Deriving Manageable Transdisciplinary Research Models for Complicated Problematics Associated with Next-Generation Cyber-Physical Systems

Part 3 - Constructing Research Models

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Abstract:*As a continuation of the work previously published in two papers in this journal, this paper addresses the problem of systematically constructing sharable transdisciplinary research models (TRMs) for definitive research problematics (DRPs). The paper discusses the underpinning fundamentals and proposes a practical methodics that is underpinned by intuitive reasoning rather than by proven theories but relies on a lucid procedural framework. The main activities are discussed through a demonstrative example designated as 'avoidance of frequent vehicle accidents at suburban road crossings'. First, a concise overview of the literature related to research models is provided and the work reported in this paper is placed in this context. Then, the operational aspects of the transdisciplinary research model development methodics are discussed. As a starting point, the proposed methodics assumes the availability of a comprehensive specification of the DRP. The conversion process includes six steps: (i) exploring research concepts by content analysis of the DRP, (ii) finding pertinent research concepts and combining them into a semantic map, (iii) selecting the most influential concepts and relations for parameterization, (iv) choosing multi-view research concept descriptor constructs and parameters (indicators, variables, and constants) for study, (v) creating sharable multi-modal representations of the research model, and (vi) external validation of the content by researchers and stakeholders. An adapted version of the validation square approach is used in the last mentioned assessment. The approved TRM is the starting point of the development of supradisciplinary research designs – this is however not addressed here due to page limitations.*

Keywords:Definitive research problematics, transdisciplinary research model, research concept, concept descriptor parameters, research construct, validation square-based approach.

1 Introduction

The notion of research models emerged several decades ago when the need to share human mental models and facilitate information transfer among researchers working in a particular disciplinary field was recognized. Driven by the intent of capturing the largest possible amount of information about the object of research, research models are typically designed and constructed before or when research activities are launched. However, they have not been regarded as absolutely necessary in small-scale, monodisciplinary or interdisciplinary research projects, in which the thoughts and ideas about the studied phenomena can be shared by direct verbal communication and the research tasks can be assigned to researchers in documents like technical annexes of accepted research proposals (Klein, 2008). Therefore, traditionally, only informal discussion models have been devised and managed intuitively by the investigators responsible for the specification of research topics and activities.

However, the ever-growing complexification of research phenomena and problematics, the initiated large-scale research programs and projects, and the concomitant need for efficient organization and management of various research conducts have necessitated the deployment of formal (textual, graphical, symbolic, or hybrid) specification-based research content models. Rendered as multi-faceted information constructs, formal research models are derived based on the aggregation and compilation of facts, goals, insights, theories, and experiences. They can facilitate both front-end and in-process knowledge and information sharing, as well as the organization and harmonization of the research activities of the involved investigators (even research collectives). At the same time, the development and use of sharable transdisciplinary research models, which are rich in both descriptive and prescriptive information, are not yet addressed explicitly in the context of systems research in the related literature.

On the one hand, it seems to be accepted in the related literature that a research model is a sufficiently detailed clarification and robust specification of a phenomenon or a problematics to be studied, including the explanation of the overall focus, objectives, objects, assumptions, problems, and challenges. On the other hand, a research model can also be seen as a dynamic knowledge construct that (i) reflects the actual state of knowing, (ii) the results of the generation of scientific knowledge, and (iii) is refined, even adapted, in line with the progression. For the reason that they are products of two distinct realms of considerations and support different purposes, conventional research models (CRMs) and transdisciplinary research models (TRMs) are typically distinguished. CRMs assume that belonging to an academic group is analogous with shared monodisciplinary beliefs and knowledge, and cultural values and attitudes.

The main inspiration for constructing TRMs can be understood by considering the scientific demands of our post-modern age and the role of TRMs in achieving these. TRMs can be constructed to reflect the transdisciplinary perspectives of multiple research collectives and intellectual cultures. In this context, a TRM has four basic functions: (i) capturing the constituents and characteristics of complicated research phenomena and problematics holistically, (ii) harmonization of views and objectives with regards to scoping and prioritizing the object of research, (iii) integration of content and process knowledge over disciplinary boundaries, and (iv) facilitation of committed cooperation and structured communication. Since the development of TRMs goes through the phases of conceptual design and detailed design, some early publications have addressed both the synthesis of conceptual research frameworks and the specification of detailed research models (Rossini and Porter, 1979). Other publications provided valuable insight into the fundamental epistemological and methodological issues and discussed some of the main challenges and achievements (Tolk et al., 2013).

Exploring and aggregating knowledge for complex and cross-disciplinary information systems has given a new impetus to deep-going studies of both conceptual frameworks and research models, as well as their semantic relationship (Palvia et al., 2006). An arbitrary but proper example of the various frameworks suggested for research is the one proposed by George et al. (2023) for driving and doing fake news research. Many of the proposed frameworks deal with content only implicitly through the identification of scenarios and activity flows, rather than explicitly. Recently, the issue and challenges of developing transdisciplinary research models have also been addressed. The literature presents many studies about the use of TRMs in the field of medicine (Lawless et al., 2024), health care (Abrams, 2006), socio-technical systems (Giugliani et al., 2023), sociology (Hansen, 2024), public transportation (Katsumi and Fox, 2018), disaster management (Omori and Fujimori, 2010) - to mention just a few. Despite this fact, there are uncertainties, as well as conceptual difficulties related to the ontological and methodological status and interpretation of TRMs. For instance, in the paper of Cooper et al. (2021), multi-method research models are seen as a means to combine qualitative and quantitative methods and to arrange research knowledge from a procedural perspective, rather than a content aspect. Certain research models have been devised based on extensive engineering content such as NASA's common research model (Rivers and Dittberner, 2014). There is no question about the usefulness of these models but (i) they are not generalizable due to their specific contents and (ii) their multidisciplinary augmentation does not bring advantages. Some documented models are analytic and prescriptive constructs rather than explorative and constructive blueprints. As an example of the former, the paper of Chikán (2008) combines research concepts with research methods and, by doing so, provides a high-level coupling between a topic-focused research model and a conduct-oriented research design.

The three works mentioned below are possible examples of explorative and constructive blueprints. Travica (1997) proposed a research model that can be used to investigate virtual organizations empirically. This model uses descriptors from both quantitative and qualitative lenses and identifies nine general but interrelated domains of interest, each of which offers many specific research parameters for studying virtual organizations. For this reason, it can be regarded as a quasi-transdisciplinary research model. Sun and Zhang (2006) completed an extensive literature study concerning research in the affective concepts used in several reference disciplines of information systems. Based on their findings, they proposed an abstract research model of individuals interacting with objects and concretized this research model in terms of specific affective concepts. Specifying the final dependent variables that characterize the intention to interact with an object or/and the actual interaction behavior, this model is a demonstrative prototype of a restricted transdisciplinary research model that captures a set of information systems-specific affective concepts as well as their relationships to each other and other factors.

A truly transdisciplinary research model should (i) identify descriptor parameters for research concepts that lend themselves to simultaneous studies from multiple philosophical standpoints and disciplinary perspectives, (ii) answer different research questions with cross-disciplinary knowledge but should (iii) also support a reflexive practice. In this latter context, Monu (1997) reported on the use of research models in agricultural research to study the involvement of farmers in research processes. The farmers' behavior has been used to guide giving preference and refining the research models. Namely, he elaborated and investigated three research models which can be described as (i) the research, development, and diffusion model, (ii) the farming systems research and extension model, and (iii) the farmer-first and last model. These examples of conventional research models conceive different behaviors of farmers (i.e., passive or active partners) in the identification of the research problem, the conduct of the research, and the development of the solution. The author provides information on both the descriptive notional basis of the models and the covering concepts that allow the formulation of input-output research variables for the studies and orientate the development of effective research methodologies.

2 Further Considerations

The literature study conducted in association with this paper has explored the existence of four categories of research models, namely (i) unidisciplinary research models, (ii) quasi-transdisciplinary research models, (iii) restricted transdisciplinary research models, and (iv) fully-fledged TRMs. The work reported in this paper attempts to establish a methodics for the last category. It presumes that a sufficient specification of a definitive research problematics (DRPs) is available and can be the object of a semantic content analysis. Instead of a fully-fledged methodology, the objective could only be a methodics because no formal scientific theories exist to underpin the whole of the development activities. Based on a forerunning study (Horváth, 2017), a theoretical framework, called 'holistic systematic combinatorial scoping', was proposed by Horváth and Abou Eddahab-Burke (2024) for deriving scoped definitive research problematics (DRPs) from vaguely demarcated overall research problematics (ORPs). Based on this theoretical framework (and praxiological foundation), a methodology was proposed that concentrates on the fuzzy front end and the early stages of handling complicated problematics systematically. As a complement to these, this paper specifically addresses the problem of constructing sharable TRMs for DRPs. The goal is to make it possible to systematically derive transdisciplinary research models before assembling a research design (a procedural blueprint) for conducting supradisciplinary research. The procedural model-based generic methodics proposed for research model development is a novelty and its applicability is demonstrated through an (intentionally delimited) sample DRP designated as 'avoidance of frequent vehicle accidents at suburban road crossings' (Abu Eddahab-Burke and Horváth, 2024).

A research model may include not only a textual and visual specification of the object of study but also a categorization of its elements and/or conditions. As an example, Agbayani-Siewert (2004) discussed a conventional research model of clustering ethnic groups into four broad categories. A study based on this research model tested the assumption of cultural similarity between Filipino and Chinese American college students by examining attitudes, perceptions, and beliefs related to dating violence. From the perspective of its informational enhancement over time, a research model is an active object of improvement based on the reflections on the outcomes of the conducted studies that have been organized based on it. Kushnir (1981) presented a specific but generalizable example of the consolidation of a multi-factorial research model as a reflexive practice. Starting from the field of social facilitation research and related to a social behavioral study, he criticized the rigid construct of the frequently applied research model and its hypothesis that the presence of the audience and the quality of performance are related to the involved arousal level. The critique concerned such functional features of the model as (i) being restricted to the study of one mediational process only, (ii) viewing the subject as a passive receiver of information, (iii) emphasizing the intensity of behavior but abandoning the directional aspect, and (iv) largely neglecting cognitive and strategic aspects of human behavior. As improvement opportunities, he suggested considering at least two operationally distinct mediational processes and defining the first one in terms of the effort invested voluntarily in task performance and the second one in terms of the arousal and the unintentionality of the subject. This informational enhancement potential of the research models is supposed to exist independent of whether they are conventional or transdisciplinary research models.

The study of research problematics and conceptualization of partial or complete solutions for them is inseparable from constructing TRMs. As discussed in Horváth and Erden (2024), research problematics are seen as large-scale, technologically and/or socially induced, multi-faceted complicated research challenges that need proper insights to become understood and resolved. Generally, they include a combination of disciplinarily complicated, application-dependent, and heterogeneous research problems. To address these, typically a transdisciplinary knowledge platform must be synthesized from the input knowledge of multiple disciplines (Hernandez-Aguilar 2018). In this context, depending on the scientific and/or professional objectives, an arrangement is needed for informing, training, coordinating, and sharing the knowledge of the researchers. Due to the intrinsic complexity of research problematics, not only vague circumscriptions of the theme of research but also detailed specifications of the subject matter are needed. However, providing such concrete specifications for transdisciplinary cases needs a new way of thinking and dedicated procedures (Pohl and Hadorn 2008). A difficulty is that there are different vocabularies in use as well as different views and practices in the current literature concerning cross-disciplinary research models and development processes.

The principal assumption and the starting point of this paper is that a research model is a digitally rendered simplified equivalent of a part of an observed or fictional reality to be studied. From a methodological viewpoint, it is a representation of a specification of a conceptualization of the targeted reality - the elements of which are semantically captured by human concepts and associations. This paper proposes a generic process scenario and a set of problem-independent analysis and synthesis actions to support the systematic preparation of research programs and projects in a supradisciplinary manner. The overall process includes three subsequent sub-processes as shown in Figure 1. These sub-processes are for (i) concretization of research problematics, (ii) specification of transdisciplinary research model, and (iii) construction of supradisciplinary research design. Figure 1 also shows the specific goals and the epistemologically and/or semantically transformative steps of the sub-processes. It is also assumed that a research model can not only deliver information about the scope and focus of the research but can also determine which multi-view research concept descriptor parameters (RCDPs) are to be jointly considered. The latter are important input information for the organization and collective conduct of supradisciplinary research programs and projects (Horváth, 2023).

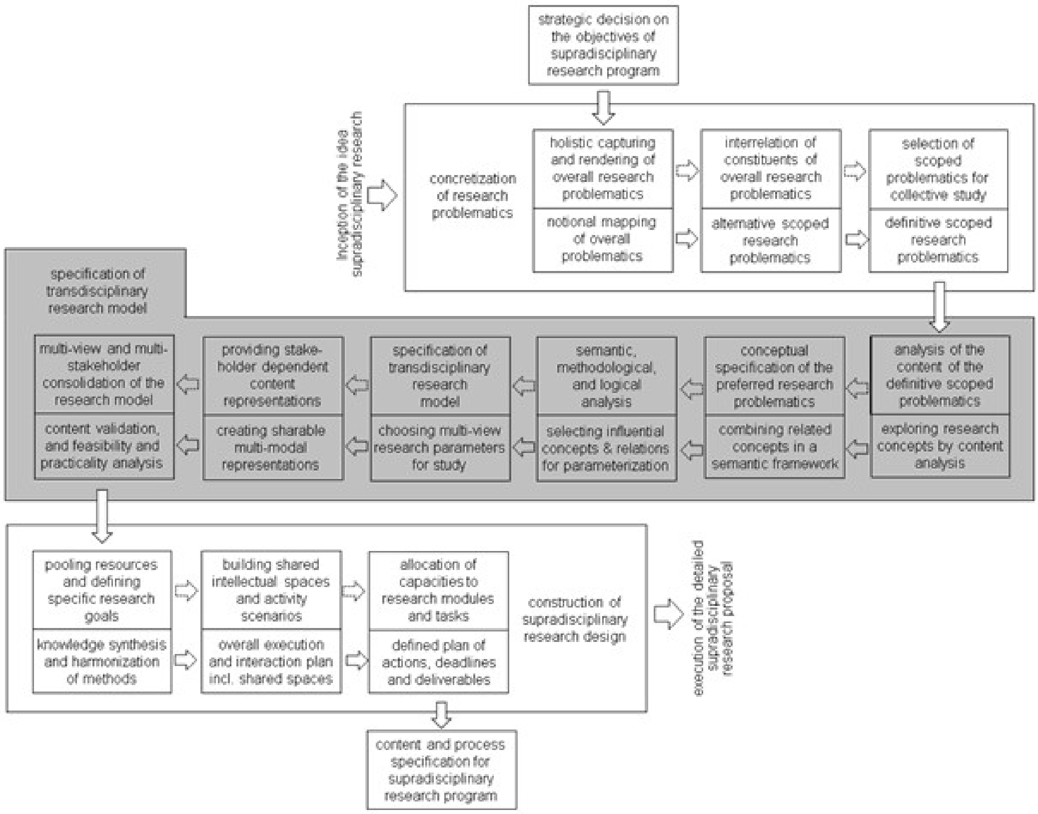

Figure 1: The steps of transferring the contents of a definitive scoped problematics into a parameterized transdisciplinary research model.

3 On Mental Concepts, Research Concepts, and Conceptual Research Frameworks

The term 'concept' plays an important role in the development of TRMs but it lacks a single and unambiguous definition due to its differing interpretations across various scientific disciplines (Jackendoff, 2012). The bottom line is that - complementing inklings and notions - concepts are the basic elements with which the human brain represents the world. Functionally, concepts are fundamental building blocks of human cognition (the minimal components of consciousness) and serve as broad or specific units of mental representations. As mental elements, human concepts convey fully formed thoughts and enable individuals to understand and organize their beliefs, as well as to perceive, reason, recognize, learn, and communicate (Goguen, 2005). As opposed to physically- or spiritually-based elements of mental models, they do not necessarily express a piece of reality. They may represent a category or a class of objects, events, changes, or relationships based on an abstract idea or a general notion.

Accordingly, concepts can be instantiated and non-instantiated. Instantiation means finding an actual instance of the concept and instantiated means that there exists a physical instance in the form of an object, process, entity, principle, etc. (Heit, 1996). Instantiated concepts can be studied with empirical (scientific) means, while non-instantiated concepts can only be scrutinized intuitively or logically. On the other hand, they can be generalized across different contexts. Consequently, human concepts play three roles, namely, they (i) provide a mental image or a general understanding of something, (ii) facilitate categorization and classification of physical or mental occurrences, and (iii) lend themselves to organization and inference of thoughts and facilitate communication, reasoning, and learning.

Research concepts (sometimes, also referred to as conceptions or constructs) are sub-sets of human mental concepts (Williamson, 2013). They (i) are chunks or bodies of knowledge that reflect what is explicitly known (or what may not be known) about the constituents of research phenomena and problematics, (ii) refer, either directly or indirectly, to something inferred from a specific set of occurrences in conjunction with the mental formation of a notion associated with these occurrences, (iii) make sense of a local world, categorize its constituents, help drawing inferences, recognizing patterns, making informed decisions, and understanding implicit meanings, (iv) enable researchers to recall and use both descriptive and predictive information in various situations, and (v) are intertwined with the elements of a conventional or symbolic language that make theoretical grasping and understanding empirical phenomena and problematics possible. From the viewpoint of research model development, research concepts should be differentiated from heuristic thoughts and subjective opinions because they may directly or indirectly refer to experienceable abstract things such as sustainability, compositionality, intelligence, or innovativeness, or generalized (abstracted) things such as homecare robot, renewable energy, or smart city which may nevertheless become physically manifested. While research concepts are vital for human internalization and structuring the object of research, their interpretation can vary significantly across disciplines, leading to potential misunderstandings and conflicts in collaborative research efforts. Semantically, research concepts may (i) be related to each other, (ii) belong to a theme, or (iii) form a pattern. Complex research concepts are captured in descriptive, explanatory, and predictive theories. Used to communicate research ideas to other people, logical expressions, verbal messages, written texts, or video footages express not only the nature of various concepts but also their interrelationships.

A conceptual research framework (CRF) is a basic construct that provides a theoretical or conceptual foundation for research activities by semantically and/or logically arranging and interconnecting relevant research concepts (Hamadi and El-Den, 2024).. A CRF is a critical element of a systematic inquiry process because it provides overall guidance for the investigations, and helps focus and organize complicated processes (Yeh, 2019). In the preparation phase of research programs and projects, a CRF (i) helps a high-level understanding of the overall research problem, (ii) systematizes the exploration of existing or conceived knowledge gaps and facilitates problem-solving, and (iii) triggers new insights and conjectures. In the case of studying scoped problematics, a CRF can deal with both abstract notions and instance objects and establish a mental representation of a problematics. CRFs are supposed to convert research ideas into common meanings to develop an agreement among researchers, and to facilitate early communication and collaboration among members of research teams. At the same time, the multi-level concepts (together with their relationships and implications) serve as building blocks of a research framework and offer a mental foundation for specific research models. While CRFs help the formulation of general research questions and make overall research hypotheses, they do not identify RCDPs and causal or correspondence relationships between them for studies (Savastano et al., 2024).

Research-enabling conceptualization of complicated problematics means transferring them into a formally rendered conceptual framework represented, for instance, as an annotated semantic network. Conceptualization specifies what is meant and what is not meant by the notions (terms) used to depict the considered problematics. A proper conceptualization is supposed to represent the problematics with sufficient fidelity and avoid interpretational conflicts during research. Therefore, focusing on a precise conceptualization is vital, while achieving a balance between structure and flexibility is necessary. Researchers have argued that overly rigid definitions may stifle creativity and exploration in research.

The first step towards constructing a CRF is to explore the relevant and important research concepts based on the symbolic and non-symbolic (verbal, visual, textual, or mixed) renderings of the selected DRP. In the context of the above-mentioned application example, concrete instantiated concepts can be a particular entity of the infrastructure, built environment, vehicles, drivers, regulatory equipment, traffic situations, driving code, and so forth. Non-instantiated generic/abstract concepts can be such as carelessness, haste, inexperience, aggressiveness, confusion, mistake, politeness, fear, obedience, social intelligence, etc. While the things (their attributes, relations, and implications) belonging to the first group are directly observable in accident situations and can be characterized directly by explicit research variables, the things in the second group can only be logically extracted from or applied to such situations and can only be characterized by research indicators and implicit research variables.

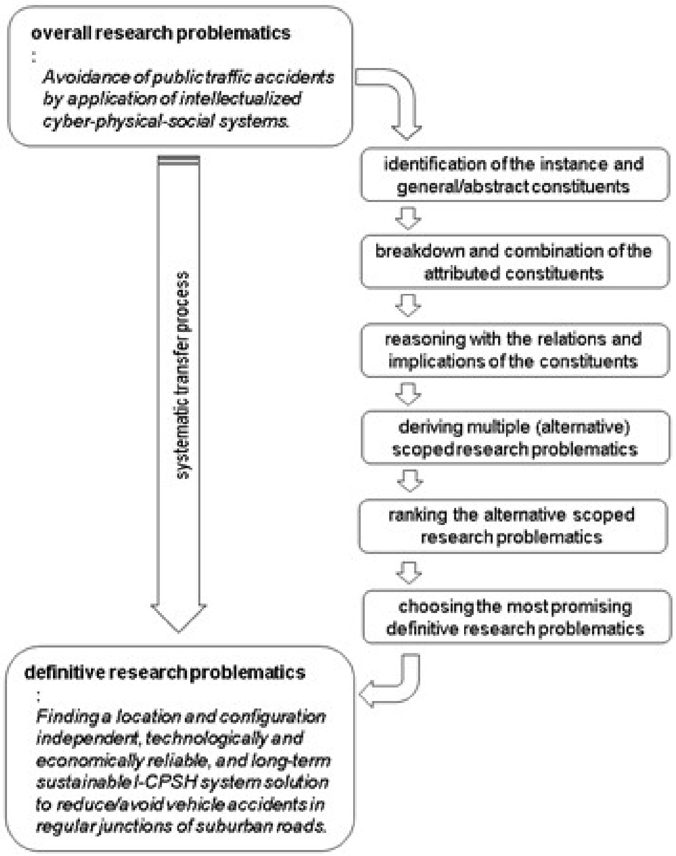

Figure 2: The main transformative activities of the specification of a DRP.

4 From a Definitive Research Problematics to the Content of a Conceptual Research Framework

The presumptions concerning the transformative actions discussed below in this section are that (i) a definitive research problematics (DRP) has been derived from the considered overall research problematics (ORP) by using the holistic systematic combinational breakdown (HSCB) methodology (Horváth and Abou Eddahab-Burke, 2024), and (ii) a proper textual, visual, and/or specification of this DRP is available. Figure 2 identifies the main transformative activities of the multi-stage process. Having an overall notional circumscription of the ORP, the process goes through the stages (i) identification of the instance and general/abstract constituents involved in the ORP, (ii) purposeful breakdown, detailing, and combination of these attributed constituents, (iii) reasoning with their relations and implications, (iv) deriving a coherent content for concrete DRPs, (v) ranking the alternative DRPs according to various criteria, and (vi) selection of a specific DRP that qualifies as the most promising one from the perspective of producing novel knowledge for addressing and resolving the challenges implied by the ORP. Figure 2 also shows a single-sentence textual description of the considered ORP and the derived DRP, respectively, for the simplified real-life example that will be used as a demonstrative case in Section 6. It can be seen straight away that the textual description of the ORP is less specific and is based on less concrete notions than that of the DRP. This is a consequence of the multi-step scoping and concretization activities by which the original specification of the ORP is transferred into alternative DRP specifications.

Intended for systematic scoping and formalization of large-scale research problematics, the rough scenario of the HSCB methodology is shown in Figure 2. The systematic procedure implied by this methodology is based eventually on the subsequent application of four clusters of content transformation activities. Activity cluster 1 is about the delimitation and circumscription of the overall research problematics and the definition of the general research objective. Activity cluster 2 deals with the identification and combination of specific instance constituents related to the ORP. The execution of activity cluster 3 results in the specification and combination of general/abstract constituents. Lastly, activity cluster 4 is about deriving coherent content and transferring it into concrete DRPs. In practice, the processing of these activity clusters means the execution of a total of 21 specific actions which, altogether, results in a systematic scoping process. The resultant DRPs capture those aspects (and constituents) of the overall problematics that the involved investigators have regarded as the most influential ones.

Though the content transformation activities of the HSCB methodology are not discussed further here, their supposed results are used as input in the case of the demonstrative example presented in this paper. Our attention is paid to the proposed TRM construction methodics that augments the above-summarized scoping and specification process of DRPs. While this methodics does not rely on a set of tested underpinning theories, it takes into account the fact that there are transitive epistemological relationships between DRPs and CRFs, as well as between CRFs and TRMs. Namely, the comprehensiveness and informativeness of the specification of a DRP influence the fidelity and effectiveness of a CRF, whereas the completeness and detailing of a CRF influence the detailed content and expectable quality of a TRM. These transitive relations mean that, in addition to serving different purposes, CRFs and TRMs are instruments with largely different dispositions, functionality, and information content and they both embed certain design concepts. Based on these considerations, the proposed methodics divides the entire process into two sub-processes. The first one aims at the construction of a CRF based on the specification of the DRP, while the second one converts this CRF into a detailed and documented specification of a TRM. These two sub-processes and the closely related knowledge are discussed in detail below.

Figure 3 shows the six main actions (logical milestones) of the entire process of research model development. The first goal is to map the notional constituents of the given DRP into the semantic construct of a conceptual framework to provide an initial circumscription of the object of the planned research. In practice, this mapping means finding the associated research concepts (entities) and interconnecting them according to their logical links (relationships). The actions belonging to the sub-process of deriving a CRF are as follows:

Action 1: Exploring relevant research concepts by content analysis of the DRP

There are several conventional textual content analysis methods discussed in the literature that differ in their goals and coding tactics. For content analysis of DRPs, a dedicated content analysis method is needed that includes both semantic analysis and relational analysis. The semantic analysis focuses on the existence, interpretation, and frequency of occurrence of the statements concerning the notional constituents in the specification. It identifies both the instance and the generic/abstract constituents of the DRP. The individual concepts may have no specific meaning inherently, but they may have a joint meaning based on their relations. Therefore, the relational analysis examines the logical relationships among the statements and attempts to reveal their patterns to deduce research concepts. It provides information about the importance, centralness, and implications of the constituents. The investigation of the constituents can be extended with (i) cognitive analysis (examination of the knowledge related to the constituents (ii) proximity analysis (evaluation of the semantic distance among the constituents), (iii) criticality extraction (hazard analysis of the constituents, (iv) affect production (dynamic evaluation of subjective aspects of the constituents), and (v) relation direction and feature analysis (evaluation of the

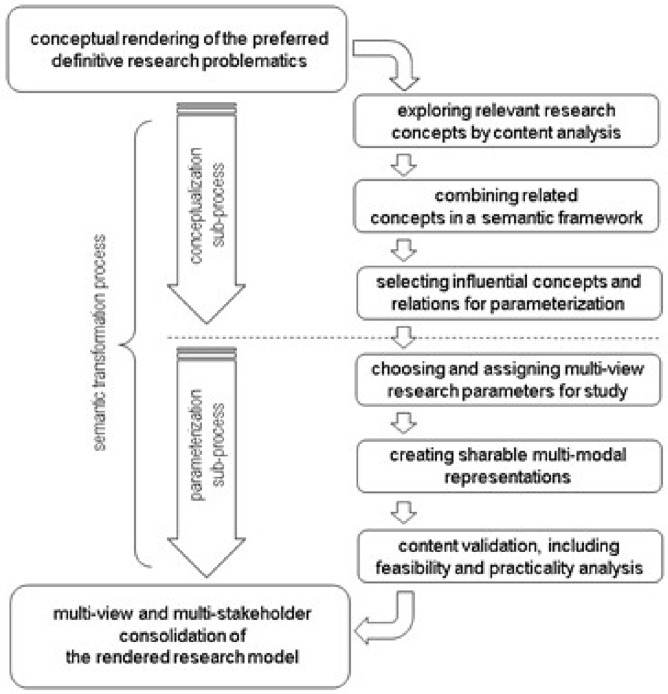

Figure 3: The sub-processes of specification of a research model.

nature of relations among constituents).

The content analysis process includes the following steps: (i) breaking down the textual specification of the DRP into constituent-related statements (semantically meaningful units), (ii) deciding on the way of handling similarities, (iii) coding the constituents for existence and/or frequency, (iv) sorting the coded constituents into clusters, (v) exploration of relations and patterns of connectivity, (vi) execution of selective (intuitive or logical) reduction, (vii) checking for consistency and coherency to ensure validity, and (viii) interpretation of the outcome of content analysis. Recognized difficulties are that (i) the statements may be explicit or implicit, (ii) they may include synonyms (having the exactly or nearly same meaning) or hyponyms (having a more specific meaning than a related general term), (iii) the level of things mentioned in the statements has to be intuitively decided on, (iv) the subjective judgments raise the issue of reliability, and (v) the translation rules may disregard the context in which the specification has been created. The input for deducing research concepts is created by the analysis of the notional constituents and the interpretation of the findings.

Action 2: Combining related research concepts in a semantic concept map

In view of the literature, a semantic map is interpreted as a graphically representable knowledge construct that defines what concept levels and concept entities belong to a meaning structure and depicts how the concepts are related to one another. Therefore, a semantic map lends itself to specification of relations, exploration of relation patterns, interpretation of relationships, and assist data/knowledge mining. Resembling semantic networks, a concept map can be rendered in a hub-and-spoke architecture using structural components such as (i) nodes (objects representing concepts), (ii) arcs (links expressing the relationship between nodes), (iii) labels (placed on links and nodes, further specifying relations between concepts), and (iv) bridges (specific nodes connecting two different semantic networks). However, a semantic map captures ‘includes-included’ relations only - instead of the ‘is_a’ and ‘has_a’ relations that are typically used in conventional semantic networks. As a visual representation, the map of research concepts is supposed to designate all associations among the primary research concepts included in the overall concept categories and the notional constituents of a given DRP.

Action 3: Selection of the most influential concepts for parameterization

Rendered as a semantic map, a conceptual framework represents a broader semantic structure that sheds light on the possible contents of transdisciplinary research and hints at the collective research knowledge necessary to do it. However, a CRF does not carry information about the significance (semantic and methodological) importance of the included same-level concepts (SLCs). This information can be obtained by the connectivity analysis of the SLCs. However, the relatedness of the concepts can be decided upon only intuitively, by semantic reasoning. As a means of visualization of the findings and results, either an N x N matrix or a relation circle can be used. The latter can show the measure of significance of a concept as the total number (cardinality) of the incoming and the outgoing relation edges. The higher the cardinality, the more important the position of a concept is. Notwithstanding this, it must be mentioned that a less central concept may prove to be equally important from the perspective of solving complicated research problematics. This makes the selection process of the most influential concepts a partly evidential and partly guesstimating procedure. In the semantic map, labels can be used to indicate the conceived importance of the concepts according to this dual assessment. The branches on the semantic map having strong labels deserve preference from the viewpoint of consideration for the research model, while those having weak labels may be ignored. This is a worthy consideration since the complexity of the research model is proportional to the total number of branches.

5 From a Conceptual Framework to a Parameterized Research Model

The content and relation information needed as input for the construction of a TRM is provided by a sufficiently elaborated CRF. The specification of a detailed research model embraces the following facts and assumptions, and involves the following actions:

Action 4: Constructing multi-view research constructs for the study

Research concept descriptor parameters are the means to capture and investigate the effect or influence of research concepts on the phenomena and problematics at hand. The tentative number of meaningful RCDPs depends, on the one hand, on the so-called ‘richness’ of a research concept (i.e., the number of sub-branches belonging to SLCs), and, on the other hand, on the relations of a concept to other SLCs. From an epistemic point of view, the most frequently occurring types of RCDPs can be (i) monodisciplinary RCDPs (having significance only from one disciplinary perspective), (ii) multidisciplinary RCDPs (having significance from multiple disciplinary perspectives disjunctively), or (iii) transdisciplinary RCDPs (research constructs) (having significance from multiple disciplinary perspectives conjunctively). The new knowledge obtained by the multidisciplinary investigation of RCDPs may be fragmented according to the disciplines involved, and disconnected or even conflicting. Therefore, it typically needs follow-up consolidation.

Multiple RCDPs of similar disposition may form meaningful patterns that are referred to as research constructs. When used in transdisciplinary research, research constructs facilitate disciplinary augmentation of the views and gaining transdisciplinary insight, collective aggregation, synthesis, and consolidation of the obtained knowledge above the level of RCDPs. In practice, they shed light on the knowledge deficit related to both individual research concepts and the conceptualization of a problematics as a whole. Normally, the unknowns related to individual research concepts can be eliminated by monodisciplinary investigations, whereas those related to the overall conceptualization need cross-disciplinary approaches. This explains the logical relationship between research constructs (patterns of RCDPs) and transdisciplinary research approaches. A very simple example is the characterization of the audible (outcome) noise of cars. The concerned disciplines can investigate it from engineering, design, safety, marketing, behavioral, social, and perceptive points of view. However, an exhaustive explanation of this phenomenon cannot dismiss a contradiction-free synthesis of the disciplinary findings. As elements of research constructs, RCDPs can be (i) research indicators, (ii) research variables, and (iii) research constants. Research indicators are means and/or ways of interpreting, qualifying or quantifying, and measuring properties or characteristics of a concept that cannot be directly captured by research variables. In the simplest cases, they only inform about the presence or absence of a concept, while in other cases they may provide some measurable characterization.

Action 5: Creation of a sharable multi-modal representation of the research model

In an optimal situation, the contents of the TRM are explored and compiled based on the collaboration of all stakeholders. As the preceding sections clarified, the actual content of a TRM includes (i) the specification of the DRP, (ii) the results of the content analysis process, (iii) the semantically multi-level clustered list of research concepts, (iv) the representation of the research concept framework as a semantic map, (v) the results of the relatedness analysis of the concepts, (vi) the results of assigning concrete RCDPs to the chosen influential research concepts, and (vii) an indication of what research questions the TRM supports. Thus, the TRM represents a theoretical image of the object of study that defines and clarifies what to study by the participants of a research program/project. The above variety of contents needs to be included in a human and/or computer-interpretable representation that should serve as a sharable and archival documentation of the research model.

The specification of the TRM is supposed to be transparent but also as complete and detailed as possible. If these are provided, the research model can indeed serve as a shared lens through which researchers can view and analyze the problematics at hand. Concerning the documentation of the derived TRM, two aspects should be considered: (i) the level of detailing and (ii) the modalities of representation. The level of detailing of the research model should (i) help researchers understand, explain, and make predictions about the definitive scoped problematics, (ii) facilitate the organization of supradisciplinary research programs/projects, (iii) provide the basis for the development of supradisciplinary research designs, including both a priory and posterior knowledge synthesis and engineering, and (iv) support the exploration of "what-if" scenarios. However, the specification of the TMR should not include any methodological or procedural information because these are left for the development and the specification of the research design.

It is important to understand that there exists nothing like "the best level of detailing" or "the best modality of representation". They should be individually determined in concert with the transferable contents and the consideration of the stakeholders. Unfortunately, the literature is very scarce on these particular topics. At the same time, if the content and the representation of a research model are designed with the consideration of the above general requirements, it can be foreseen that the cooperating researchers will be able to (i) organize and share their thoughts about the research problematics more effectively, (ii) underpin their work by fusing and synthesizing relevant disciplinary theories, and (iii) draw meaningful insights and ideas from their data and experiences during the knowledge inquiry and/or solution generation process.

Action 6: Validation of the content and implication of the research model

After the execution of Actions 1 - 4, the notional information carried by the chosen DRP is transferred into a structured TRM content and the used multimodal representation makes it an exchangeable specification, or in other words, an actionable and referable orientation document. As a last step, the researchers must approve the appropriateness of the included contents. Procedurally, this complements and concludes their joint activities that have been done in the preparation stage of the research program/project. This is not only a possibility but a necessity before starting the detailed planning of the research activities. First of all, a common view on the interpretation of the research model and the formal and informal requirements should be achieved. In addition to this, the content of the research model should be critically reviewed to ensure that it accurately represents the research interests of all involved parties. This implies the need for some external validation method/means that allows considering the objectives of the planned transdisciplinary research and, additionally, represents an effective and reliable approach. However, the literature discusses only a very limited number of practical methods for similar tasks - but not the same purpose, in particular, not for the validity assessment of the chosen multi-view RCDPs. It seems that a standard and easy way of external validation of non-trivial transdisciplinary research models does not exist yet. What it means is that there is no “royal way” of conducting external validation of TRMs (Ramspek et al., 2021).

Research models have two dispositions, namely, on the one hand, they are silos of research contents, and, on the other hand, they are means of research communication. This implies the need to conduct their assessment as external validation for which there are both assumptions and expectations. One issue is that such validation cannot be done exclusively in a theoretical manner (i.e., relying on rational principles and rules only) because it should also consider application-dependent matters. Eventually, external validation would need complex test cases but it is not obvious how to generate such test cases in the case of complex TRMs. Considering the objective of creating TRMs, external validation must focus on (i) how comprehensive the model is from the viewpoint of capturing the concerned research problematics (completeness), (ii) what concepts the model operationalizes to study the problematics (conceptualization), (iii) how effectively the model supports the understanding of the problematics (comprehension), and (iv) how much it can support sharing of knowledge and informing about the specific target of investigations (communication). Therefore, there is a need for an approach that resolves this theoretical-practical contradiction.

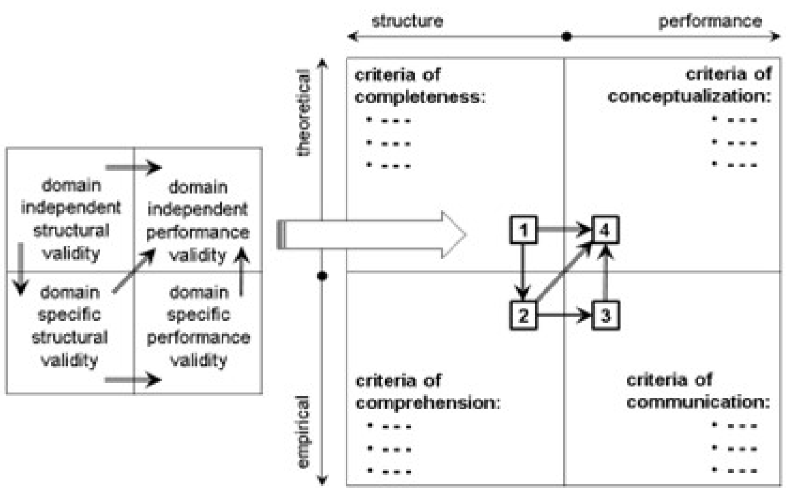

Figure 4: The strategy of external validation using the adapted validation square approach.

Based on the findings and proposals of several forerunning works, it has been conjectured that the validation square approach (VSA) can be adapted to fit these aspects and used in a collective external validation of contents and implications of the TRM. Initially, it was proposed by Pedersen et al. (2000) for external validation of design methods (and other functional knowledge constructs). The underpinning concept, procedural framework, and representative application examples of VSA have been relatively extensively discussed in the literature (Seepersad et al., 2006). This powerful validation approach is based on a validation square that is divided into four quadrants. Each quadrant specifies a particular dimension of validation and represents complementing aspects of assessment (validation), as shown in Figure 4. For each dimension of validation (quadrant) a sub-set of important criteria is defined. Procedurally, the VSA-based validation means the assessment of the compliance of the TRM to the quantitative and/or qualitative criteria in the order shown in Figure 4. The assessment (i) can happen in concert with the stated overall objectives of the external validation, (ii) allows the consideration of both theoretical validation aspects (left side) and empirical validation aspects (right side), and (iii) can handle both disciplinary domain independent criteria (upper half) and disciplinary domain-specific criteria (lower half). The theoretical parts have a predictive nature, while the empirical parts have a reflective nature. An obvious advantage of the validation square-based approach is that it can include both unidisciplinary criteria and transdisciplinary criteria. Typically, the criteria are generic, such as correctness, consistency, sufficiency, comprehensiveness, usefulness, performance, risks, implications, and reliability. Furthermore, VSA-based assessment can also support reasoning on different levels of conceptualization and complexity.

First of all, the criteria associated with the theoretical structural validity of the TRM define how comprehensive the model should be to appropriately represent the research problematics without any internal contradiction. The criteria for empirical structural validity help analyze what research concept levels and concepts the model operationalizes to study the problematics and provide information about the feasibility of addressing the theoretical content in the research practice. The criteria for empirical performance validity help explore how effectively the model supports understanding the problematics and, thereby, the generation of transdisciplinary knowledge. Lastly, the criteria for theoretical performance validity define how much the model should be able to support the conveyance of knowledge (research communication) about the specific target of investigations. These together help determine the overall affordances and limitations of the specified research model. Checking the extent of fulfillment of the various sub-sets of criteria provides information for the researchers about the logical soundness of the content of the TRM specification considering the objective of the planned research program/project. The theoretical performance validity also concludes about the capability of the TRM to produce useful results beyond the chosen example problem(s). The processing of the squares combines them in a particular semantic and procedural arrangement. Some limitations of the VSA have been discussed in the literature. For instance, it does not (i) offer specific methods/tools of validation, (ii) explore and reduce biases and errors (i.e., does not increase the credibility of the research model by internal validation), and (iii) test potentials and implications in other contexts (e.g., transferability of the model). Furthermore, VSA has some other limitations concerning model enhancement. For instance, the criteria-based assessment is not tailored to (i) mediating the validity of the body of knowledge that is used as know-how in the development of TRMs, (ii) reducing the subjectivity in judging the fulfillment of the criteria, and (iii) navigating the semantic overlap or dependence among the set criteria. Nevertheless, the usefulness of the VSA-based external validation is difficult to disprove as a pragmatic validation approach (Du Bois and Horváth, 2013).

6 Demonstrative Content Development for a Research Model

Rather than real-life case studies, a demonstrative practical example is presented in this section to exhibit the main resources of the methodics proposed for the development of TRMs. Due to page limitations, the issues of using sharable representation modalities and the execution of the VSA-based assessment of the TRM will not be addressed. As far as the validation of TRMs is concerned, only examples of the applicable criteria will be provided due to the high-level context dependence. The demonstrative application example is chosen to be a limited scale, structurally transparent, and everyday problematics, namely: 'frequent occurrence of traffic accidents at uncontrolled road crossings in suburbs of a town'. Though it is of relatively low complexity, it is a proper example because single-level road crossings (at-grade intersections) continue to be one of the most accident-prone areas in the suburban regions of cities. According to the Federal Highway Administration, about one-quarter of traffic fatalities and approximately one-half of all traffic injuries in the U.S.A. occur at or near intersections. Misbehavior, inexperience, distraction, impairment, and the driving style of drivers, the vehicles, roads, surroundings, and conditions, as well as non-motorized road users (e.g., cyclists and pedestrians) can be the cause of the happening with equal chance. In other words, it is typically not possible to reliably attribute the cause of injuries and fatalities to one factor and to look for single-aspect resolution because an accident can be the result of several different intertwining factors.

Perhaps the transdisciplinary nature of the chosen everyday problematics is not felt immediately but several areas of knowledge and expertise are essential for its holistic comprehension and successful resolution. The areas of knowledge include technical, behavioral, and social sciences such as (i) traffic engineering, (ii) human psychology, (iii) public health, (iv) social sciences, (v) data science, (vi) systems science, (vii) design engineering, (viii) social education, and (ix) behavioral ethics. The assumed dual goal of the intended research is to explore the common reasons for the injuries and fatalities and provide knowledge for the development of a cyber-physical technology-based solution to prevent, or at least to reduce, the occurrence of these unsolicited happenings. Thus, the planned research has a strong explorative-constructive nature, rather than an operative one, and must be conceptualized accordingly. That is to say, the expected new knowledge is not about who is liable for a traffic accident at a particular road crossing, but about what happens at road crossings in daily life and what can be done at all by technological, organizational, educational, and/or psychological means to reduce injuries and fatalities road crossings with a high probability. In other words, the conceived transdisciplinary research is targeted to (i) explore the most influential factors and their correlations, (ii) find an explanation for the formation of critical traffic situations, and (iii) hint at the possible preventive functionalities of a foreseeable adaptive cyber-physical solution. The underpinning transdisciplinary research model is supposed to consider all these aspects. The main procedural elements and results of compiling and rendering contents for a TRM are discussed below, following the order of actions presented in Sections 4 and 5.

Action 1: Exploring relevant research concepts by content analysis of the DRP

Let us start with the concise textual specification of the problematics that depicts the observable infrastructural environment, range of vehicles, traffic situations, human behaviors, and other influential factors. They together establish the physical and non-physical basis of the problematics:

> *The* ***physical infrastructure*** *typically includes two* ***standard suburban roads*** *and their* ***levelled intersections****. Frequently, there are* ***bike lanes*** *on both sides of the roads and* ***painted crosswalks*** *(pedestrian crossing) near the crossing. Not only the* ***infrastructural arrangement*** *of the intersections shows similarities, but also the* ***nature of the traffic,*** *the* ***types of vehicles,*** *the* ***conditions of the roads,*** *and the usual* ***surrounding environments.*** *The latter is formed by largely similar* ***suburban houses,*** *not influencing* ***driving on the roads*** *and* ***passing the intersections. Characteristic buildings*** *next to the roads are* ***single-family detached houses*** *surrounded by* ***gardens*** *and* ***vegetation.*** *Typically, there are no* ***public buildings*** *or* ***public facilities*** *in the broader neighborhood. The intersections are not equipped with any* ***electromechanical traffic regulators*** *or* ***electronic traffic control.*** *conditions,* and **vehicle conditions.**There are no **stop signs, yield signs, pavement markings,** or **traffic lights** to regulate the traffic in the **uncontrolled road crossings.** In the intersections, drivers are supposed to apply the **right-hand rule,** rather than the basic**right-of-way rule,** to **determine priority.** Though **children** and other **assistance-needing individuals** also frequently cross the roads, usually no **human agents** are present to manage the traffic. Accidents happen with **everyday frequency,** typically **in the rush hours, independently of the suburbs** considered. The typical **time frames of accidents** are between **7.00 a.m. and 9.00 a.m.** and between **4.00 p.m. and 6.00 p.m.** Observed is that personal cars are dominantly involved in and the accidents are **more frequently caused** by vehicles **moving from the city center** than by vehicles **moving into the city center,** and **much more frequently** than by the vehicles **moving on the ring roads.** The **reason for accidents** is **over speeding** in the overwhelming majority of cases. The fatalities and causalities are **caused by drivers** usually **in normal traffic circumstances, weather conditions, road conditions,** and **vehicle conditions.**

As the above specification hints at, a DRP typically includes a composition of instance things (IT) with their attributes (IA) in specific relations (IR) and with concrete implications (II) and attributed generic/abstract things (GT) with their attributes (GA) in general relations (GR) and with general implications (GI) so as:

$$DRP = \{IT,\ IA,\ IR,\ II\} \oplus \{\ GT,\ GI,\ GR,\ GI\ \}.$$

Originating in the multiple-situation orientated nature of the problematics, the above specification is dominated by generic/abstract notional constituents such as “uncontrolled road crossings” and “normal weather conditions" and includes only a few notional instance things, such as "peak time 7.00 a.m. and 9.00 a.m.". In the demonstrative example, the association of the notional constituents with research concepts is based on the assumption of the principle that everything has a cause. This principle guides the exploration of causalities, formulation of the possible concepts as causes, and their association with the constituents included in the specification of the DRP based on the relationship between causes and effects. Accordingly, the information concerning the notional constituents can be associated with six categories of general research concepts, namely: (i) infrastructure, (ii) instrumentalization, (iii) vehicles, (iv) environment, (v) circumstances, and (vi) humans. These can equally well be general causes of accidents in the given context. The result of the association process is shown in Figure 5.

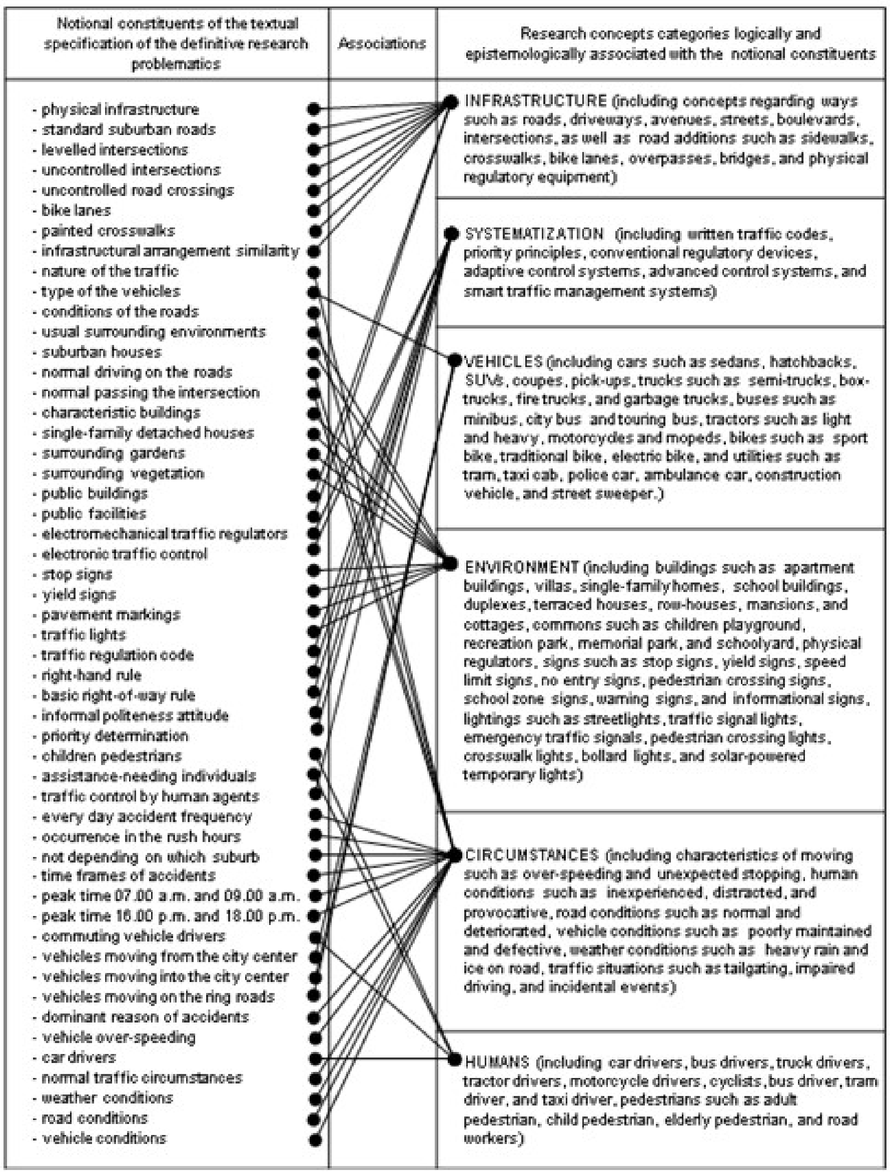

Figure 5: Association of the notional constituent with overall research concept categories.

The above six categories of research concepts can be mapped to various sets of concrete human mental

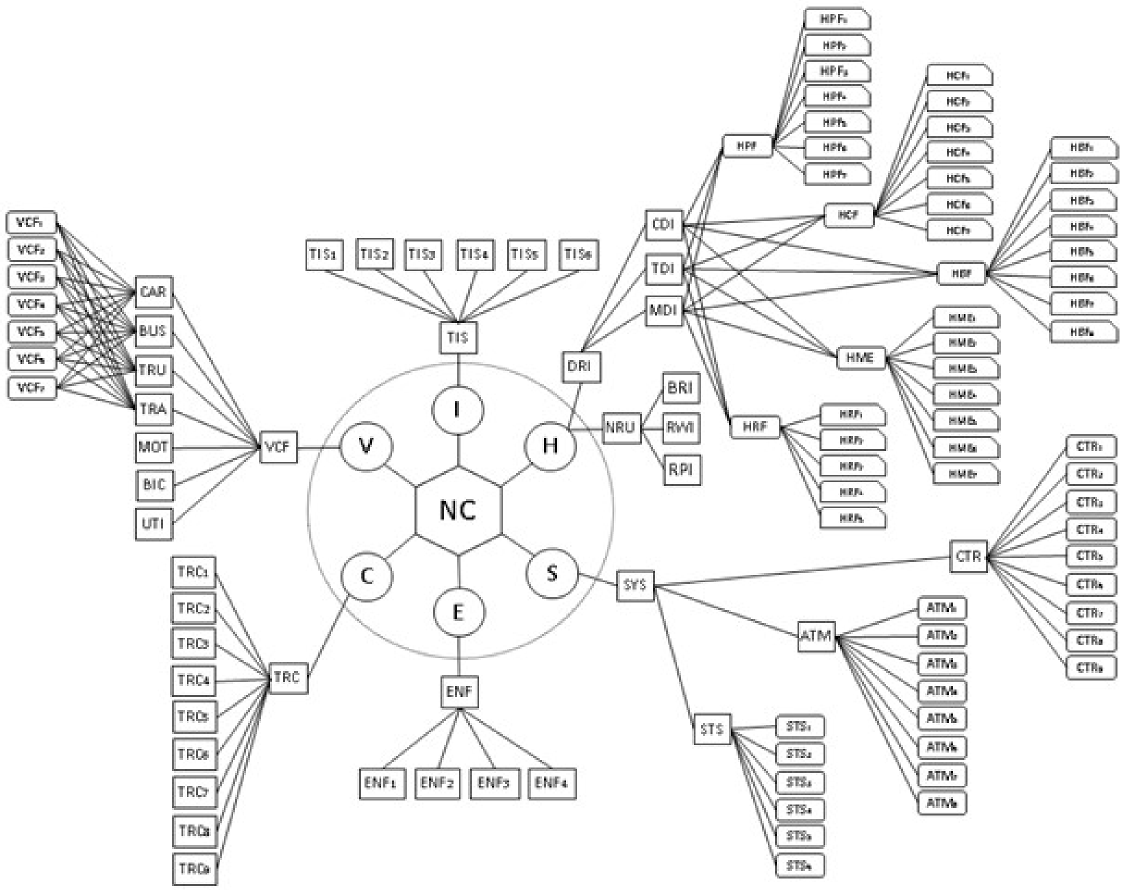

Figure 6: Semantic map of the relevant research concepts.

concepts through a semantic decomposition (logical exploration). The same first-level concepts related to possible causes of accidents are (i) defective infrastructure, (ii) conventional traffic regulation system, (iii) active traffic management system, (iv) smart traffic security system, (v) vehicle condition factors, (vi) environmental factors, (vii) traffic-related circumstances, (viii) human perceptive factors, (ix) human cognitive factors, (x) human behavioral factors, (xi) human psychological factors, (xii) human real-life factors, (xiii) non-motorized road users.

Action 2: Combining related research concepts in a semantic concept map

Given the notional constituents of the DRP, a semantic concept map captures the results of the concept exploration and association (Figure 6). More specifically, it is a graphical scheme reflecting the semantic resolution of the overall research concept categories to multiple concept levels according to the intricacy of the first-level concepts. For instance, the human-related concepts relevant to the demonstrative example are dissolved into two second-level, three third-level, and many more lower-level research concepts. The complete overview of the lower-level concepts generated by the semantic resolution of the first-level concepts for this demonstrative study is included in the Appendix. As shown in Figure 6, the generated semantic concept map is not a purely hierarchical scheme but a heterarchical one, which includes multiply-connected relations. This conveys information about the disciplinary position of the lower-level concepts.

This kind of visual diagramming helps the semantic exploration, i.e., to disclose transdisciplinary concepts about possible causes and causalities of the definitive research problematics. In this context,

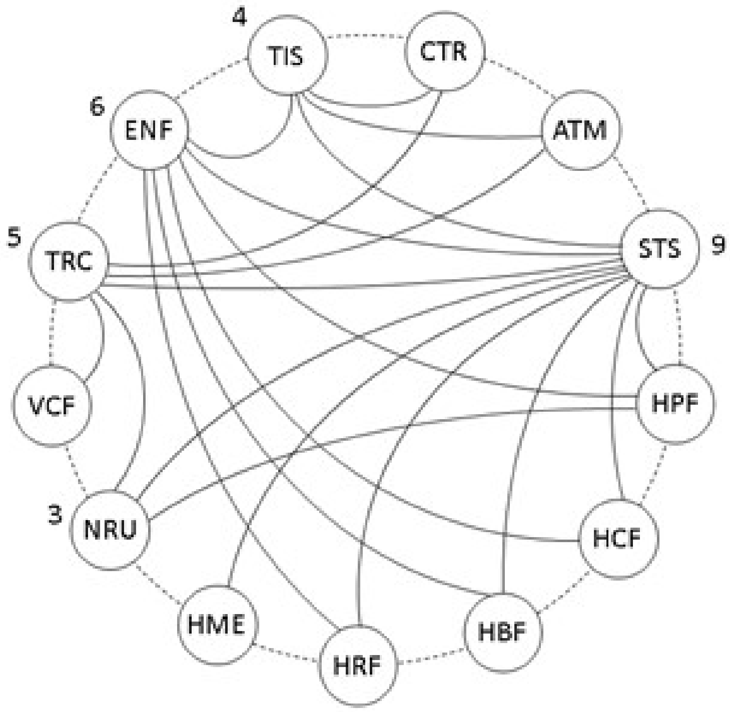

Figure 7: Cardinality of the relations of the first-level concepts.

causality is interpreted as any action, event, or process (the cause) that produces a change (the effect) that would not otherwise have occurred. As far as the reasons for the collisions are concerned, it is more about why they happen, rather than about how they happen. The concepts hint at the relationship between cause and effect.

Action 3: Selection of the most influential concepts for parameterization

As explained in the introductory part of this section, the planned research has a dual objective, namely, to reveal the reasons for the collisions and accidents at non-subordinated intersections of double-lane roads in suburban regions, and to propose a reasonable solution in the form of a cyber-physical system that can be deployed in multiple applications. This duality necessitates a simultaneous consideration of concepts that are related to (i) the traffic environment (TIS, VCF, TRC, and ENF), (ii) the human factors (DRI and NRU), and (iii) the regulatory systems (CTR, ATM, and STS). Based on this, 13 concepts have been considered in the demonstrative example. These should be seen as a holistic whole in the research, which needs the consideration of not only the lower-level concepts but also their intrinsic relationships. They and their semantic/logical relations are indicated in Figure 7. The interpreted relations provide an opportunity for the quantification of relatedness, and to make assumptions about the relative importance of the chosen concepts. The numeric values in Figure 7 show the number of relations (the cardinality of connections). On the one hand, the connector lines (i.e., semantic/logical relations) indicate the causalities, and, on the other hand, shed light on the crucial role of the regulatory systems (and underpinning the generic research hypothesis).

According to the elaboration of the demonstrative example, though the defective traffic infrastructure, environmental factors, and traffic-related circumstances have a relatively large influence as causes (ENF∼6, TRC∼5, TIS∼4), the concept of smart traffic security system is seen as even more important because it is deemed to influence all causes, expect the other system related ones. These intuitive considerations explain the relative rank of the concepts.

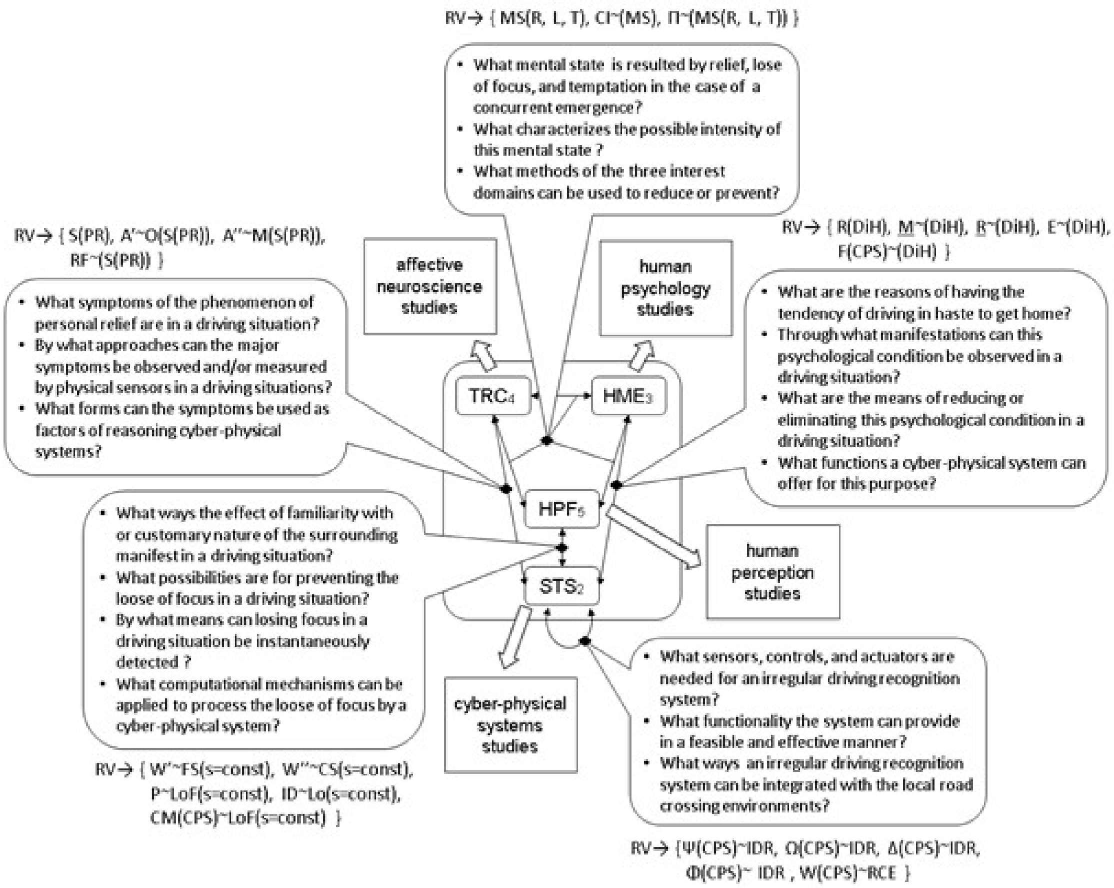

Figure 8: Elaboration of a sample research construct for transdisciplinary research.

Action 4: Constructing multi-view research constructs for the study

As introduced in Section 4, discipline-orientated research concept descriptor parameters do not have the power to stimulate transdisciplinary research. At the same time, multiple RCDPs may form meaningful research constructs that imply and necessitate transdisciplinary investigations and the findings of these efforts may be synthesized into a cross-disciplinary body of knowledge. Research construct can be devised by combining a finite number of different types of RCDPs considering their relations (interplay). In harmony with these, several research constructs can be defined as objects of investigation in the demonstrative example. Considering the page limitations, only one example is presented below. The goal of creating this example was to illustrate how a far-distance concept can be combined with three disciplinarily close-neighbor concepts in a research construct. The concerned concepts are shown in Figure 7. In selecting these concepts, both the semantic/logical relations and the relative influential nature of these concepts have been taken into consideration. Namely, the considered driver-related concepts are (i) HME_3, i.e., driver is influenced by the psychological effects of getting close to home, (ii) HPF_5, i.e.,the driver loses focus due to familiarity and customary surroundings, and (iii) TRC_4, i.e., the driver relieves at reaching from central to suburban areas. The considered regulatory system-related concept is STS_2, i.e., there is no irregular driver behavior recognition system. Please see the concept categories including these concepts in the Appendix. Figure 8 shows the formal specification of the research construct derived to stimulate transdisciplinary research activities.

Transdisciplinary research is supposed to investigate research constructs (patterns of RCDPs). As shown, HME3 can be the object of human psychology studies, HPF5 of human perception studies, and TRC4 of affective neuroscience studies, whereas STS2 implies the need for intellectualized cyber-physical system design, engineering, and deployment studies. The dual-headed arrows indicate the mutual relations (interdependences). The questions listed in the call-outs are representative working research questions (WRQs) these can be stated either by the disciplines mentioned above or by their pair-wise or triplet-wise collaboration. The explanation for the lists of WRQs in the call-outs necessitates knowledge aggregation, integration, and prediction from each and all of the mentioned disciplines. The WRQs may imply one or more research variables (RV) and research constants. For instance, the mental state (MS) of the driver is an output (dependent) variable that is influenced by the phenomena of relief, loss of focus, and temptation as input (independent) variables. In addition to this correspondence relation between the input and output variables, descriptive, causality or predictive relations can also be projected to research variables. This transdisciplinary research driven by this sample research construct is supposed to provide information for the conceptualization and design of an irregular driver behavior recognition system using the paradigmatic operational principles and resources of intellectualized cyber-physical systems. Should the goal be the aggregation of foundational knowledge for other types of smart traffic security systems described by the concepts STS1 (vehicle communication and warning system), STS3 (active transit vehicle and freight signal priority system), or STS4 (weather condition monitoring-based regulation system), different research constructs must be devised.

Action 5: Creation of a sharable multi-modal representation of the research model

As discussed in Section 5, the modalities used for the representation of the TRM should facilitate both effective communication and easy comprehension. Furthermore, the representation of the specification of the TRM should be rendered as a recordable, documentable, and transmittable document. Consequently, the representation may include both symbolic and non-symbolic (textual, verbal, image, or video) types of representation modalities, or any combination of these (mixed representation) according to the parts of the contents mentioned above. In other words, the task is to choose an advantageous combination of possible modalities that provides information from multiple perspectives and for different recipients, rather than only one specific one (e.g., text). However, the needed representation depends on (i) the nature of the object of research, (ii) the representation opportunities offered by the contents of the research model, and (iii) the actual needs of the participants and the stakeholders of the research program/project. Therefore, a trustworthy representation that conforms to real life and satisfies all stakeholders can only be achieved by considering the entire use context. As a consequence, no sample representations are included in the paper.

Action 6: Validation of the content and implications of the research model

For the external validation of the above content of the research model, the assessment criteria can be defined based on the following representative sub-sets of questions: such as resource utilization, size of local buffers, and throughputs for sub-systems or particular types.

a. *Theoretical structural validity (sample assessment criteria are: comprehensiveness, rendering, consistency, comprehension, and transparency).*

- How comprehensive is the model from the viewpoint of covering the notional constituents of the problematics?
- Does the model provide an appropriate mapping of the notional constituents to research concepts?
- Is there any internal contradiction among the multi-level research concepts with which the research problematics is theorized?
- How much and effectively does the model support the understanding of the problematics?
- Does the model properly clarify the relations and dependencies among the notional constituents of the problematics?

b. Empirical structural validity (*sample assessment criteria are: detailing, facilities, availability, parameterization, and instrumentality).*

- Are the scope (breath) adequate and the levels (depth) of detailing the research concepts sufficient for the planned study?
- Does the model entail a realistic need concerning the research resources, experimental facilities, and development means?
- Are the (cross-)disciplinary knowledge and methodological skills assumed by the model available and/or shortly obtainable?
- Are the specified research concept descriptor parameters the most relevant for studying the research problematics?
- Are the preferred research constructs instrumental for transdisciplinary knowledge exploration and synthesis?

c. Empirical performance validity (*sample assessment criteria are: approaches, collaborations, operationalization, manageability, and feasibility).*

- Does the model imply the need for unknown knowledge exploration and consolidation methods?
- Does the model suggest what kind of disciplinary collaborations are needed during the investigations?
- Can the lowest-level research concepts be operationalized in explorative and /or constructive research actions?
- What management and supervision needs are entailed by a complete implementation of the research model?
- Does the model hint at the feasibility of the theoretical content in the research practice?

d. Theoretical performance validity (*sample assessment criteria are: novelties, influentiality, usefulness, scheduling, and transferability*).

- Can the overall research objectives, fundamental assumptions, and guiding research questions considered in the model development result in novel scientific insights?
- Does the model address influential working research questions and promising specific research hypotheses?
- Can the model result in knowledge that supports finding or designing solution(s) for the entire research problematics or for at least a part of it?
- Does the model imply a program/project activity scenario and cooperation framework manageable in the planned runtime?
- With what efforts can the model be further enhanced and transferred into a detailed research design?

As shown above, the criteria and assessment aspects are application context-dependent. The common methods of information gathering and assessing the fulfillment of the criteria are interrogation during focus group sessions and/or questionnaire-based interrogation of the research collective. The summation of the assessment result may happen with or without weighting of the criteria.

7 Reflections and Further Research Opportunities

The work presumed that transdisciplinary research models are needed to address complex problems and to face concomitant challenges where individual disciplines alone can no longer provide proper and sufficient intellect. TRMs help bear a collective focus and co-produce ‘actionable knowledge’ as the means of building shared intellectual spaces. On the other hand, our explorative literature survey pointed to the fact that only restricted attempts had been made to develop systematic TRM methodologies and methods. Despite its limitations, the work presented in this article stretches the boundaries of current knowledge.

The paper has drawn a demarcation line between research frameworks and research models though they are often used interchangeably in the literature and have the common feature that both are instrumental for transdisciplinary research. It posits that they have dissimilar contents and serve different purposes, and argues that a research framework is supposed to provide only a broader theoretical structure for capturing the idea and object of research. It is rendered as a semantic arrangement of high-level notional, logical, or procedural concepts of the overall research interest. It informs researchers about the set of RCDPs relevant to the to-be-studied problematics and the relations among them. Being less specific than a research model, a research framework cannot stand for or replace a research model. The latter provides a detailed description (in fact, a prescription) of the specific object of research, and its contents are compiled and structured to provide a blueprint for studying a complicated problematics. It identifies the most relevant research parameters for unidisciplinary and transdisciplinary studies.

Considering the above ontological differences„ the paper proposes a methodics to transfer the specification of a DRP into a TRM through the involvement of a CRF. The two-part process makes it possible for the concerned research collectives to (i) agree on their scientific interests and research objectives, (ii) develop hypotheses about both the core and the borders of the target problematics, (iii) identify the associated unidisciplinary and transdisciplinary concepts and priorities, (iv) select the crucial research constructs and parameters, and the logic of their study, and (iv) interpret the findings within both theoretical and practical contexts. The necessary and possible content of a TRM has margins. The lower-margin (threshold) is the knowledge that can be included in a reasonable specification, whereas the higher-margin (ceiling) is the knowledge known at all about the object of research.

The paper discussed a methodics for the development of transdisciplinary research models. The proposed procedure involves six activities that are supposed to be executed sequentially. The analysis of the notional constituents of the definitive research problematics allows their mapping to generic concepts and resolves these into interconnected lower-level concepts that can be represented in a semantic concept map. Based on the mutual semantic relations between the first-level concepts, the most influential ones are determined and further processed. The concepts having a transdisciplinary nature are characterized by multi-view research constructs for collective studies or by research variables for disciplinary studies. The aggregated knowledge is included in a sharable multi-modal representation of the research model. The process is concluded based on the findings of the external validation of the content and implications of the research model that can be changed and further enhanced even during the conduct of a research program/project.

Due to obvious space limitations, the paper could not deal with several important and closely related epistemological and social issues such as (i) the indispensable forerunning transdisciplinary knowledge synthesis, (ii) setting up transdisciplinary research teams, (iii) deriving road maps and activity scenarios for research activities, and (iv) the principles of supradisciplinary research design development. Neither extends the discussion to the issues related to the construction and representation of research designs. The professional reason is that it is seen as a resource- and asset-sensitive actionable strategy of a research project that involves a specific plan of actions that defines the processes, methods, and techniques, as well as a plan of capacity allocation and utilization. The above-mentioned technical limitations explain why the paper could not address other relevant issues such as applicability in the case of largely differing problematics, present findings of application case studies, analyze the performance measures of the supradisciplinary research conduct, and elaborate on the always-present human attitudinal and behavioral questions. Releasing the results aggregated in these aspects for a public debate is left for follow-up publications, together with examination of the needs and opportunities for follow-up research work.

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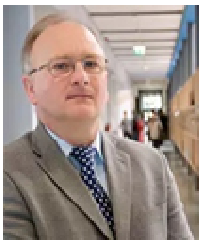
About the Author



Imre Horváth, C.Dr.Sc., Ph.D., dr.univ., is a professor emeritus of the Faculty of Industrial Design Engineering, Delft University of Technology, the Netherlands. In the last years, his research group focused on research, development, and education of smart cyber-physical system design, with special attention to cognitive engineering. Dr. Horváth has done explorative research in systematic design research methodologies. He was the promotor of more than 25 Ph.D. students. He was the first author or co-author of more than 480 publications. His scientific work was recognized by five best paper awards. He has a wide range of society memberships and contributions. He is the past chair of the Executive Committee of the CIE Division of ASME. Since 2011, he has been a fellow of ASME. He is a member of the Royal Dutch Institute of Engineers. He received honorary doctor titles from two universities and the Pahl-Beitz ICONNN award for internationally outstanding contributions to design science and education. He was distinguished with the Lifetime Achievement Award by the ASME's CIE Division in 2019. He has served several international journals as an editor. He was the initiator of the series of International Tools and Methods of Competitive Engineering (TMCE) Symposia. His overall research interests are in various philosophical, methodological, and computational aspects of smart product, system, and service design, as well as in synthetic knowledge science and the development of intellectualized self-adaptive systems. His latest studies are related to the evolution of the paradigm of cyber-physical systems and the associated transdisciplinary knowledge, research and education approaches.

Appendix

Lists of research concepts epistemologically associated with the notional constituents of the problematics as well as logically associated with various possible causes of accidents:

Concepts related to accidents caused by defective traffic infrastructure
TIS1 - control equipment is not working
TIS2 - there are no traffic controls whatsoever installed
TIS3 - crossing road is masked by stationary or parked vehicles
TIS4 - no public lighting at the road crossing
TIS5 - there is an inadequate signage
TIS6 - no round-about implementation is possible

Concepts related to accidents caused by by the lack of a conventional traffic regulation system
CTR1: there is no road-side traffic warning and signs regulation system
CTR2: there is no electronic turning and crossing control system
CTR3: there is no proactive local advisory radio system
CTR4: there is no dynamic adjustment of the signal timing
CTR5: there is no bicycle monitoring and warning system
CTR6: there is no human and animal monitoring and warning system
CTR7: there is no time-of-day operation management system
CTR8: there is no emergency vehicle preemption system
CTR9: there is no pedestrian signal timing system

Concepts related to accidents caused by by the lack of an active traffic management system
ATM1: there is no real-time queue warning display system
ATM2: there is no momentary speed regulation system
ATM3: there is no dynamic distance keeping warning system
ATM4: there is no variable real-time speed reduction and limits system
ATM5: there is no changeable and variable electronic message system
ATM6: there is no adaptive traffic sign and signal control system
ATM7: there is no automated weather observing system
ATM8: there is no gross vehicle weight estimation system

Concepts related to accidents caused by the lack of a smart traffic security system
STS1: there is no vehicle communication and warning system
STS2: there is no irregular driver behavior recognition system
STS3: there is no active transit vehicle and freight signal priority system
STS4: there is no weather condition monitoring-based regulation system
STS5: there is no integrated information, communication, and control system
STS6: there is no congestion mitigation and air quality enhancement system

Concepts related to accidents caused by vehicle condition factors
VCF1: suddenly breaks down or malfunctioning
VCF2: visor, mirror, or windscreen is dirty, scratched, or frosted
VCF3: is overloaded by passengers or goods
VCF4: spreads mud, oil, or debris on road surface
VCF5: has a flat tire
VCF6: has no working headlights/taillights
VCF7: side mirrors are defective or missing

Concepts related to accidents caused by environmental factors
ENF1: blocks driver's visibility by natural/artificial objects
ENF2: influence by non-predictable road environment factors
ENF3: there are unsupervised animals or object in carriageway
ENF4: there is emergency vehicle on a call at the crossing

Concepts related to accidents caused by traffic related circumstances
TRC1: poor road design and maintenance state
TRC2: not adequate or masked signs or road markings
TRC3: temporary road layout (e.g., contraflow)
TRC4: driver relieves at reaching from central to suburban areas
TRC5: control equipment is defective or completely failed
TRC6: control equipment provides misleading traffic signal
TRC7: driver drives excessively above the speed limit
TRC8: there is an incidental event in the crossing
TRC9: effects of naturally occurring phenomena

Concepts related to accidents caused by human perceptive factors
HPF1: fails to notice the motional behavior of own and other vehicles
HPF2: makes error in perception of the environment
HPF3: fails to recognize emerging traffic situation in time
HPF4: fails to pay attention to traffic signals
HPF5: loses focus due to familiarity and customary surrounding
HPF6: does not observe traffic calming (e.g., road humps, chicane)
HPF7: ignores a stop sign

Concepts related to accidents caused by human cognitive factors
HCF1: makes error by performing de jure rule-violating own behavior
HCF2: misses recognition of de facto rule-violating behavior of others
HCF3: makes wrong assumption on or misjudges driving behaviors
HCF4: believes falsely in own right of way
HCF5: neglects poor road conditions
HCF6: acted negligently of road construction work
HCF7: fails to yield the right of way

Concepts related to accidents caused by human behavioral factors
HBF1: runs red lights with increased speed
HBF2: breaches the duty of care
HBF3: neglects to cede the right of way
HBF4: disregards dangerous weather conditions
HBF5: does not obey speed and overtaking regulations at arriving to suburbs
HBF6: drives in haste or under effects of drug or alcohol
HBF7: maneuvers so as to cause danger to other road users
HBF8: is driving a stolen vehicle

Concepts related to accidents caused by human mental-emotional factors
HME1: suffers from unique mental or individual psychological mental-emotional disturbances
HME2: miss resistance to distractions or impeding effects
HME3: is influenced by the psychological effects of getting close to home
HME4: suffers from tiredness, exhaustion, or micro-sleeps
HME5: losses patience due to increased traffic and frequent stops
HME6: is fearful because of past experiences
HME7: shows hesitant or indecisive behavior

Concepts related to accidents caused by human real-life factors
HRF1: has a blocked view by the permanent arrangements of surroundings
HRF2: is learner or inexperienced or is not mastering the vehicle
HRF3: has a blocked view by incidental vehicle situation
HRF4: is disturbed by chatting passengers
HRF5: is disturbed by signs or communication of other drivers or pedestrians

Concepts related to accidents caused by non-motorized road users
NRU1: motorcycle driver behaves unpredictably
NRU2: bicycle driver behaves unpredictably

NRU3: children are playing on the road
NRU4: animals appear on the road
NRU5: pedestrian crossing the road at unmarked place
NRU6: pedestrian crossing the road at marked/secured place