Transdisciplinarity and the Future of Engineering
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Doing Transdisciplinary Studies Through the Lens of Intervention Based Research

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Abstract. Transdisciplinary research commences with exploratory research to understand and solve complex real-world problems followed by explanatory research to generate academic knowledge. This paper conceptualises transdisciplinary engineering through the lens of intervention-based research, which seems useful to solve societal problems when practical knowledge to handle the problematic situation contradicts solution proposals emerging from prevalent theories. The proposed model combines academic knowledge, practical knowledge, and artefact portraying the problematic situation into means to achieve the end, which when implemented transforms the problematic situation into the desired situation. To explicate the proposed model, the study draws on a longitudinal research conducted by the two authors of this paper. In this study, which focuses on designing digitalised solutions for data-driven decision-making at shop floor level, we faced serve research-related challenges. The academic knowledge revealed a clear picture of how to design the solution, but the practical knowledge exposed that the digital solution was merely an illusion; i.e. a gap between theories and practical understanding. The proposed model to handle this gap forwards the role of artefacts and suggests that artefacts, academic knowledge and practical knowledge rank alongside.

Keywords. Transdisciplinarity, Intervention-based research, Design science, Knowledge, Pragmatism

1. Introduction

Transdisciplinary Engineering (TE) is a prerequisite for solving wicked real-world problems [1]. TE involves scientists and practitioners and unfolds *"between, across and beyond"* [2, p.68] various professional disciplines. This disciplinary heterogeneity entails the presence of various understandings and intentions [2]. To cope with differences in understandings and intentions make a rigor TE logic topical. But what kind of TE logic affords practitioners and scientists to align understandings and intentions?

In contrast to scientists, who are keen on creating generalisable and decontextualised knowledge [3], practitioners focus on designing and implementing interventions to handle real-world problems, which often result in the creation of artefacts and highly contextualised knowledge [4]. To contribute both new academic knowledge, practical knowledge, and artefacts to solve real-world problems, Intervention-Base Research (IBR) seems valuable. Based on Oliva [5] and Chandrasekaran et al. [6] IBR is the transformation of a problematic situation (**S**) to a desired situation (**S***) by a deliberate use of means (**M**) and a basket of theoretical knowledge (**T**).

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Differences in intentions and understandings are an inherent nature of TE. A group of researchers suggests that the TE logic unfolds at a crossroad between different disciplines [7]. Potential differences in understandings and intentions are aligned by drawing on the principles of backward planning [8] or the outcome space framework [9]. However, intention(s) does only influence the TE logic if the individuals are acting intentionally [10, 11]. Because of the TE logic has such an unfolding nature and the fact that both existing knowledge, accessible artefacts and different intentions in a non-predetermined way have an influencing role(s) we still lack a rigour TE logic. Indeed, Wognum et al. [12] call for a research approach to manage TE.

Accordingly, with the purpose of suggesting a TE logic this paper draws on a longitudinal research project aiming at digitalising shop floor management (SFM) visualisation boards (VBs). During this project, we (the two authors of this paper) faced comprehensive research related challenges. To explore a workable transdisciplinary research approach, the following research question guide the study *What logic fits with a transdisciplinary study?*

2. Theory

After defining knowledge and artefact, the chapter presents the background of the study. Knowledge is vital for solving societal problems [9]. Knowledge be it academic and/or practical knowledge is both the fuel for and simultaneously the telos for TE processes [10]. Knowledge is "justified trued belief" and in line with Nonaka et al. [13] the focal point is "justified" rather that the "true" aspect of belief. This understanding entails that academic knowledge is justified belief rather than true belief. Academic knowledge and practical knowledge differ [14]. Practical knowledge is localised, embedded, and invested within disciplinary boundaries [15] and in the utility of accomplishing actions [16]. For a pragmatist [2, 16] practical knowledge and actions are two side of the same coin. Knowing how and intelligent reflections are inseparable.

Artefacts are thinking tools and the social glue [17] for reflective conversions [16] and knowledge sharing across disciplinary boundaries [18]. Given that artefacts follow a journey that starts as a hand-made sketch and ends as a final product [19], which is instrumental in solving real-world problems, artefacts are central for TE [20].

2.1. Background of the study

TE is considered as a prerequisite for solving wicked real-world problems [12] and for generating generalisable and decontextualised knowledge [1]. Fundamentally, the trans-disciplinary logic affords border-work, which involves scientists and practitioners [21] and spans disciplinary boundaries including natural and social science [22]. Despite a great many research projects under the umbrella of natural and social science deals with problem-solving issues, the pivotal is the creation of novel knowledge rather than the design of an artefact to solve relevant real-world problems. If artefacts, for instance in the form of materiality, are included in these studies, the focal point is artefacts-in-use and rather than artefacts-in-the-making (see [23]). While natural sciences are concerned with how things are and social sciences are concerned with how society works, the design sciences are concerned with how things should be, with creating artefact(s) to solve real-world problems [4].

Design science includes how designers use artefacts and knowledge to create new artefacts and new knowledge; for instance, reflective conversations with artefacts [16] form the linchpin for using and for creating knowledge and the design of new artefacts to solve real-world problems [4]. Design science falls in between the logic of deduction and induction and thus the use of academic knowledge and practical knowledge to explore an intervention. This in between approach [24] turns down the classical linear deductive- and inductive logic [2].

Design science is a rich research tradition in engineering to handle ill-structured problems in a systematic manner [25]. By looking through the lens of design science and in particular the IBR approach [5, 6], the transdisciplinary problem-solution work can gain rigour and thereby contributes both new academic- and practical knowledge. However, being involved in IBR entails that the problematic situation(s) must be explored and solved before the solution(s) can be field tested in practice and explained theoretically. Hence, IBR involves both exploratory research to transform the problematic situation into the desired situation and explanatory researcher to contribute academic knowledge [26].

Figure 1 draws on the design science work of Simon [4], Holmström et al. [26], Oliva [5], and Chandrasekaran et al. [6] to bring the means-end analysis to the fore in our conceptualisation of the TE logic. The series of actions between the leftmost triangle "means" and rightmost triangle "end" for the exploratory research. The starting point for the means-end analysis – the TE logic - is the current problematic situation (**S**) and the end is the desired solution to the problematic situation (**S***). The means (**M**) to transform the current situation (**S**) into the desired end situation (**S***) is a basket of theoretical knowledge (**T**) and the achieved practical knowledge of the working practice in which the intervention – solution – will be implemented and tested. The explanatory research part of IBR involves a rigor study of the designed and implemented artefacts from a theoretical point of view. The purpose is both to contribute to the generalisability of contextualized knowledge and decontextualised knowledge.

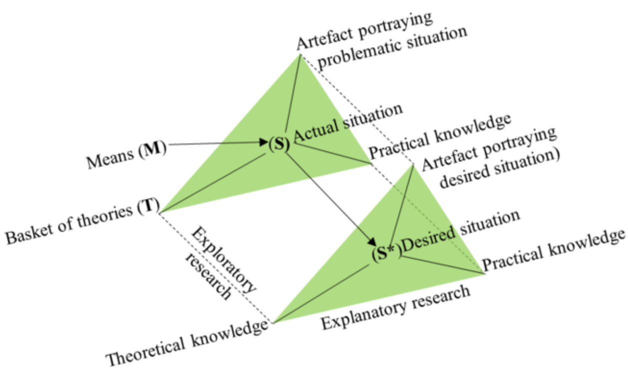

Figure 1. Transdisciplinary engineering logic of design

Figure 1 proposes a methodological model to transcend disciplinary boundaries, which results in the creation of academic knowledge, practical knowledge and an artefact solving a societal problem. When practitioners and scientists are involved in TE their individuals' actions enter into the means-end relation [4, 26, 27]. For Dewey [27], the means (**M**) in the form of a basket of theories (**T**) and practical knowledge gradually acquire meaning when applied to understand the problematic situation (**S**) and in the achievement of the desired situation (**S***). During the exploratory phase of a TE intervention in which the purpose is to reach the desired situation the borders between academic knowledge and practical knowledge are artificial. However, when initiating the explanatory phase, it is crucial to make a distinction between the creation of generalisable academic knowledge and contextual practical knowledge. Before elaborating our proposal, the following chapter presents an example of a project in which the authors of this paper faced comprehensive methodological challenges in their attempt to design digital SFM VBs.

3. Digitalisation of SFM visualisation boards – an example

The overall purpose of the project was to create a digital SFM solution to support data-driven decision-making at shop floor level, which integrates digital equipment, digital VB technology, and data analytics. Given that both the social systems and technical systems criteria seemed pivotal, the research project involved different scientific disciplines and practitioners having different professional experience. The project was initiated in 2018 and so far three different research projects have been accomplished; (1) a quantitative study consisting of a survey sent to around 900 companies in Denmark, 97 companies answered the survey; (2) a four hour workshop with 38 companies discussion in which five themes were discussed in detail; (3) and final unstructured interviews with 6 manufacturing companies, in average one hours interviews and one hours observation in each of the companies. Based on these three different studies we gained academic and practical knowledge about digitalisation of SFM VBs at the outset of the fourth phase of the study. In the following, we draw on this fourth phase of the study to explicate a number of methodological considerations.

In the fourth phase, the intention was to explore the socio- and technical prerequisites for digitalising SFM VBs. This explorative nature of the research posed methodological challenges, mainly because of the grounding theories (academic knowledge) and empirical foundation (practical knowledge) for clarifying the prerequisites were completely decoupled. The grounding theories drew on two pillars; respectively, representational capacities of SFM VBs and digitalisation at shop floor level to enable data-driven decision-making. We realised that: (1) The extant literature of SFM VBs revolved around theories developed in the mid-1940s advocating malleable representational capacities and in particular the power of the pen principles (e.g., see [28]. A very limited number of studies focused on digitised SFM VBs, and these did only address unmalleable representations; (2) As for data driven decision-making, the focal point was mainly to prescribe how technical solutions can enable digitalised VBs and data-driven decision making at shop floors (e.g., see [29]).

The fourth phase of the study drew on 16 Danish manufacturing companies, all operating globally. All companies accomplished SFM meetings regularly and used VBs. Three case companies were selected from these 16 companies. The criterion for selecting these companies was to gain a broad understanding rather than a narrow and very detailed understanding. Two of the three selected companies used both analogue and digitised VBs, but all three showed interest and proactiveness in terms of enhancing the use of digitised SFM VBs. We did four observations and three interviews in Company A (pseudo name) and three observations and three interviews in both company B and company C. In all three companies, the applied digitised VBs were useful to handle simple problematic situations, but the digitised VBs were not used to handle complex problems. When facing such situations, practitioners made handmade notes and sketches on papers or on analogue VBs; the digitised VBs were considered too inflexible to guide the dialogue when finding solutions to complex problems.

As it appears from the above, we faced a study in which the academic knowledge and practical knowledge seemed rather fragmented. On the one hand, the scientists presented a trustworthy image of combining different technologies to enable a digitalisation of VBs and data-driven decision-making. On the other hand, despite practitioners in all companies strove to enhance shop floor decision-making and could see the benefits of using digital solution to enable data-drive decision making they put matters as for instance *perceptions of*, *beliefs of*, and *sense-making of* digitalisation at the forefront. Gradually it became clear that the data-driven decision-making and the use of digital VBs at the shop floor was basically a mirage.

Methodologically, we realised that it is pivotal that the applied TE logic could be instrumental in bridging academic and practice knowledge; it can be argued that the methodological challenge is to gradually reduce the gap between the scientists' image of digitalising SFM level and the practitioners' mirage of this phenomenon. The next chapter proposes a TE logic in which academic knowledge, practical knowledge and the design of an artefact to solve a problem evolve in symbiosis.

4. Transdisciplinary engineering logic

The TE logic suggested by Dieleman [2] and Mitchell et al. [9] emphasises an inseparable interplay between solution-oriented actions and creation of knowledge. For Dieleman [2] the TE logic unfolds within the logic of imagination and the logic of experimentation and involves various "reflective practitioners". Dieleman [2] draws on the Schönian pragmatism [16] to highlight that different reflective practitioners are exploring the problems under consideration simultaneously and on various levels. Mitchell et al. [9], who also subscribes to the Schönian reflective practitioners, provide a conceptualisation of the transdisciplinary outcome framework; (1) a pragmatic logic to improve the situation, (2) knowledge artefacts and (3) knowledge creation. Mitchell et al. [9] suggest that the TE logic unfolds through progressively used of artefacts and underline that the contribution to new academic and practical knowledge occur through reflective and situational use of artefacts.

By combining the transdisciplinary work of Dieleman [2] and Mitchell et al. [9] with the design science [4] and of IBR [5, 6], this paper suggests that the framework for doing TE consists of and results in; (1) basket of theories, (2) practical knowledge, and (3) artefacts portraying the actual or desired situation. The basket of theories (**T**), practical knowledge, and ongoing refinement of the artefact portraying the for now situation are the means (**M**) to achieve the end; i.e., transformation of the actual situation (**S**) into the desired situation (**S***). Figure 2 on next page illustrates the proposed framework.

The TE logic is about knowing through actions [2]. Academic knowledge, practical knowledge and artefacts are progressively developed through ongoing reflective actions; i.e., through a series of exploratory actions followed by explanatory actions [26]. The TE logic starts with reflective actions of the actual situation at time T_0 and ends at time T_n with the arrival at the desired situation; illustrated as the green line in figure 2. The leftmost green triangle in figure 2 defines the action space at T_0 (actual situation) for **M**-*means* to gradually reach the *end* (desired situation) at T_n. In other words, at time T_0 the basket of theories **T**, practical knowledge and artefacts portraying the current understanding of the problematic situation are the **M** *means* for the involved scientists' and practitioners' reflective actions. The outcomes of these reflective actions are practical knowledge T_1, basket of theories T_1 and artefact T_1. The following light green triangles illustrate the spaces for the *means* T_1, T_2 …T_{n-1}., while the rightmost green triangle symbolises the *end* of the exploratory actions, the achievement of the desired situation **S***. Reaching the *end* in the means-end analysis triggers the explanatory actions of the TE methodology, which focuses on creating new generalisable theories, both contextualised and decontextualised knowledge.

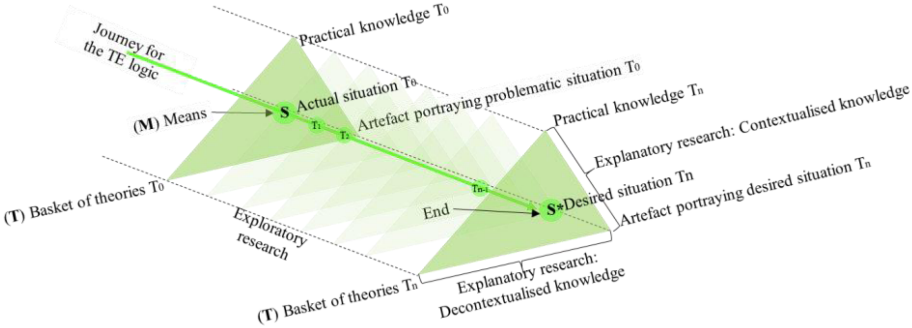

Figure 2. Framework for transdisciplinary research

The illustrated timeline T_0, T_1 …. T_{n-1}, and T_n in Figure 2 does not illustrate a logical step-by step design of a solution from start to end. Rather the opposite as the journey of designing an artefact to solve a wicked problem is characterised by ongoing iterations between different design stages and testing [30]. The timewise sequence in figure 2 highlights the facts that when we - scientists and practitioners are involved in TE projects our actions are not isolated actions (see [10, 11]. Past actions and what we are keen on achieving (reaching the desired situation) influence present action. Past actions chart a trajectory which influence "*the way for the actions [activity] that follow*" [27, p.33]. Our understanding of the basket of theories, the practice we study, and the current artefact is the fuel for our present actions and the telos for our present actions is to reach the desired situation. Thus, the desired situation that scientists and practitioners have in their views influences present action(s), but this desired situation may never be reached [10]. In other word, when doing the field test and evaluation it might be concluded that we did not successfully transform the problematic situation (**S**) into the desired situation (**S***), but we arrived at situation (**S´**). Despite the exploratory phase arrives at **S´** rather than at **S*** the achieved knowledge and designed artefact(s) might be useful for explanatory research [5, 6].

Explanatory researchers are keen on contributing generalisable contextualised and decontextualised knowledge. Useful foundation for explanatory research is that the outcome of the intervention – the outcome of the means-end relation - was to some extent remarkable, either unexpectedly successful or mismatch between expectations and reality [5]. Facing an unexpected gap between **S´** and **S***, gaining an unexpected result, triggers an abductive reasoning, which addresses *what had gone wrong*? …. *why did we arrive at the wrong place*? [6]. Or, if the arrival at **S*** shows a remarkable good situation for the practitioners the abductive reasoning focuses on gaining new insight about the practitioners' new working practices.

Unexpected gaps and remarkable good solutions make it possible for the researchers to re-enter the journey of the TE logic; e.g. by reflecting on why did the use of **M**-*means* at time T_x (x symbolises any time from T_0 to T_n) results in the unexpected outcome. Contextualised knowledge is created if the unexpected outcome **S´**or **S*** is studied from the **M**-means perspective. Focusing on **M** sheds light on how we as researchers has gradually adapted the basket of theories **T** to fit with the contextual setting in which **S ➔ S*** or **S ➔ S´**. Developing decontextualised knowledge requires the scientists to bring the basket of theories **T** to the fore in the analysis of **S ➔ S*** or **S ➔ S´**.

Explanatory research iterates between academic- and practical knowledge and the activities of designing the artefacts. Given that a TE understanding is created via a conjunction of different knowledge domains the basket of theories enabling a rigour process is inclusive rather than being exclusive [2]; in other words, useful academic knowledge transcends disciplinary boundaries. Academic knowledge, the outcome of the explanatory research, is not the "true belief", but it is the "justified belief" (see [13]). Accordingly, to contribute academic knowledge it is crucial to ensure that the justified belief including the applied TE methodology is testable for public inquiries as the "*inquiry is the life-blood of every science*" [27, p.12]. The next section exemplifies the understanding of the TE logic. The digitised SFM VBs research project presented in chapter 3 is used to exemplify the transdisciplinary process.

4.1. The framework for transdisciplinary research – the logic of design

The outcome of our research presented in section 3 was not as expected. Based on a profound study of relevant scientific papers and a solid practical understanding it was expected that the fourth phase of our project would gradually unfold as a straight journey in the centre of the TE logic triangle with arrival at **S*** (see figure 2). In other words, we faced a gap between **S´**and **S***, which afforded us to re-enter the journey of our TE logic. However, instead of addressing the gap between **S´** and **S*** from a **M** perspective to elaborate contextualised knowledge or from a **T** perspective to elaborate decontextualised knowledge, we remained in a solution mode.

Reading additionally scientific articles, conducting new observations and interviews, and using accessible artefact to clarify both social and technical prerequisites implied that issues related to disciplinary boundaries blocked the journey of the TE logic. A narrative review of Technology Management and Operations Management literature revealed two kinds of disciplinary boundaries; a boundary between academic and practical knowledge and a boundary between scientific disciplines. Gradually, it became obviously that academic knowledge of digitalising shop floors is a world apart from the actual state within manufacturing companies. As for the boundary between scientific disciplines, it seems Technical Management researchers foreground technical prerequisites to digitise shop floors as for instance digital twin data or/and the use of cyber physical systems to enable preventive and prescriptive analytics. Implicitly, these researchers give technologies a deterministic effect, meaning that practitioners' actions are predetermined by technical matters. Operations Management researchers suggest that SFM decision-making, knowledge creation, and social interactions go hand in hand. In general, these researchers advocate for the power of the pen principles, meaning the use of analogue VBs rather than software-based systems. Despite digital technologies to enable a new way of managing shop floors workers were sporadic addressed in few papers, we faced a disciplinary boundary in the reviewed papers. Additional papers were consulted, but at the end of the day it was realised that the digitisation of SFM VBs was (is) still a nascent technology. More specifically, we decided to increase the pace of iterations between the practical knowledge and academic knowledge as it was expected that this type of logic would be instrumental in spanning a nascent theory (digitising SFM VBs) with extant literature (shop floor decision-making). However, as explained above we did also face a disciplinary boundary between practitioners and academia; the basket of theories portrayed a trustworthy image of digitally enabled data-driven decision-making at shop floors, while the practical knowledge exposes that the use of digital VBs to enable data-driven decision-making was basically a mirage. A logic of design iterating between a clear image and mirage is neither testable for rigour reviews nor for creating a solution to a societal real-world problem. Thus, it seemed necessary to dig deep into involving practitioners in the exploration of a digitised VBs. It indicates a TE logic of design, which forefronts practical knowledge at the expense of basket of theories – at least when clarifying the technical and social prerequisites for digitising VBs. For a while the TE logic of design was pushed from the centre of the green triangle in figure 2 towards the right part of the figure, which enabled a sufficient understanding of technical and social prerequisites for digitising VBs. Basically, neither the journey of nor the nature of the TE logic of design can be predetermined because the solving of societally relevant real-world problem involves various academic and non-academic disciplines; the only way to grasp the journey and the unfolding nature of the logic of design is to put a laser-like focus on actions [31].

5. Discussion and concluding remarks

The paper aimed at suggesting a methodology for TE. The question guiding the study was "*What logic fits with a transdisciplinary study"*?

The TE logic is embedded in actual actions of gaining useful knowledge – to mull things over, to design a new artefact, to evaluate a solution, to review theoretical contributions and to draw conclusion. Academic knowledge, practical knowledge and artefacts portraying the actual situation are both the input to and simultaneously the outcome of the TE logic. When an individual(s) – scientist(s) and/or practitioner(s) is involved in doing TE, their individual logic of design enters into a kind of "means-end relation" [4]. The individuals' end-in-view (desired solution) differ [10]. By its nature, TE transcends boundaries – academic, professional, organisational and so on. While scientists focus on contributing academic knowledge, the pivotal for practitioners is the creation of workable artefact(s) to solve real-world problems. It seems that differences in intensions are the rule of accomplishing TE. For this reason, both the scientists and practitioners need to cope with the intentions of others. To facilitate that, Blumer [32] suggests us that an individual's actions (re)shape other individuals actions. The viewpoint is that one's own actions and the actions of others influence the alignment of intentions. Accordingly, to cope with others' intentions "one may abandon an intention, revise it, check or suspend it, intensify it, or replace it" [32, p.8].

Academic knowledge, practical knowledge, artefacts and the actions of others are the means to accomplish the TE logic. Schön [16] describes the process as reflective conversations with artefacts. However, academic knowledge, practical knowledge and artefacts do not in themselves have an influencing role on the logic of design. Rather, academic and practical knowledge, artefacts, tools, digitalised equipment and/or other individuals' actions and intentions do only acquire meaning and thus gain an influencing role if both scientists and practitioners are capable of using these deliberately as means to achieve the end [10, 11]. Despite the differences in intentions, the use of means to achieve the end should pave the way for combing grounding theories and understanding of practical requirements; thereby contributing justified true knowledge and field evaluations of workable artefacts solving real-world problem as illustrated in figure 2. This study of digitising SFM VB illustrates that scientists and practitioners do not just accomplish a single activity when they are involved in a TE projects, but they are involved in accomplishing a web of activities. Actually, is not just a web of TE activities, but a myriad of actions within and across disciplinary boundaries in which various artefacts function as the linchpin of transcending disciplines [18]. In our IBR frameework for TE research artefacts are pivotal, which is not the case in TE research. TE research forefronts the complex collaboration between different academic and professional disciplines [2, 12, 21, 24] at the expense of the role of materiality (artefacts) in solving a complex societal real-world problem. For instance, Dieleman [2] focuses on handling the problematic situation within the space of experimentation and imagination and omits the role of artefacts. Horlick-Jones and Sime [21] conclude that both social and material matters influence human reasoning and collaboration without elaborating the role of materiality (artefacts). For Mitchell et al. [9], the logic of transdisciplinary research unfolds through progressively use of artefacts, but the proposed outcome spaces framework does not address how artefacts are used to created new artefacts (artefact-in-making) when accomplishing TE. Our proposed model in figure 2 forwards the role of artefacts, but neither at the expense of academic knowledge nor practical knowledge. Rather, artefacts, academic knowledge and practical knowledge rank alongside meaning that all are pivotal for the TE logic of design.

Referring to Dieleman [2] and Mitchell et al. [9], the TE logic has an explorative nature. This paper subscribes to this viewpoint, but the contribution of academic knowledge requires an explanatory mindset in which the researchers put a laser-like focus on the gap between S′ and S*. Through the lens of IBR, the research starts with exploring the problematic situation, which involves social interaction and reflective conversations within the space of academic knowledge, practical knowledge and an artefact-in-the-making, which as a final product has the capacity to solve societal problems. IBR suggests parallelism between matching academic and practical knowledge alongside designing artefacts. Findings in this paper partly echoes this systematic and parallel bridge-building, but in some situations, it seems necessary to prioritise the creation of and the use of practical knowledge, in other situations bring academic knowledge to the fore when designing artefacts to solve societal problems. In the light of the proposed model in figure 2, the TE logic is place somewhere in the green triangle; at the centre of the green triangle, towards the right part of the figure or towards the left part of the figure. Hence, the TE logic of design does neither follow a straight journey from T_0 to T_n nor does it unfold in the centre of academic knowledge, practical knowledge, and artefact portraying actual situation. Indeed, the journey for the TE logic can be straight ahead, be uphill a mountain road, chase a course on a blind road, bump into various obstacles, or it can be necessary to make a U-turn and so forth.

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