous modes are replaced by new forms characterised by complexity, hybridity, non-linearity, reflexivity, heterogeneity, and transdisciplinarity (Klein, 2004). In essence, transdisciplinary research requires collaboration across discipline boundaries beyond interdisciplinary and multidisciplinary research (Ertas, 2010). Mode 2 transdisciplinarity is not merely aimed at integrating disciplines, but at relating disciplines (Scholz and Steiner, 2015a). In 2012, the European Commission also emphasised that solving the complex and ill-defined problems of current societies requires collaboration not only across various disciplines, but also with incorporation of the innovative and creative capabilities in society itself (European Commission, 2012).

In the literature, several characterisations can be found of transdisciplinarity:

1 Scholz and Steiner (2015a) emphasise that an ideal transdisciplinary process is not aimed at implementation of a solution. Instead, the outcome of a transdisciplinary process is an improved decision-making capacity, built during the transdisciplinary process.

2 A transdisciplinary process starts from a real-world problem (Scholz and Steiner, 2015a). It thus turns the scientific process upside down.

3 A transdisciplinary process needs social and scientific goals, as well as personal and financial resources (Scholz and Steiner, 2015a).

4 Transdisciplinarity is a development of new knowledge, concepts, tools and techniques shared by researchers from different families of disciplines (social science, natural science, humanities and engineering). It is a collaborative process of a new way of organised knowledge generation and integration by crossing disciplinary boundaries for designing and implementing solutions to unstructured problems (Ertas, 2010).

5 Transdisciplinarity raises not only the question of problem solution but also problem choice (Klein, 2004). A large focus of transdisciplinary research is on problems of sustainability and environment.

6 There is no transdisciplinary language. Transdisciplinarity is a context-specific negotiation, linked with the concept of communicative action (Klein, 2004).

7 Transdisciplinarity tackles complexity in science and it challenges knowledge fragmentation (Lawrence and Després, 2004).

8. Both research and practice need to benefit from a transdisciplinary process (Scholz and Steiner, 2015b), which implies that both research and practice have their own goals in a transdisciplinary process, but sharing the overarching goal.

In two extensive papers on transdisciplinarity Scholz and Steiner (2015a, 2015b) define and discuss transdisciplinarity based on experiences with over 40 small and large transdisciplinary processes they have been involved in the past 20 years. They emphasise that transdisciplinary processes should be aimed at socially relevant ill-defined problems like sustainability transition. The question is whether a transdisciplinary approach is applicable to and useful for ill-defined problems in the engineering domain. In this paper, we identify some implications of adopting a transdisciplinary way of working in the engineering domain. Not all problems need a transdisciplinary approach for solving them, only ill-structured or ill-defined problems that are relevant for society. We will identify some of those problem domains.

In summary, a transdisciplinary approach is:

1. Problem-oriented. Ill-defined, society-relevant problems are dealt with in a transdisciplinary approach.
2. In solving ill-defined, society-relevant problems both academia and practice need to be involved. From academia, both technical and social sciences need to be involved. From practice, also technical and social disciplines need to be involved.
3. Both research and practice need to benefit from a transdisciplinary process.
4. Research goals need to be defined, encompassing both technical (e.g., disciplinary or inter- or multidisciplinary) and social science goals (e.g., encompassing business management, human resources, or team composition and culture).
5. Practice goals need to be defined, encompassing different functional goals, like technical as well as human resources and management goals.
6. Project goals need to be defined, which may shift in the course of the project, because of the dynamic nature of the project and unexpected situations that may emerge.
7. Measures need to be defined for the various outcomes of the project. It is still a challenge to define such, very different, measures.

Below, some implications for the engineering domain are identified.

2.2 Implications for engineering

From the current literature on transdisciplinary research and transdisciplinary processes, it can be inferred that there is a focus on knowledge exchange and knowledge formation as well as on the process of transdisciplinary problem solving. Knowledge exchange and knowledge formation are also important in engineering processes.

Not much literature can be found yet on transdisciplinary engineering. As one example, Gumus et al. (2008) have developed an extended version of the axiomatic design approach, covering the whole product life cycle. The model may be embedded in and support a transdisciplinary approach, but cannot be considered a transdisciplinary model as such, because the focus is mainly on engineering disciplines.

There are approaches that aim to tackle ill-structured or ill-defined problems that are relevant for society. One of them is design thinking (Dorst, 2011). The emphasis of design thinking, as described by Dorst, is on design approaches and methods and on designers, whatever disciplines they may have and in whatever contexts they may operate. Also in social sciences, design approaches are used, for example, when designing new business processes. Design thinking may offer relevant and useful approaches for tackling an ill-defined or ill-structured society-relevant (engineering) problem. It is beyond the scope of this paper to explore the relationships and differences between design thinking and transdisciplinary engineering, but is certainly an interesting subject for further research.

When applying transdisciplinarity in engineering environments there are several conclusions to draw as well as questions to pose. One conclusion is that also in engineering both research and practice need to benefit from a transdisciplinary approach. Moreover, a transdisciplinary approach needs the involvement of people from both science and practice, requiring a multitude of methods and tools to support and manage collaboration between them. Below, we aim to identify some processes in engineering that may require a transdisciplinary approach.

First of all, open innovation processes may have all prerequisites for a transdisciplinary approach. The innovation problem is often ill-defined. People from user communities, financial and legal institutes, and different disciplines from both scientific institutes and practice need to collaborate to define a feasible business model for a new innovation. People from social science disciplines should be involved to manage and support the brainstorming, idea formation, team formation and management, and business model creation. The knowledge created in the open innovation process should be extensive and an encompassing basis to support the subsequent product creation and implementation phases. Scientific goals in such a process may include identification of new knowledge, generation of new process management methods, or establishing new team formation guidelines. Practice goals may include the establishment of new working relationships, the concept of a new design or a new business model.

Second, the realisation of a business model as created in an open innovation process may also require a transdisciplinary approach, when the business model is different from business models known to the participants. An existing business may need to be extended or a totally new organisation needs to be set up. Next to detail development of the product, processes need to be defined as well as organisation models. People from different science communities need to be involved as well as different disciplines from practice, bringing their own knowledge and insights. The management of the transdisciplinary processes needs to be supported by a variety of tools and methods. Science goals may include the formation of new technological knowledge as well as the identification of new methods for managing the detail design phase with a variety of disciplines, business functions and user communities. Practice goals may include the identification of feasible product technologies and solutions for the new product and business to be established.

Third, implementation of a product in practice may also require a separate transdisciplinary approach. The implementation process may include the going life of a new factory. Representatives of user communities may test a new product with tests developed by scientists and practitioners from marketing departments. Science goals may include new knowledge on production layouts, test environments and systems for gathering information on usage and on user behaviour. Practice goals may include reduction of the number of errors in products ready for use.

Fourth, an interesting process requiring a transdisciplinary approach is the implementation of a smart production factory in the context of Industry 4.0 and as a special case of the internet of things (IoT) (Rojko, 2017). Implementation of such a factory requires collaboration between many different disciplines, both from research and practice. These disciplines should also encompass both technical and social disciplines, because not only new technology is implemented, but also new practices, new processes, and new knowledge, that employees should be able to understand and use. A change process is needed that requires thorough management and guidance. Also in this example, research goals (technical as well as social) and practice goals (performance, motivation, and acceptance) need to and can be set.

As in all complex projects and processes, many challenges exist in managing transdisciplinary teams (Gaziulusoy et al., 2016). In transdisciplinary engineering processes a lot is still to learn about the specific challenges in such processes. We need to specify research goals for managing and supporting transdisciplinary engineering processes.

In Section 3, transdisciplinary engineering research will be further detailed with examples from engineering research. In Section 4, technology that can be used to support transdisciplinary engineering processes, is presented.

2.3 Implications for engineering education

As can be inferred from the discussion above, education for transdisciplinary engineering should incorporate all facets of transdisciplinary research and processes. It is important to recognise that it is useful but not sufficient for students to acquire knowledge about different disciplines. Students also need to experience collaboration with other disciplines to encounter differences in thinking and problem-solving approaches.

In education for transdisciplinary engineering practice problems should lead transdisciplinary engineering courses (Carew et al. 2006; Jakobsen and Bucciarelli, 2007). Students from different disciplines, technical as well as social, should be involved. Technical students focus on the technical side of the practical problems. Students from social science departments may design and support the overall research, including the formulation of research questions and the setup and management of multi-disciplinary teams including practitioners.

In addition, a team of teachers is necessary, coming from faculties of technical and social sciences. They should guide and judge students with respect to the science goals to be achieved. Openness to each other is necessary and the willingness to collaborate.

Finally, practitioners should participate in the teams to guide and judge students with respect to the practical goals to be achieved.

It is not an easy task to manage multi-disciplinary teams, like student project teams. Many challenges exist in managing transdisciplinary student project teams (Jakobsen and Bucciarelli, 2007). An important challenge is the proper assessment of process and achievements in such projects (Del Cerro Santamaría, 2015). In Section 5, transdisciplinary engineering education including its challenges will be discussed in more detail.

3 Transdisciplinary engineering research

Transdisciplinary research comes in a variety of flavours. A sizeable body of work focuses on definition of the concept, process and outcome(s) of transdisciplinarity [e.g., Lyall et al. (2015), Mitchell et al. (2015), Pohl (2011), Polk (2015), Wickson et al. (2006)]. Furthermore, a dominant stream in the existing state of the art considers transdisciplinary case studies. These either substantiate methodological definitions and contributions [e.g., Mitchell et al. (2015)], or communicate the findings of (sets of) transdisciplinary research initiatives [e.g., Polk (2015)].

As mentioned previously, the full scope of the discussion on transdisciplinarity as a concept is beyond the purpose of this paper, but several relevant ideas will be used to characterise the positioning and features of transdisciplinary engineering research in this Section. In particular, we seek to

1 connect transdisciplinary engineering with the principles and features of transdisciplinarity discussed in Section 2

2 highlight challenges that are particularly relevant for the pursuit of transdisciplinarity in engineering

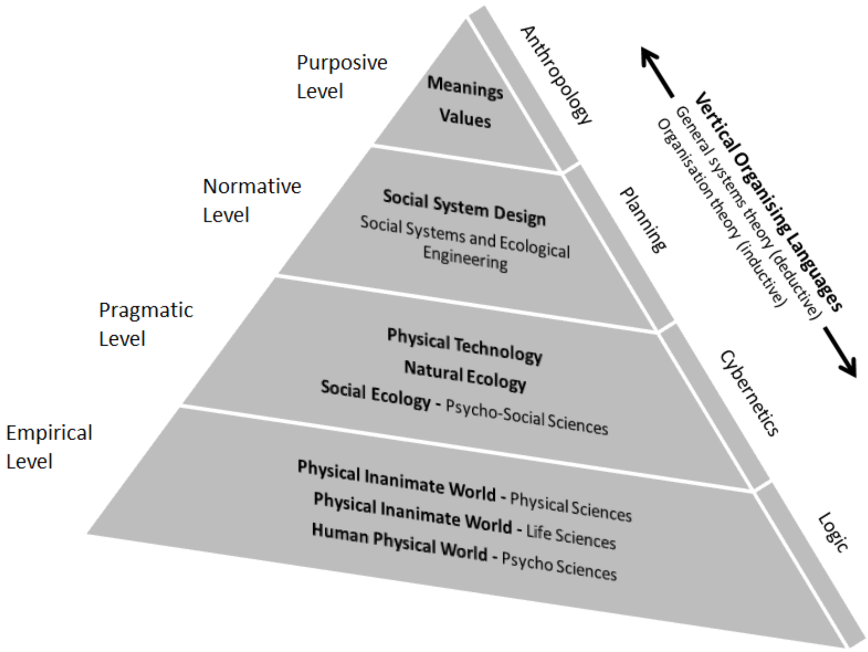
3 briefly introduce and discuss typical application areas for transdisciplinary research in the engineering domain.

3.1 Engineering research from a transdisciplinary perspective

Engineering, as a full set of activities covering the lifecycle of products from design, manufacturing, operation, support and disposal, is typically denoted as the intermediary between our empirical understanding of the physical world (as studied by the physical sciences) and physical technology and associated systems. Engineering, in other words, is the set of activities that transforms our understanding of physical phenomena into realisable and usable physical products and systems. This interplay between the physical environment and its application towards technology has been proposed by Jantsch (1972), and visualised and put into a transdisciplinary perspective by Mitchell et al. (2015). This is reproduced in Figure 1.

Figure 1 makes clear that technology, as a result of engineering activity, does not operate in a vacuum. The physical manifestation of technology at a pragmatic level is dependent on direct connections with the physical inanimate world at an empirical level, and drives and in turn is driven by the design of social systems at a normative level. Furthermore, there are clear and important interconnections – indirectly represented in Figure 1, but arguably direct as well – with what Jantsch (1972) denotes the 'human physical world', which is covered by the social sciences. Through interconnections at different levels of abstraction, technological products are a function of inputs from the societal environment in which they are positioned, and in turn influence this societal environment through technology uptake and use in socio-technical systems.

Figure 1 Physical technology within the education/innovation system as proposed by Jantsch (1972) and adapted by Mitchell et al. (2015)



Aspects of the perspective visualised in Figure 1 may be challenged, for instance the hierarchical organisation and its completeness. Nevertheless, the engineering community has taken one of its key messages, namely that of connection and integration, to heart. This has been realised first of all in multi- and interdisciplinary approaches, which promote the efficiency and success of product lifecycle processes through increased collaboration across disciplines and involvement of multiple stakeholders (Wickson et al., 2006). Key examples can for instance be found in the Systems Engineering research field (Fiksel, 2003, Holt and Perry, 2008, National Aeronautics and Space Administration, 2007), with its focus on integrated processes for product development. Transdisciplinarity in engineering can be considered as a useful follow-up as the engineering community seems to explicitly and/or implicitly realise that the products it creates play an indispensable role in addressing and solving otherwise near-intractable societal problems (Polk, 2015).

In Section 2.1, seven key features of transdisciplinary approaches have been mentioned. These can be connected to the engineering domain as follows:

1 *Problem orientation:* by its nature, engineering typically deals with problems that have a high relevance and (potential) impact on society. Engineering problems are sometimes crisply defined, especially when moving towards more fundamentally oriented engineering disciplines such as applied physics or material sciences. In design-oriented or operations-oriented engineering studies, ill-defined problems involving multiple stakeholders from academia and practice are common.

2 *Involvement from academia and practice:* In solving ill-defined, society-relevant problems both academia and practice need to be involved. Participatory research, involving collaboration between academic and non-academic stakeholders, is relatively commonplace in engineering when considering the involvement of stakeholders from related lifecycle stages. These issues have long been studied from the systems engineering and concurrent engineering perspectives [see e.g., National Aeronautics and Space Administration (2007)]. However, formalised studies tend to follow academic methodologies. The involvement of societal users and communities is not a common feature when considering the available range of engineering domains. For some domains that have sustainability at the foreground (e.g., maritime engineering/water management), the involvement of societal stakeholders is much more prevalent.

3 *Benefits from participatory research:* Addressing societal relevant issues is high on the agenda of a variety of national and international funding agencies and bodies, for instance the UK research councils (Polk, 2015) and the Horizon 2020 research and innovation programme of the European Commission (Horizon 2020, 2014). A common request in generation of scientific proposals is to motivate the industrial and societal impact of the proposed research. As such, there is a clear external impetus driving the establishment of multi-, inter- and transdisciplinary research initiatives to address societal problems with clearly defined benefits.

4 *Definition of research goals:* These goals need to be defined for the technical part, but also for the social part. The engineering community has spent considerable effort over the years to reconcile disciplinary paradigms, as evidenced in the development of multi-disciplinary optimisation (MDO), cyber-physical systems (CPS), IoT and associated advances in data, information and knowledge representation. Industry 4.0 is highlighted in Section 4.0 as representative examples. In addition, several academic communities are focused on the development of transdisciplinary engineering cases and approaches (Borsato et al., 2016). Knowledge generation and retention is traditionally pursued from mono-disciplinary perspectives within engineering. Recent decades have seen the introduction of research institutes and centres with a multi- or interdisciplinary focus, but the adoption of truly transdisciplinary teams with the avowed aim of unifying knowledge is, to the best of our knowledge, not widespread.

5 *Definition of practical goals:* as mentioned previously, the definition of practical goals is relatively commonplace in engineering projects, but these typically focus on industry objectives. Defining practical goals for society as well as different functional goals such as human resources and management goals is not prevalent in research.

6 *Definition of project goals:* the definition of project goals usually aligns with research goals as stated above, but may be different, since also mono-disciplinary research goals may be formulated for part of a project. The dynamic nature of projects and resulting emergent contexts and situations are usually not acknowledged in engineering settings.

7 *Definition of measures:* measures are typically defined in traditional ways, focusing on the economic effect or efficiency resulting from research. Societal measures are much less frequently defined and measured.

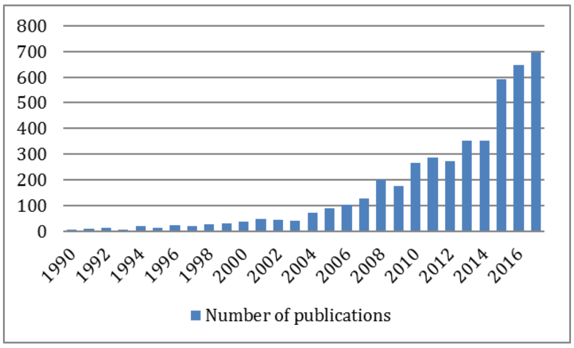
An area that is worth further investigation is the relationship between transdisciplinary engineering and open innovation. As indicated in Section 2.2, transdisciplinary engineering may well apply to open innovation trajectories, since the stakeholders in open innovation are very divers, from engineers to business managers and people from user communities. Also research institutes may be involved (Chesbrough, 2006). The outcome of an open innovation process is an extensive business case, which is the input of the next stage in product and process development. The business case defines a (possibly new) business or business process, which also needs further (transdisciplinary) development and implementation.

Another distinctive element of transdisciplinary research in general, and transdisciplinary engineering as a subset, reflects on the purposive level of research initiatives – the top of the pyramid in Figure 1. Pohl (2011) proposes four possible purposes of transdisciplinarity in defining transdisciplinary research as "research that frames, analyses and processes an issue such as [sic]: 1) the issue's complexity is grasped; 2) the diverse perspectives on the issue are taken into account; 3) abstract and case-specific knowledge are linked and; 4) common-good-oriented descriptive, normative, and practical knowledge to address the issue are developed" (Pohl, 2011). In contrast, Mitchell et al. (2015) maintain that Pohl's characterisation is more 'what' and 'how' than 'why', i.e., with more attention towards descriptions and means than towards actual outcomes. As a response, Mitchell et al. (2015) distinguish three distinct 'transdisciplinary outcome spaces': situation, knowledge, and learning. They are elaborated as relating to "1) an improvement within the 'situation' or field of inquiry; 2) the generation of relevant stocks and flows of knowledge, including scholarly knowledge and other societal knowledge forms, and making those insights accessible and meaningful to researchers, participants and beneficiaries and; 3) mutual and transformational learning by researchers and research participants to increase the likelihood of persistent change" (Mitchell et al., 2015). These outcome spaces will be used to structure the identification of specific challenges for transdisciplinary engineering research, as covered in the next subsection.

3.2 Challenges in transdisciplinary engineering research

A first and perhaps obvious challenge for transdisciplinary engineering research is its adoption: methods, tools and case studies being developed under the label 'transdisciplinary engineering' are highly limited. A simple query in Clarivate's Web of Knowledge on the terms 'transdisciplinary engineering' yields only 235 records. When expanding the search to include either 'transdisciplinarity' or 'transdisciplinary' – so, without taking into account engineering as related term – yields the numbers as visualised in Figure 2. Two elements can be distilled: first, the absolute number of publications incorporating (aspects of) transdisciplinarity is relatively sizeable, being in the same order of magnitude when for instance comparing with terms like Industry 4.0 and CPS. Second, there is a growing body of work, with a sizeable majority of publications arriving in the timespan 2010–2017.

Figure 2 Number of publications related to transdisciplinarity (see online version for colours)



Source: Web of Knowledge

In addition to this challenge of adoption, we identify three major challenges related to the previously mentioned outcome spaces.

First of all, to achieve an improvement within the 'situation' or field of inquiry, it is necessary to establish improvement metrics. The question then becomes which metrics are acceptable to all stakeholders involved in the transdisciplinary setting. Identification and acceptation of these metrics relies on a shared conceptualisation of the underlying field of inquiry. Striving towards such a shared conceptualisation in the first place is one of the hallmarks of transdisciplinarity. From an engineering research perspective, an extensive set of work has been pursued with respect to the development of core and domain ontologies [e.g., Borgo and Leitão, (2007), Jureta et al. (2008), Noy and Hafner (1997)], which aim to establish a common underlying view on a domain, its concepts and the relations between these concepts. The underlying view expressed via ontology is sufficiently flexible to allow for domain- or discipline-specific interpretations. These efforts are, however, often driven from the academic perspective and are commonly interdisciplinary in nature, lacking involvement of societal, non-academic stakeholders or addressing a topic of limited societal impact. However, the development of semantic web technology and advent of the IoT may bring ontology development into fully transdisciplinary settings.

Another major challenge for transdisciplinary engineering research lies in the aspect of generalisability. Research initiatives which are primarily geared towards the first outcome space defined by Mitchell et al. (2015), i.e., considering improvement for a 'situation' or field of inquiry, have the pitfall of being constrained towards that situation. In other words, the outcomes generated by a project may only be valid for the specific situation and its context being addressed. Given the complexity typically present in transdisciplinary engineering applications, it is non-trivial to generalise findings from one project to another. Only general guidelines may be developed from lessons learned.

Here, the two other outcome spaces point towards a solution: while the specific improvement(s) generated for a problem may not be generalisable, the stocks and flows of knowledge and the learning achieved during the transdisciplinary process may be incorporated into other projects. Furthermore, on lower levels of abstraction some methodologies can feasibly be generalised, for instance to manage collaboration between heterogeneous teams or management of technical multidisciplinary sub-teams.

A final challenge facing transdisciplinary research, and transdisciplinary engineering research as the subset of interest, relates to the consistency of approaches, metrics and results for transdisciplinary research. As mentioned before, the concepts of transdisciplinarity itself as well as its features are still not settled, almost 50 years after its conception, and metrics to adequately assess the performance of transdisciplinary research are lacking. This points to a larger problem: to properly assess the effect of transdisciplinarity beyond the gains possible via the adoption of 'competing' approaches such as multi- and interdisciplinarity, the scientific method would dictate a (set of) carefully controlled experiment(s). Experiments should account for and measure the influence of explanatory and confounding variables on dependent variables as expressed in appropriate metrics, leading to evaluation of the performance and effectiveness of a transdisciplinary approach in comparison with alternatives. However, given the dynamic, fluid and flexible nature of transdisciplinary (engineering) projects, involving multiple stakeholders and addressing real-life problems, a systematic experimental study for evaluation of the available options would be very difficult, if not impossible, to achieve.

4 Transdisciplinary engineering research: smart factories

With the development of new technology 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 (Rojko, 2017). Industry 4.0 is the name for the current trend of automation and data exchange in manufacturing technologies. It includes CPS, the IoT, cloud computing, and cognitive computing (Hermann et al., 2016, Hermann et al., 2015).

In Section 4.1 we briefly describe the concept of the smart factory and the concept of Industry 4.0. In Section 4.2 we identify the consequences for the company and for the workers in the company. In Section 4.3, the need for a transdisciplinary approach in research and practice will be emphasised. In Section 4.4, an example of a smart factory under development will be presented.

4.1 Smart factory and Industry 4.0

In a smart factory, products, processes, and machines have both a real and a virtual presence. Products, process, and machines are, therefore, called 'smart'. Data on products, processes, and machines as well as their statuses, are stored in cloud devices. These data are continuously updated and used during a production process and during product and machine life. Factories are becoming 'smart' and 'adaptive' thanks to new intelligence embedded in machines and systems, will be able to share data and support enhanced functionalities at a factory level, and include collaborative and flexible systems able to autonomously solve problems arising during the process (Hermann et al., 2016).

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 decentralised decisions. Over the IoT, CPSs communicate and cooperate with each other and with humans in real time and via cloud computing.

Smart factories can be extended to include the whole value chain. Both internal and cross-organisational services are needed to enable the smart factory to cross companies in the value chain.

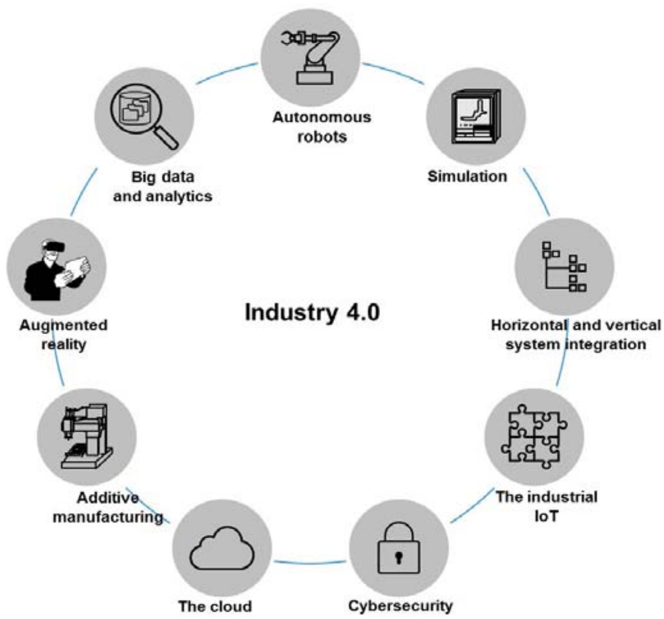
In summary, the main characteristics of Industry 4.0 are:

1. The vertical networking of smart production systems, such as smart factories and smart products, and the networking of smart logistics, production and marketing and smart services, with a strong needs-oriented, individualised and customer-specific production operation.
2. The horizontal integration by means of a new generation of global value-creation networks, including integration of business partners and customers, and new business and cooperation models across countries and continents.
3. A through-engineering approach throughout the entire value chain, taking in not only the production process but also the end of life, considering the entire product life cycle.
4. The acceleration through exponential technologies that, while not really new in terms of their development history, are only now capable of mass-market application as their cost and size have come down (e.g., sensor technology) and their computing power has risen massively.

Industry 4.0 has also its foundations in nine advanced technologies that will transform the manufacturing production: isolated, optimised machines and/or cells will be aligned in a network to achieve a fully integrated, automated, and optimised production flow, leading to greater efficiencies and changing traditional production relationships between suppliers, producers, and customers, as well as between human and machine.

The Industry 4.0 pillars are represented in Figure 3.

Figure 3 Industry 4.0 pillars: technologies transforming the modern industry (see online version for colours)



Source: The Boston Consulting Group (2015a)

In Industrial IoT devices (sometimes including even unfinished products) are enriched with embedded computing and connected using standard technologies. This allows field devices to communicate and interact with one another and with more centralised controllers, when needed. Contemporary analytics based on large data sets can be used in the manufacturing world to optimise production quality, to save energy, and to improve equipment service. The collection and comprehensive evaluation of data from many different sources (i.e., production equipment and systems, enterprise, customer-management systems) will become standard to support real time decision-making.

In this context, autonomous robotics is evolving the actual use of robots to even greater utility. Robots are becoming more autonomous, flexible, and cooperative. Eventually, they will interact with one another and work safely side by side with humans and learn from them. These robots will cost less and have a greater range of capabilities than those used in manufacturing today.

Furthermore, Industry 4.0 cloud-based software allows increased data sharing across sites and company boundaries, achieving reaction times of just several milliseconds. As a result, machine data and functionality will increasingly be deployed to the cloud, enabling more data-driven services for production systems, to better monitor and control the industrial processes.

Moreover, 3D simulations of products, materials, and production processes will be used more extensively to mirror the physical world in a virtual model, which can include machines, products, and humans. This allows operators to test and optimise the machine settings for the next product in line in the virtual world before the physical changeover, thereby driving down machine setup times and increasing quality.

Finally, augmented reality-based systems can support a variety of services (e.g., selecting parts in a warehouse and sending repair instructions over mobile devices) to provide workers with real-time information to improve decision-making and work procedures.

These systems are currently in their infancy, but in the next future, companies will make much broader use of such technologies to create a fully integrated factory, where machines are flexible, auto-adaptive and partially self-controlled, and workers are provided with real time information to improve decision making and work procedures. In this direction, the potential worldwide impact of Industry 4.0 is huge. The German government declared relevant benefits to be achieved in manufacturing during the next five years: from boosting productivity by €90 billion to €150 billion, with a productivity improvements from 15 to 25 %, to an additional revenue growth of about €30 billion a year, or roughly 1 % of Germany's GDP.

4.2 Consequences of adopting Industry 4.0

Industry 4.0 is radically changing the way people interact with machines, systems, and interfaces. Many different skills will be required in this new context. In the short term, the trend toward greater automation will displace some of the often low-skilled workers who perform simple, repetitive tasks. At the same time, the growing use of software, connectivity, and analytics will increase the demand for employees with competencies in software development and IT technologies, such as mechatronics experts with software skills (The Boston Consulting Group, 2015a). This competency transformation is one of the key challenges ahead.

The Boston Consulting Groups recently reported a set of examples to illustrate the possibilities for deployment and the implications for the workforce in the Industry 4.0 context (The Boston Consulting Group, 2015b). For instance, companies will need algorithms to analyse real-time or historical quality control data, identifying quality issues and their causes and pinpointing ways to minimise product failures and waste. In addition, the application of big data will reduce the number of workers specialised in quality control, while increasing the demand for industrial data scientists.

Manufacturing companies will use robots can be easily trained to take on new tasks, in contrast to humans. Safety sensors and cameras allow the robots to interact with their environment. Such advancements will significantly reduce the amount of manual labour, such as assembly and packaging, but create also a new job, the robot coordinator.

Similarly, the introduction of automated transportation systems that navigate goods intelligently and independently within the factory will reduce the need for logistics personnel but increase the need for skilled controllers and programmers.

Furthermore, the use of production line simulation prior to installation to optimise operations will increase the demand for industrial engineers and simulation experts. In all examples, there is a change in the job typology. On the one hand, the demand for workers who perform simple, repetitive tasks will decrease, because these activities can be standardised and performed by machines. On the other hand, new jobs will be required with respect to the implementation of such new technologies, system programming and control, process simulation, and data analytics.

Industry 4.0 will also imply a radical shift from physical and manual interaction with machines and products, to a more cognitive, complex and mental interaction.

In summary, Industry 4.0 will drastically change the concept of a production factory. The business model will change including the markets that can be served, because the range of products and the degree of customisation will change. In addition, employees' tasks, procedures, knowledge and skills will need to change, requiring different human resource management approaches. Lay-out of the factory needs to be flexible to accommodate the changes that are expected to be frequent. Technical support departments need to change because of the advanced technological demands of products, processes and machines. New IT systems, like CPSs, are needed to manage the physical world and interact with the virtual world represented in the cloud. In addition, these systems need to be able to cross-organisational borders.

4.3 Development, implementation, and management of a smart factory

To develop and implement smart factory collaboration between many different disciplines both from academia and practice is needed. These disciplines should encompass not only technical disciplines, but also social ones, because many different facets of a company and its processes are involved. In particular, as indicated above, the smart factory dramatically changes a business model including the markets that can be served, the practices needed to perform the processes, and the knowledge workers need to perform their tasks. A complex and dynamic change process is needed to achieve the smart factory.

A smart factory in operation is not a static factory. The technology enables the factory to dynamically react to changed plans and volumes, to changed requirements and to unexpected events. Smart decision-support systems enable people, in addition, to make fast decisions. The management of a smart factory in operation is not only a technical matter, but requires also involvement of human resource management and business management.

Social-science research should be aimed at developing management methods and procedures to manage collaboration between the different functions and disciplines, as well as ways to deal with the dynamics in a smart factory. Technical research in connection with social sciences should be aimed at developing suitable man-machine interfaces, for example, and identify the knowledge and skills workers need to have. Technical research could be aimed at developing and improving suitable systems, physical systems as well as software, to enable process automation and flexible process adaptation.

The practical goals of a transdisciplinary approach to the design of manufacturing systems in the Industry 4.0 context are related to avoiding risks in data security and to achieve the potential benefits. IoTs and CPSs involve a high amount of data and information, but they have to be properly managed to improve human-machine interaction and properly control the adaptive behaviours of both machines and interfaces. As a consequence, adopting a transdisciplinary approach fundamentally requires inclusion of human factors in system design to be more efficient, adaptive, flexible and sustainable, and to manage the growing complexity of systems that are hard to manage and maintain (Peruzzini et al., 2017, Peruzzini and Pellicciari, 2017). Machines are becoming more and more digitised and technologically more advanced, thus they require more experience but also higher mental abilities, which inevitably decrease with age (NTIA, 2001). These trends can be divergent, and only the inclusion of human factors in the design of industrial systems can overcome the current issues due to changes in working conditions, new technologies, and new demands on workers (e.g., higher flexibility, extended knowledge, polyvalence) (Toomingas and Kilbom, 2007).

In this direction, systematic engineering approaches are required bridging gaps between technical and social sciences. They will bring intelligence into the shop floor required to provide factories with flexible and adaptive behaviours. The human-centred design approaches allow to correlate the workers' needs and the system features at different levels (considering the users, the context, the machine, and the interface) and to test the designed adaptability on virtual prototypes.

4.4 An example of a smart factory under development

An important area of transdisciplinary engineering is the factory on a macro level and the industrial workshop on a micro level. Both levels have impact on physical effects, signals, information and, last but not least, human factors under social and economic considerations (Kahlen et al., 2016). The vision of Industry 4.0 and of smart factories manufacturing smart products is subject of discussion widely and is confronting enterprises in many industries with a range of new challenges and opportunities (Lu, 2017, Zhong and Ge, 2018). One of the most important tasks in the Industry 4.0 concept lies in the continuous cross-disciplinary synchronisation of simulation and operation in production, which is subject of some recent initiatives.

In Germany, the prostep ivip association, as a pioneer of harmonisation and standardisation worldwide with more than 160 members in industry and research, has conducted a survey among its members. Based on the outcomes of the survey, it has prepared a study on the further development of digital manufacturing. The most important conclusion was the large need for synchronisation in production planning data for products, processes and resources (Stark et al., 2014). A large need for action has been identified, both at the strategic level, where unstructured data from production would be needed in a planning environment (e.g., maintenance of factories and plants), and at the tactical level, where operation data would be used to adjust the plan values (Branger and Pang, 2015). A consistent data flow needs to be included due to more intensive standardisation, tools for assessing the level of the digital production environment, and analysis of the economic benefits on both the macro and micro level.

4.4.1 Synced factory twins

The concept of the Synced Factory Twins (synchronisation of the Digital Twin in the factory) has been derived from daily business and demonstrates the transdisciplinarity in the era of Industry 4.0. The implementation of this concept should taking place in a large consortium project, including industry, research institutes and associations (Weber et al., 2015). Observing a gap between real and virtual factory measurements, this project should turn into reality the continuous synchronisation of planning data and simulation models from product development, production planning and production by assessing early feedback from the real factory. An essential prerequisite is the continuous update of planning data throughout the entire product lifecycle right from the start of production (SOP) (Nawari and Kuenstle, 2015, Yu and Madiraju, 2015).

Adopting a transdisciplinary approach, the Synced Factory Twins project is divided into two sub-projects (seamless and looped information flow; mixed simulation environment), which use the information model and interoperability means, that both sub-projects can run almost simultaneously and be completed at a similar point in time. Based on a uniform target representation, an information model is derived which includes the modelling and specification of data objects, attributes and their relationship to each other in a hybrid simulation environment. The synchronisation between virtual and real products, processes, and resources occurs in the sub-project mixed simulation environment. Specific scenarios in three use cases with mixed simulation environments and with the combination of real and virtual products, processes and resources in digital production are provided. The use of the X-in-the-loop simulation to optimise functionality, quality and costs, should be realised by provision of the early feedback of field data to product development and production planning. The bidirectional and cross-domain exchange of a uniform description of the information objects between virtual and real production in product development, production planning and production should be assured using standard models OPC UA, Automation ML and STEP AP 242 (Yu and Madiraju, 2015).

The expected deliverables of the subproject Seamless and Looped Information Flow include the following elements (Weber et al., 2015):

- A functional target representation for Synced Factory Twins: it shows the high level functional building blocks and their key information objects in a structured and hierarchical manner.
- A functional information model including a description of information objects, which are exchanged between product development, production planning and production, mastered by and structured according to the functional target model.

- A product maturity model for determining the current maturity level of production digitisation in an enterprise
- A capability map for Synced Factory Twins: based on the capability map for manufacturing, the main functionalities required for synced factory twins, are identified and detailed in a hierarchical structure.
- A maturity model for digitised production: enabling 'self-assessment' for determining the own current progress of digitisation of the production according to the previously defined target model.
- A roadmap for digitised production: based on gap analysis with respect to the target model, a roadmap for digitised production is derived.
- A proof-of-concept (PoC) for Seamless and Looped Information Flow: verification of the previously defined functional information model by implementing a specific use case for a seamless and looped information flow (e.g., by applying AutomationML, OPC UA) (Yu and Madiraju, 2015).

The subproject Mixed Simulation Environment creates a synchronous digital map of the real factory, which closes the gap between the virtual and real factory (Weber et al., 2015). It enables, for example, the verification of the manufacturability of products by using existing production processes and resources. Similarly, the application of simulation methods can be extended to products, processes and resources in the virtual and the real world (and vice versa). The aim in the future is to combine real and virtual products, processes and resources in a mixed simulation environment to not only save time and costs during planning but also to ensure planning reliability and consequently bring about greater stability during production.

For example, in a mixed simulation environment, it is possible to test whether a new product or a given variant (virtual model) can be manufactured using the real, existing, production process and existing resources. Further example is the combination of a real product, a virtual process and a real resource. In this case, the process, i.e., the system control parameters, can be programmed in advance and validated virtually without having to stop ongoing production to do this. The virtually validated system program can then be imported directly into the real system and started up.

The expected outcome of the subproject Mixed Simulation Environment comprises the following elements (Weber et al., 2015):

- Concrete use cases relating to the use of Synced Factory Twins including a qualitative and quantitative appraisal of the benefits.
- Reference data and process models for the use of mixed simulation environments encompass the modelling and specification of data objects, attributes and their relations which are required in a hybrid simulation environment.
- Recommended measures for the standardisation of the required data exchange formats: based on the previously defined data model and alignment with currently applied standards (e.g., AutomationML, OPC UA), recommendations for data.
- An application blueprint for targeted harmonisation with software vendors defines the key logical functions of logical applications and interfaces for implementing an information flow and specifies requirements for shaping vendor roadmaps.

- A reference process model, which includes the definition of process activities and applied technologies to improve interaction between product engineering, production planning and execution.
- Quantification of the micro- and macro-economic benefits resulting from the implementation of synced factory twins (Figure 4). Such an outcome heavily facilitates manufacturing execution systems (MES) and decision making in production.

The presented concept provides several advantages, especially when in ongoing production, frequent and large deviations from planning data are observed, like in the ramp-up phase of a new production. This also allows simple consideration of changing human factors, like when experienced and efficient employees are replaced by less qualified employees, who have to work with a collaborative robot. Furthermore, the variations in the psychophysical capabilities of workers can also be considered as well as employment of workers with disabilities as well as impact of specific human factors (fatigue, age-related restrictions, etc.). Finally, the big advantage is that simulation runs in ongoing production and their implementation can be realised continuously in real time, without disturbing the operation. The vision of the X-in-the-loop simulation will be turned into practice in a running factory. As a long-term vision in this context, it is conceivable that each worker also incorporates the function (role) of a (human) sensor (e.g., in the assembly shopfloor of a car) that continuously delivers video streams, signals and data to the production planning.

This ambitious project is still in the formation phase due to its complex cross-industrial approach, quantity of involved industries and other partners, and, last but not least, funding circumstances.

5 Transdisciplinary engineering education

Solving complex problems requires a contribution from many disciplines, including engineering, social sciences, human/machine interaction, business, environmental sciences, life-cycle cost, etc. However, universities tend to deliver their programs in discipline-specific courses, e.g., materials, propulsion, dynamics, etc. This may be the best process to transfer knowledge within a given domain, but does not give students the opportunity to apply this knowledge to realistic problems that require a transdisciplinary approach. How do we educate our students to be prepared for solving complex problem?

The relevance of transdisciplinary engineering and science in education has been subject of study. For example, the University of Technology Sydney (UTS) has a faculty dedicated to transdisciplinary innovation (University of Technology Sydney, 2018). Their Bachelor of Technology and Innovation takes a transdisciplinary approach and engages students with open, complex and networked problems and in doing so, enables them to develop the technological knowledge, practices, perspectives and strategies drawn from a diverse range of discipline areas. The Tokyo Institute of Technology (Tokyo Tech) has a Department of Transdisciplinary Science and Engineering in the School of Environment and Society (Tokyo Institute of Technology, 2018). Transdisciplinary science and engineering is a way of study where researchers go beyond the boundaries of academic fields to solve the complex problems shared by global society. The Department of Transdisciplinary Science and Engineering is a fusion of a wide range of fields –

chemical engineering, mechanical engineering, electrical and communications engineering, civil engineering, biological engineering, encompassing even environmental policy and planning, applied economics, sociology, translation studies, and applied linguistics. Students acquire practical skills – not simply academic knowledge.

Key in transdisciplinary education is the creation of opportunities in the curriculum for students to experience and practice design on a realistic problem through project-based learning (PBL). PBL is a student-centred exercise that involves a dynamic classroom approach with the objective for students to acquire a deeper knowledge through active exploration of real-world challenges and problems. It is a style of active and inquiry-based learning as opposed to teacher-led instruction that presents established facts or knowledge. John Dewey initially promoted the idea of 'learning by doing' (Dewey, 1910). The outcome of PBL can be a report, a model or some other artefact that defines the proposed solution. There are currently many sources for inspiration for project-based learning topics. For example:

- The *Warman Design and Build Competition*, organised by Engineers Australia, offers an outstanding, ready-made, annual, creative, hands-on design-and-build project at second-year level to all Australian universities running a broadly 'mechanical' course (Churches and Smith, 2016). The aim is to increase students' experience in creative thinking, practical engineering design and hands-on construction.
- The *Engineers without Borders Challenge* is a design program for primary year university students coordinated by the EWB Challenge team and delivered in partnership with universities around the world (Buys et al., 2013). It provides students with the opportunity to learn about design, teamwork and communication through real, inspiring, sustainable cross-cultural development projects.
- The more senior year's students can participate in global competitions or grand challenges. *Global Grand Challenges* is a family of initiatives fostering innovation to solve key global health and development problems (Grand Challenges, https://grandchallenges.org/). Within a specific aerospace domain both Airbus (*Fly Your Ideas*) and Boeing (*GoFly*) offer global design competitions related to solving or improving issues specific to aerospace engineering and aviation (Champion, 2016, Go-Fly, https://herox.com/GoFly). *Telanto* is an organisation that bring together companies and students to solve real-world problems, usually related to the company business (Telanto, https://www.telanto.com/).

In 2015, SpaceX established a global competition to design and build a hyperloop pod to achieve efficient, high-speed, short range transport, typically Los Angeles to San Francisco (Musk, 2013). The pod would travel through a low-pressure tub at a speed of 1,220 km/hr. RMIT University students took the initiative to enter the competition and it became immediately obvious that this project required a transdisciplinary approach, not only from an engineering point of view, but also the interaction with the media, interaction with industry for sponsorship, business and financial aspects. The team quickly grew to about 30 students from different schools, including engineering, business, computer science and media and communication. The VicHyper team were invited to participate in the 'fly-offs' at SpaceX Headquarters in Los Angeles (Figure 4). There the pod was subjected to safety tests and students were required to produce technical documentation and answer questions. Although this project is relatively unique, it does emphasis the complexity of the project and the need to cross-domain boundaries to produce a good solution.

Figure 4 RMIT University hyperloop team at SpaceX, January 2017 (see online version for colours)

This project has shown the benefits of multi-disciplinary education, not only for the good of the outcome, but also for the students who are exposed to the requirements and limitations imposed by disciplines beyond their own. Because universities are traditionally discipline-structured, organising a transdisciplinary project will require support from different units and is usually more work to manage. Typically, transdisciplinary projects are not part of a curriculum and primarily organised as a one-off exercise, driven by an enthusiastic lecturer. Competitions, like Hyperloop, are a good incentive to organise multi-disciplinary teams, and universities should consider a transdisciplinary project as an elective part of the curriculum.

An educational framework that embraces the need of engineering education to focus more on the development of real-world systems and products based on societal needs is conceive, design, implement and operate (CDIO). The concept originates from the Massachusetts Institute of Technology and was further develop in collaboration with three Swedish Universities (Chalmers University of Technology, Linköping University and the Royal Institute of Technology) in the beginning of this century. To date, the number of schools being member of the CDIO-organisation is more than 120 and they are spread across the globe.

According to Crawley et al. (2014) the overall objective with engineering education is to deliver persons that are 'ready to engineer' (Crawley et al., 2014). PBL is a central part of CDIO where knowledge and skills required to collaborate in heterogeneous environments are trained and technical knowledge is put in action to produce real products and systems based on the need expressed by society represented by external stakeholders. In the overall education curriculum there is a challenge to include and balance the various sources of discipline knowledge that are required to make a thorough contribution with development of personal and interpersonal skills, an ability to adopt a holistic view, and view beyond sub-optimisation. Further, CDIO challenge the organisation of engineering faculty in disciplines where depth traditionally is valued more than application and synthesis. In engineering education, there is a tradition of modelling of systems and phenomenon and methods for analysis supporting assessment. More emphasis must be on methods and training of creativity supporting the synthesis of ideas and concepts. It is also essential to train the students to identify, thoroughly understand and clearly formulate problems followed by independently planning and conducting the work where a solution is to be developed and verified. To deal with open problem definitions, work in teams with people from different disciplines and different background, and reach a shared vision takes a lot of energy which initially takes a lot of time and hampers the productivity but paves way for reaching a state where everyone is working on the same problem, with a shared objective, plan and ambition.

The School of Engineering at Jönköping University became member of CDIO in 2006 and was the first university in Sweden to include all engineering curricula in first and second cycle level (Karltun, 2013). In 2013, shared course modules covering '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', and 'sustainable development' were included in all curricula. PBL, internationalisation, multidisciplinary projects and a focus on societal challenges where also part of the shared educational concept. In Table 1, examples of courses at the bachelor and master programs in mechanical engineering/product development are summarised where CDIO inspired project-based learning is implemented.

The course Product Development Project has been given on a yearly basis since 1998 in collaboration with different companies. 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 vitalising for the organisation. One project that was especially successful focused on assistive technology where the teams collaborated with students from health sciences and interacted with persons with disabilities that needed novel support/devices in their daily life. One of the solutions won a national competition and a company was later founded to bring the product to the market. The industrial product realisation course is common for students studying at the master programs product development and materials engineering, industrial design, software product engineering, production development and management, and sustainable building information management. One objective is to train the students to act and collaborate in an international multidisciplinary environment. Another objective is to change focus from technology to need driven development considering a multitude of stakeholders and all life-cycle phases. Due to the size of the course and the different experiences among the students (international recruitment) an internal assignment (e.g., provide a mix of hot drinks) is used to minimise the uncertainty and manage the complexity. In the course integrated product development, the project focuses on the re-design of an existing product with an emphasis on efficient manufacturing and assembly, although, the design changes should not cause negative effects in other areas. One example of an assignment from an industry concerned lighting solutions for public environments. The design of lightning solutions is a multidisciplinary task where user experiences, work science, architecture, industrial design, material science, electrical engineering, mechanical engineering, industrial engineering, purchasing, supply chain and marketing are important to thoroughly consider and continuously take into account in the development.

Table 1 Examples CDIO inspired project-based learning courses

Course	*Level and position*	*Team composition*	*Societal involvement*	*Scope*	*Results*	*Disciplines*
Product Development Project 15 ECTS credits	Bachelor In the end of the program 3rd year	Homogeneous	Assignment from industry, participation from industry	New product	Detailed design and prototypes	Mainly industrial design and engineering design in focus although manufacturing, marketing etc. should be considered
Industrial Product Realisation: *Process – Methods – Leadership* 9 ECTS credits	Master Introduction course in the first year	Heterogeneous with students from different engineering disciplines and countries	Guest lectures. Internal assignment.	New product	System-level design and prototypes	Industrial design, engineering design, mechanical engineering, information engineering, production and logistics are main focus although marketing, business model etc. should be considered
Integrated Product Development 12 ECTS credits	Master First year on master program	Partly heterogeneous teams with students from mechanical engineering and engineering design from different countries	Assignment from industry, participation from industry	Re-design	Detailed design and prototypes	Engineering design, mechanical engineering, tool design, production are main focus although industrial design marketing, business model etc. should be considered
World Solar Challenge 45 ECTS credits	Master Elective course	Heterogeneous teams with students from different countries and disciplines (engineering and business)	External assignment (global student competition). Industry support by knowledge, technology, material and facilities.	New product	Detail design and complete product	Industrial design, engineering design, mechanical engineering, information engineering, electrical engineering, production and marketing are main focus

Figure 5 Solar-powered car developed by Jönköping University Solar Team 2015–2017 (see online version for colours)

World Solar Challenge is a bi-annual race through the Australian outback from Darwin, Northern Territory to Adelaide, South Australia (3,022 km) for solar-powered cars. The regulations for the cars are changed for every competition as technology evolves and to challenge the participant teams. The changes commonly require that a new car, more or less, has to be developed and built from scratch every time. Jönköping University has participated three times – 2013, 2015 and 2017. The objective to push the development solar-cars origins from the societal need of sustainable transportation which includes reduced usage of the endless resources and the carbon footprint. This project requires more of a transdisciplinary approach, where students from different engineering disciplines (e.g., mechanics, structural, aerodynamics, materials, manufacturing, electrical, control, and software) collaborate with students from industrial design, business administration and marketing to enable the team to work on the challenge and in the end reach an overall solution that is (hopefully) optimal and participate in the race. There are many trade-offs between various aspects, such as battery capacity and weight, comfort for driver and aerodynamics, side-wind stability and design of solar panel area etc. The students are provided with mentors, facilities and some financial support by the university. To succeed, they need to interact with industry for sponsorship (financial support, material, manufacturing facilities, components, systems, expertise, test facilities, transport, etc.). To ensure that companies can have a benefit of sponsorship, they need to work with communication, marketing and get media interested so the sponsors can be exposed (Figure 5). A lot of work is also required to organise the transportation of the car from Sweden to Australia and plan the actual race. Everything finally put to test when the race is run.

5.1 Challenges for transdisciplinary engineering education

Based on the characteristics of a transdisciplinary approach outlined in Section 2.1, transdisciplinary education should combine:

1. Problem-orientation based on ill-defined society-relevant problems.
2. Students from both technical and social sciences to be involved and work in mixed teams.
3. Training of teams to collaborate with practitioners.
4. Both technical and social defined goals.

5 A dynamic setting where goals are not static and may shift in the course of the project because of the progression, understanding and unexpected situations that may emerge.

6 A supporting team of teachers from faculties of technical and social sciences.

7 Practitioners to guide and evaluate the work of the students.

8 Assessment of outcomes concerning shared processes and methodologies used beside the assessment of the solution and reporting.

A great deal is already going on in a direction towards transdisciplinary engineering education as can be concluded based on the examples from different Universities. However, the focus is still for a large part on technical disciplines. By example, the CDIO concept does not fully embrace all aspects of transdisciplinary engineering. Problem solving is directed towards needs expressed by society represented by external stakeholders but the actual involvement of people and knowledge from social sciences is not emphasised. There still is some progress to be made to fully transform into transdisciplinary education. Currently, there are projects that focus on ill-defined society-relevant problems where the students collaborate with practitioners and practitioners are involved in guiding and evaluating the work exists. The large projects seem not to be part of a curriculum; they are primarily organised as a one-off exercise, driven by some enthusiastic lecturers.

The challenges to fully transform into transdisciplinary education include:

- The organisation of faculty. Research is mainly disciplinary, going in to more details than multidisciplinary. Research is commonly based upon, conducted within and evaluated by peers within a specific area. The organisation of faculty is commonly based on a disciplinary logic, which inevitably has an impact on the teaching staff ambitions and focus.
- Mutual responsibility and engagement. To succeed in the transformation, faculty staff from social science as well as faculty staff from engineering needs to take equal responsibility, be engaged and be ready to collaborate.
- Inclusion in curricula. There is a continuous progress in every discipline that creates opportunities for novel solutions. It is important that the students are educated and trained in the state-of-the-art. However, they should also be able to collaborate and contribute in solving society-relevant problems. A question is if this should be expected for all engineering and social science students? An improved balance, and maybe differentiation, in curricula between discipline knowledge, overall understanding and collaboration training is needed.
- Financing and time for projects. There is a common view that transdisciplinary education should include project work. The projects tend to be large when it comes to credits and the effort required from teaching staff. A lot of other expenses and cost for travelling need financial support. It is difficult to make a budget as the direction of the work cannot be planned with a set of pre-defined work packages. The need and time for individual teachers is difficult to estimate.
- Preparation and training of students. The students from social science as well as students from engineering need to be prepared and ready to collaborate.

- Emphasis on learning of shared processes and methodologies. Problem solving as a means for supporting learning of specific discipline knowledge or skills cannot be expected as the problem is ill-defined and the direction of the work cannot be set. It might even turn out that no solution is fully reached, which doesn't necessarily imply that the project is a failure. The learning of shared processes and methodologies that may be incorporated in other projects needs to be more emphasised.
- Increased involvement of practitioners. Practitioners from both social science as well as engineering should be more involved in the project. They should take part in the problem formulation, evaluation of progress and final assessment of the result. They should act as mentors, coaches and experts continuously during the course of the project and support learning of shared processes and methodologies from which they also can benefit.

Interdisciplinary and multidisciplinary projects with different scopes are still needed in the education for the development of knowledge (within engineering, resp. social, science) and collaboration skills. The progress to transdisciplinary education requires teachers, students, practitioners and knowledge from engineering and social sciences. The motivation, ambition and effort of solving socially relevant problems should be a mutual effort from the beginning.

6 Discussion and research agenda

In this paper the history of transdisciplinary research and processes has been briefly described followed by envisioned implications for engineering research, practice, and education. The current status of transdisciplinary research has been described including still existing challenges. Industry 4.0 is seen as an environment in which a transdisciplinary approach is deemed essential, because of the many research and practice aspects that need to be taken into account.

An application has been presented for the realisation of an Industry 4.0 environment, in particular a smart production factory in which not only products are smart, but also all equipment and machinery, including the production processes. Development, implementation, and management of such a factory requires a transdisciplinary approach, because of the many research and practice goals that need to be achieved and because of the dynamics of such a factory, which involves continuous adaptation and renewal. The realisation of the concept of Industry 4.0, however, is still very limited at this point in time (Rojko, 2017).

The current situation of problem-based learning has been described which is essential for educating students in a transdisciplinary way of working. Students, teacher, and practitioners collaborate in such projects. However, the involvement of students, teachers, and practitioners from social science disciplines is still lacking most of the time. An important challenge is the proper assessment of process and achievements in such projects (Del Cerro Santamaría, 2015).

The concept of transdisciplinary research and transdisciplinary processes has been described extensively in the literature, including the many challenges that still exist, for example in managing transdisciplinary projects and transdisciplinary teams. In addition, the translation of the concept to the engineering domain has only partly been achieved at this point in time. Apart from the challenges mentioned in the literature, additional challenges have been identified.

As identified in previous sections, research in transdisciplinary engineering needs to address the following challenges:

1 Identification of the engineering problems that require a transdisciplinary approach. By contrast, engineering problems that can be solved by a disciplinary, inter-disciplinary or multi-disciplinary approach need not be solved by a transdisciplinary approach.

2 Technical disciplines should have an open mind to disciplines from social sciences, before they can collaborate with them, and vice-versa. Many problems require integration between and alignment of thoughts and insights from many different worlds. No one discipline can provide the only and best answers to the many complex problems in society and engineering.

3 In each transdisciplinary project, in which both research and practice are involved, both science goals (social as well as technical) and practice goals (e.g., performance, culture, knowledge) need to be set. A proper measurement system needs to be development to assess achievement of the goals. These goals need not be static during the course of the project.

4 To prepare students of engineering programs to engage in solving real-life society-relevant problems, they need to be prepared for collaboration with people from other, including social-science disciplines. Methods and tools need to be developed to manage and support transdisciplinary student work. Teachers need to acquire the necessary skills for guiding complex education projects, while also companies and people from practice need to be involved, understanding the nature of student projects.

While the concept of transdisciplinary research and processes has existed already for several decades, much research is necessary to increase understanding of the nature of transdisciplinary work, support and manage the complex teams, measure their output and progress, and manage and support collaboration between people with many different backgrounds. Extensive case studies of transdisciplinary engineering processes are needed. These case studies can to be longitudinal and involve a team of people from different disciplines with different perspectives on what to learn from the cases. In addition, comparative case studies can be performed, possibly retrospectively, of processes in which a Design Thinking approach was used and in which a transdisciplinary approach was used to identify similarities and differences. Again, several perspectives can be chosen in a team of people with different backgrounds. A rich picture of the cases can then be created.

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