How Transdisciplinarity Can Help to Improve Operations Research on Sustainable Supply Chains—A Transdisciplinary Modeling Framework

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We present a transdisciplinary modeling framework that enhances collaborative research on sustainable supply chain management (SSCM). Decision support concerning such systems is commonly provided using operations research (OR) methodologies. The quality of respective models depends on the appropriateness of both mathematical representation of the focal system and data input. Concerning this matter, OR faces severe criticism as groundwork is commonly neglected. This results in a lack of holistic understanding and in insufficient modeling of real-world problems. Crucial characteristics of the underlying system are often over simplified due to single-discipline assessments. Particularly, in the context of complex sustainability challenges, multiple nonacademic competencies and expertise are required. Although latest research indicates that collaborative research settings are highly beneficial regarding SSCM, a dearth of integration between disciplines exists. Therefore, we develop a conceptual framework that helps to overcome these shortcomings based on the paradigm of transdisciplinary research (TDR), which needs substantiation to enhance collaboration and to ensure applicability. Accordingly, we propose appropriate methodologies for each step within the framework. Overall, the framework enables holistic analysis of a focal system by providing a sound approach for SSCM-oriented TDR projects. The value of the framework is eventually demonstrated by two cases that deal with SSCM issues.

Keywords: interdisciplinarity; collaboration; operations research; closed-loop supply chains; sustainability; energy systems

INTRODUCTION

The production and distribution of goods as well as the sourcing of raw materials negatively impact the environment in many ways. In order to address these ecological effects under consideration of both economic necessities and societal pressure, increasing attention is paid to the concept of sustainable supply chain management (SSCM). Decision problems in this area are commonly analyzed and assessed using operations research (OR) methods. This toolset aims on translating unstructured real-world problems into quantitative models. The quality of the solution depends on the appropriateness of both mathematical description and data input. In this context, OR on SSCM is subject to criticism based on the observation that it is diverging from reality and lacks holistic, real-world approaches (van Wassenhove and Besiou 2013). Complementary perspectives are needed for proper assessment of such systems (Sahamie et al. 2013) and "researchers must transcend disciplinary boundaries and adopt a more holistic approach" (Sanders and Wagner 2011, 321). Hence, the shortcomings of OR may be tackled by the paradigm of transdisciplinary research (TDR) as it integrates researchers from different academic backgrounds as well as nonacademic stakeholders, like practitioners, politicians, or nongovernmental organizations (NGOs) (Baumgärtner et al. 2008).

TDR requires a process of knowledge integration, which is subject to various obstacles that endanger the project's success. Thus, structured approaches that address these challenges and steer collaboration are required but are not extant for issues of SSCM. Based on this observation, we develop a framework entitled "transdisciplinary modeling framework" (TMF) that supports analyses of SSCM issues relying on transdisciplinarity. Accordingly, we state the research question as follows:

> *Which approaches are appropriate to effectively improve OR-based analysis of SSCM issues by means of a TDR process?*

Considering the OR-oriented generic problem-solving process (see Figure 1), the TMF emphasizes and improves the step of verbal modeling. This step is crucial as it defines goals, characteristics of a focal system, cause-and-effect relationships, decision alternatives, and information, which are eventually transferred to the subsequent step of mathematical modeling. In common OR literature verbal modeling is often underdeveloped, which causes a dominant part of shortcomings in mathematical modeling. Addressing this, the TMF provides a conceptual framework for SSCM-oriented TDR, which eventually supports the development of holistic OR models. As the TMF is designed to support relatively complex TDR projects, it may also prove to be beneficial for interdisciplinary collaboration or may assist corporate projects, where employees from different backgrounds and divisions are involved.

Finally, we apply the TMF to two cases dealing with SSCM issues. First, we demonstrate the application of the TMF in the context of a TDR group that tackles the challenge of evaluating sustainable energy systems. Second, we exemplify the framework regarding management and assessment of a closed-loop supply chain (CLSC) in the plastics and polymer industry. These demonstration cases deepen the understanding of the TMF and highlight typical pitfalls that are experienced in common OR studies.

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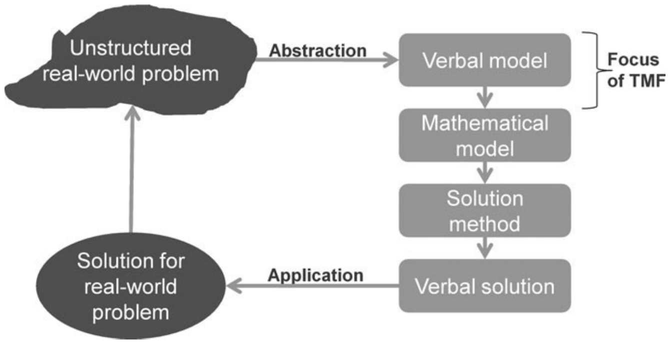
Figure 1: Generic problem-solving process (inspired by Werners 2008).



SHORTCOMINGS OF OR IN SSCM

SSCM is defined as "creating goods by using processes and systems that are nonpolluting, that conserve energy and natural resources in economically viable, safe, and healthy ways" (Glavic and Lukman 2007, 1883). In accordance to the given definition, these kinds of challenges regularly comprise decision problems, like energy-oriented production scheduling (Rager et al. 2015), emission and waste reduction (Tan 2007), utilization of raw materials (Majozi and Gouws 2009), and reverse logistics and CLSC management (Carter and Ellram 1998; Rubio et al. 2008). Generally, such problems require multiple expertise as the focus on economic factors is extended by ecologic and social criteria, which are commonly barely understood by management scientists (Sahamie et al. 2013). A majority of these decision problems is tackled by OR methods.

By reviewing according OR studies, it becomes obvious that an integration of multiple knowledge carriers from academia and practice does not happen sufficiently although it would be beneficial in many cases (Sanders and Wagner 2011). For instance, "technical peculiarities of unit operations are often over-simplified or are even neglected" (Schultmann et al. 2004, 737) or the central process of goal formation and defining an objective function is widely under developed (Eden and Ackermann 2013). Furthermore, assumptions are not realistic (Jayant et al. 2011). In line with that, van Wassenhove and Besiou (2013) as well as Sodhi and Tang (2008) state that OR becomes disintegrated from practice. It seems that recent OR studies focus on "mathematical optimization in the first place" (Ulrich 2012, 1229) instead of generating system understanding upfront. Although this "research-practice gap" is widely recognized in management sciences, there is little guidance to bridge it (Bansal et al. 2012, 73).

Summing up, OR is suffering from shortcomings regarding groundwork in the field of verbal model development and a lack of knowledge integration regarding expertise that is required for sufficient analysis of SSCM problems. To address the stated shortcomings, traditional OR methods need to be complemented with participative and interactive problem structuring methods that enable elicitation and convergence of divergent knowledge (Rosenhead 1996). A promising approach is provided by the research paradigms of inter- and transdisciplinarity.

COLLABORATIVE RESEARCH—APPROACHES AND CHALLENGES

Collaborative research, namely inter- and transdisciplinarity, goes beyond the scope of isolated traditional disciplinary boundaries. Interdisciplinary research represents an approach that transcends the narrow scope of disciplinary views by breaking down disciplinary boundaries. It occurs through coordination by a higher level concept, mutual understanding of terms, and knowledge integration among academic disciplines (Jantsch 1972). The paradigm of TDR is even more comprehensive than interdisciplinarity "involving not only scientists but also practitioners from beyond the realm of science (e.g., the users) in the research work" (Defila and Di Giulio 1999, 13). Regarding industry-academia collaborations, academia may benefit from such collaborations through higher transferability of research results to the economy, while corporate players profit from an increased competitiveness and responsiveness on the market (Kaufmann and Tödtling 2001).

Most TDR contributions are directly deduced from real-world projects. Table 1 summarizes transdisciplinary case studies and research papers clustered in accordance to their epistemic background. Sustainable landscaping of rural or urban areas is a major topic of investigation. In these studies, the transdisciplinary team regularly comprises academic experts from disciplines like biology, chemistry, geology, and societal as well as political stakeholders. Corporate involvement is rather scarce. Research on water management issues is similarly structured. Studies that evaluate the effects of environmental legislation, support green policy setting, or work on measures for climate protection are explicitly located at the interface between academics and politics. Research groups that examine sociological dynamics and behavioral patterns are less common. Studies on socio-technical issues conduct technical assessments considering ethical or social aspects of innovative technologies. Summing up, the spectrum for applying TDR is wide. Concerning the scope of our research, we can conclude that articles developing best practice models for TDR within the broad field of SSCM or other OR problems are scarce.

In general, frameworks for structuring and steering TDR are needed as such research organizations cause substantial challenges. These emanate from the involvement of divergent and domain-specific mindsets, different values and beliefs, as well as different modes and cultures of communication. Apart from the participants' attitude toward transdisciplinarity and their "willingness to learn, to listen, to cooperate, and to accept other interests and values" (Scholz et al. 2000, p. 485), challenging situations within such multiple-stakeholder projects mainly emerge from two causes:

- A lack of clarity about focus and objectives of the project (Lang et al. 2011)
- A high level of complexity (Rosenhead 1989, 343).

In the first case, methodologies for mutual learning and convergence of understanding are required. In the latter case, there is a need for methodologies that structure and reduce complexity. Complexity challenges in TDR projects mainly arise along two

Table 1: Epistemic backgrounds of transdisciplinary research studies

Topic	Articles
Urban and landscape development	Baccini and Oswald (2008), Bergmann and Jahn (2008), Despres et al. (2004), Farley et al. (2010), Hindenlang et al. (2008), Hubert et al. (2008), Jeffrey (2003), Messerli and Messerli (2008), Munoz-Erickson et al. (2010), Penker and Wytrzens (2008), Pinson (2004), Scholz et al. (2006), Stauffacher et al. (2008), Walter et al. (2008), Wiek and Walter (2009)
Water management	Burkhardt-Holm (2008), Kiteme and Wiesmann (2008), Luginbühl (2008), Scholz et al. (2000)
Environmental legislation and policy setting	Castells and Guardans (2008), Scholz et al. (2009), Schwaninger et al. (2008), van de Kerkhof and Wieczorek (2005)
Climate protection	Held and Edenhofer (2008), Martens and Rotmans (2005)
Sociological and behavioral studies	Horlick-Jones and Sime (2004), Simoni et al. (2008)
Health care	Lawrence (2004), Monteiro and Keating (2009), Piko and Kopp (2008), Schelling et al. (2008), White (2002)
Socio-technical assessment	Bernhard and Schweizer (2008), Rip (2008)

dimensions (Pidd 2008). First, such projects gather and process huge amounts of information. The interpretation of these data and information may be ambiguous, which necessitates a formal process to reach a uniform interpretation within the project team. Second, different participants in the research project have different perceptions of a problem as well as different preferences regarding problem solving and project organization (Baumgärtner et al. 2008). Here, the task of problem definition and structuring is stated as the most demanding and crucial part of a transdisciplinary project (Shaw et al. 2004). Regarding these issues, research in the context of transdisciplinarity is dispersed and lacks both guidance and tools that provide insights into the process and methodological perspective of collaboration (Lang et al. 2011). Accordingly, several authors articulate the need for more systematic approaches and frameworks that steer transdisciplinary collaboration (Broto et al. 2009). Moreover, the literature review above reveals that TDR approaches within SSCM are not well documented if applied, although SSCM as a subdiscipline of SCM is at least multidisciplinary by nature. Therefore, the implementation and documentation of structured TDR approaches may be useful to develop best practices and to further advance theory building in (S)SCM research (Sanders and Wagner 2011; Sahamie et al. 2013).

To conclude, there is much space for further research on developing an appropriate toolset for facilitating, structuring, and guiding transdisciplinary collaboration in SSCM. Accordingly, the TMF contributes to both the academic discussion and the actual implementation of TDR in SSCM-oriented decision problems. The TMF tackles the challenge of a lack of clarity in Steps 1 and 2 and the goal of complexity reduction within Steps 3–5 (see next section). It supports knowledge integration by implementing methodologies that help participants to transcend the boundaries of their respective discipline and enable structured discussions.

TRANSDISCIPLINARY MODELING FRAMEWORK

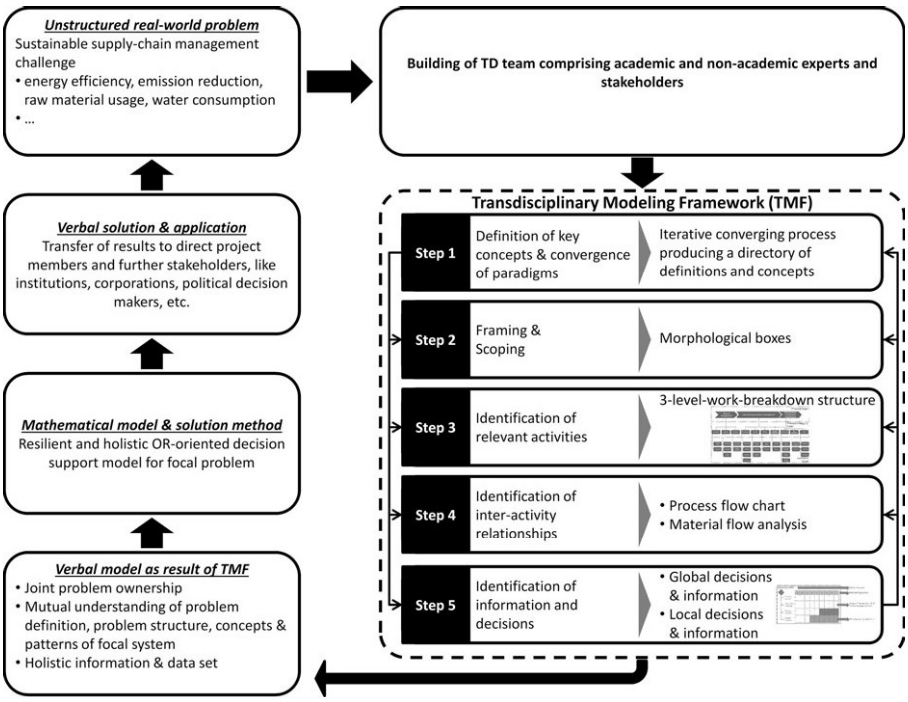
As TDR is rather a paradigm than a concrete research methodology, one major challenge is the actual implementation of such projects. We provide a framework for collaboration regarding a certain subset of problems that consider OR projects dealing with SSCM. As detailed approaches on TDR for such instances do not exist, the TMF is developed inductively based on experiences in academia and practice.

Methodological development of TMF

The steps that constitute the proposed framework based on a theory building methodology presented by Wacker (1998), which is applied to the specific characteristics of SSCM research in transdisciplinary organizations. The methodology is appropriate for TDR as it aims on turning knowledge into a visualized model enabling people to understand vague and nonexplicit perceptions. This is done by developing a conceptual model which is defined as "a mental model of deduced relationships [...], which may then be evaluated using a framework that captures the essence of the systems under investigation" (Wacker 1998, 373). Conceptual models are part of the soft OR methodology (Checkland 1999; Pidd 2008). Soft OR assumes that the "problem definition is not straightforward, but is itself problematic" (Pidd 2008, 108). These kinds of models are used to analyze unstructured problems, capture people's perceptions and interpretations of a certain system, and eventually detect feasible and desirable changes. Consequently, the corresponding methods strive for revealing disagreements and uncertainties. Based on these insights, dialogue, consensus, and commitment among all stakeholders are facilitated and finally the convergence of perceptions and interpretations of a problem should be reached (Pidd 2008). Regarding mathematical modeling, the TMF contributes to thoroughly identifying the key elements that constitute modeling (Pidd 2008): Boundaries (Step 1 and 2), components (Step 3), internal organization of elements, and behavior of elements (Step 4 and 5).

The TMF (see Figure 2) uses an ordered sequence of five process steps encompassing (Step 1) definition of key concepts and convergence of paradigms, (Step 2) framing and scoping, (Step 3) identification of relevant activities, (Step 4) identification of interactivity relationships, and (Step 5) identification of

Figure 2: The transdisciplinary modeling framework embedded into research cycle.



information and decisions. We also propose an appropriate repertoire of methods to be deployed in each step. In order to identify those methods, we reviewed existing and well-acknowledged methodologies that support the goal of mutual learning and knowledge integration. We implement simple and well-known methods wherever possible. Such methodologies are more successful than complex ones (Okhuysen and Eisenhardt 2002). Also, practitioners generally tend to rely more on known methods, which leads us to concentrate on established methods in order to facilitate transferability to practice. Regarding each method, we basically asked the key questions articulated by Bammer (2008, 885): Is the method effective? Would other methods make useful contributions? The methodologies are selected due to their ease of use as well as to their ability to translate knowledge and perceptions into images of reality.

In order to put the TMF into a broader context, we embed it into a research cycle that is adopted from the TDR cycle presented by Jahn et al. (2012). Therefore, the TMF can be seen as a refinement of the knowledge generation process. The framework supports TDR teams to reach an agreed understanding of the problem. Ultimately, this may result in an OR model that represents the problem at hand more accurately and holistically than present examinations frequently do. Accordingly, the components of the research cycle in Figure 2 correspond to the problem-solving process previously depicted in Figure 1.

Structure of TMF

Although the TMF consists of five chronological steps, recursions are regularly needed within a project as information and decisions on later stages of the process require a readjustment of preceding steps. The five steps are generically described in the following.

Step 1 and Step 2 serve the purpose to develop a mutual fundament for understanding. The proposed methodologies help to delineate the perceptions of each discipline regarding the overall topic and help to converge their interpretations eventually. This is an essential prerequisite for all succeeding steps and for the research project as a whole. Step 3–5 provide methodologies to capture the decentralized knowledge regarding more detailed elements of the system in a structured manner. These three steps are hierarchical as the results of the preceding step are used as input for the succeeding ones.

Step 1

Participants of a TDR project team origin from various disciplines, which implies divergent understandings, mindsets, and paradigms. In order to address this heterogeneous situation and to generate a basis for collaboration, it is crucial to agree on key concepts. Here, we identify two major tasks. First, fundamental terms and concepts need to be identified. In a structured and facilitated process, relevant terms and concepts are named in a brainstorming session without discussion of individual perception or understandings of these concepts. The advantages and reasons for such an approach can be traced in Keeney (2013). Second, terms and concepts are defined for the purpose of the project. They are articulated from a single-discipline view using a Delphi approach. The Delphi methodology is helpful within TDR projects as it is used to gather unknown information, identify relevant concepts, exposing personal values and, a fortiori, is used to reveal patterns of complex issues (Linstone and Turoff 2002). Okoli and Pawlowski (2004), who give a detailed guideline for conducting rigorous Delphi studies, also name identification of theoretical perspectives, identification of relationships, defining constructs as well as creating a common language as major application fields for Delphi methods. These characteristics match the purpose of the present framework. Within the Delphi process, perceptions and definitions are articulated in isolation under supervision of a facilitator, who should pay special attention on translating tacit and implicit disciplinary knowledge into explicit knowledge. This way, disciplinary differences are detected, which lays the ground for an iterative converging process. Ultimately, the agreed content should be recorded in a directory of definitions and concepts that represents a basic document for the project.

Step 2

The participating researchers have to agree on the domain of the TDR project by defining the focal system. The perceived structure of a problem is usually dominated by values, ideologies, and believes of participants (Climaco and Craveirinha 2010). Accordingly, problem identification and structuring are fundamental within a TDR project (Campbell 2005). Therefore, it is important to introduce a methodology that depicts all perspectives and makes them transparent. Based on this transparency, the mutual problem framing can be done. Framing aims on defining a holistic picture that broadly characterizes the focal system. Tackling this, a morphological box is developed. The dimensions of the box reflect certain characteristics and according attributes of the system representing the frame of the issue. To develop the box, we propose a thorough review of discipline-specific literature regarding the topic at hand supplemented by expert discussion. This way, dimensions and attributes are derived based on disciplinary classification frameworks and individual expertise. Further dimensioning can be done pertaining to industrial structures, drivers of the development (e.g., legal, economic, or sociocultural developments), corporate structures, relevant stakeholders, and industry players, or the kind of considered goods. Overall, the integrated morphological box serves as a platform for discussion. On one hand, this approach certainly urges agreement on the respective content, which sometimes necessitates iteration of Step 1. On the other hand, the mutual discussion reveals relevant aspects of the problem and shows where borderlines can be drawn and how dimensions interact with each other. Consequently, the frame of the focal system is delineated and delimiting attributes that describe each dimension are named. Based on that, the scope of the project and its overarching goal is defined. In sum, collaboration enables to define more precise system characteristics and according boundaries.

Step 3

A work-breakdown structure decomposes the complex problem into manageable activities. This way, relevant processes and more granular activities of the assessed system are identified. We propose disaggregating within a three-level hierarchy, as it regularly produces a good degree of detail. A well-known example for such a decomposition approach is the Supply Chain Operations Reference model (Poluha 2007). The first level depicts processes that are highly generic and show a low degree of detail. As the application of the TMF aims on SSCM issues, the processes may be adapted from generic supply chain structures, like the “value chain” (Porter 2004) or the “supply chain planning matrix” (Fleischmann et al. 2005). The degree of granularity rises with the decomposition level, which means that the identified elements are becoming more context specific. Therefore, the processes are resolved to subprocesses, which are eventually fractionized to activities. While the process level and partially the subprocess level can be deduced from generic structures, the activity level should be worked out individually for the focal system. The activities depicted at the bottom layer of the hierarchy are used as input for both Steps 4 and 5.

Step 4

Complex systems are characterized by interdependencies and feedback loops between activities. Within an SSCM environment, these interdependencies dominantly exist along the flow of materials. Therefore, a first substep comprises the depiction of the generic process flow resulting in a flow chart that depicts an ordered sequence of activities. Thereby, a first hint on interdependencies between activities is given as this methodology puts the activities into a mutual context by means of an organizational and temporal order. In a second substep, the quantitative input—output structure is determined. Here, we propose to enrich the process flow by technology-specific substance flow analysis. This methodology aims on the delineation of a system through reduction of complexity and gives a comprehensive picture of such systems (Bouman et al. 2000). Substances comprise all inputs and outputs ranging from material, energy, emissions, and wastes. Smith and Ball (2012) give an extensive and valuable example for using substance flow analysis in analyzing production systems including qualitative and quantitative data. They also provide guidelines that steer the derivation of a substance flow model. The resulting set of equations and functions represents input—output relations between and within activities. As the substance flows depend on technological choices and process parameters for conduction of each activity, the flow charts have to be determined for each choice individually, which enables calculating different scenarios later on. In addition, especially in SSCM examinations, the substance flow analyses should be complemented by eco-balancing. This is important information for further ecological assessment and should be attached to every single activity as well as to the overall system. Lambert et al. (2011) provide an example of process maps for CLSC operations concentrating on the flow of recoverable goods. Various attempts exist to integrate ecological perspectives into flow analyses of techno-economic systems (Torres and Gati 2009; Paju et al. 2010). Faulkner et al. (2012) add societal examinations to technical, economic, and ecologic ones. Based on the flow charts, variations of the flow are assessable in further analysis. At this point, the relevant activities and their interdependencies are revealed and a number of relevant information is gathered.

Step 5

This step allocates information and decision requirements to certain parts of the system. A major part of knowledge integration takes place as the information from all participating disciplines is merged. It comprises the identification of unknown but relevant information, which are qualitative and quantitative in nature. A transdisciplinary perspective is needed as the relevant information is often, especially in sustainability examinations, uncertain and the measurement of these data is questionable. In many cases, specific metrics have to be developed (Faulkner et al. 2012). In addition to expertise from team members, the National Institute of Standards and Technology (www.nist.gov) or Reuter et al. (2005) provide a useful list of potential sustainability metrics. We distinguish local and global information. Latter are exogenous factors, like legislations, or general patterns that affect the system as a whole, for example, societal trend that drives product backflows. Local information refers to one activity only and is mostly depicted as input−output relations. Hence, the project team should examine the system as well as its activities from each discipline's perspective. This way, all potentially relevant influencing factors and parameters are gathered. By matching the known with the unknown information, the information gaps are identified. These gaps are allocated to certain disciplines or groups of disciplines, which are responsible for obtaining information or are in charge of formulating resilient assumptions. The same procedure is conducted to identify potential decisions within the system and their interdependencies with certain parameters. Here again, the distinction between local decisions on the activity level and global decisions on the subprocess level is made. The upfront decision in favor of a certain recovery option in a CLSC system is an example for a global decision that impacts many operations and the area of decision making in several aspects of the system. By conducting Step 5, the elements of the objective function and restrictions are defined and influenceable mechanisms are brought in focus.

Discussion of TMF

"Transdisciplinarity arises only if research is based upon a common theoretical understanding and must be accompanied by a mutual interpretation of disciplinary epistemologies" (Gibbons et al. 2010, 29). Contrasting this, the goal, the techniques that should be applied as well as the input that is required from each discipline in TDR are not clearly defined (Stauffacher et al. 2008). The TMF resolves this discrepancy as its overall goal is the development of a mutual understanding among all participants regarding the project content and the required commitment of each stakeholder. The structured methodology facilitates the integration of stakeholders in the crucial processes of problem definition, objective, and criteria determination (Klein 2004). Klein (1996) emphasizes the context-specific negotiation of key terms and project content which is mediated through conduction of the TMF. It forces the participants to operate at different levels of abstraction that facilitate dialogue in potentially conflicting situations through a formal structure. Hence, the procedure results in an agreed interpretation of the problem.

The results of Steps 3 and 4 support understanding and communication as they are used "to better understand the "functioning" of the system under study" and give an image of the system (Baumgärtner et al. 2008, 391). It serves the purposes of explanation, prediction, and decision support. Bergmann et al. (2012) describe the process of developing the research goals as "drawing" the boundary object. This is what we literally propose within the fourth step by drawing the material flow and balances. Accordingly, Pidd (2008) emphasizes the importance of graphical representation of the investigated system. The overall intention of the framework is the acquisition and presentation of information in a structured and logical process for the purpose of quantitative examination of an SSCM system. Step 5 supports deriving a mathematical model in terms of objective function and restrictions by delineating areas of decision making and influencing factors.

By integrating the TMF into the TDR cycle, a broader picture and holistic approach to TDR projects is given. Generally, the framework developed for TDR settings can also be "downscaled" to research settings that are classified as multidisciplinary or interdisciplinary (Huutoniemi et al. 2010).

DEMONSTRATION CASES

We demonstrate the utilization and benefits of the TMF regarding the holistic modeling of SSCM systems by means of two cases. Although both deal with SSCM issues, the two cases show significantly different characteristics. Hence, the implementation to both cases demonstrates how the generic structure enables a broad application of the TMF to OR-related research settings and how the TMF enables to reach in-depth representations of a focal system.

The first demonstration case relies on experiences that we gain through participation in an interdisciplinary research group granted by the Bavarian State Ministry of Education, Science and the Arts. It deals with strategic resource concepts for sustainable energy systems. This institution unites several research teams from the natural science department, engineering department, and business department as well as further experts with geological, geographical, and sociological sciences background. The integration of practitioners evolves from projects with industry partners that are conducted by the adjacent "Material Resource Management" institute.

The second case deals with the planning and control of a CLSC system in the plastics and polymer industry, which represents a common application area for OR methods. Sahamie et al. (2013) underline the importance of TDR settings for appropriately tackling CSLC challenges. The authors give an in-depth discussion of the relevant disciplines and the knowledge that can be derived from each one. Generally, the corresponding planning and management problems deal with issues that require specific knowledge about material, technological, and economic aspects. This demonstration case is based on expertise that emanates from collaboration with engineering sciences, material sciences, informatics, and management sciences as well as from collaboration with corporate decision makers that are involved in product recovery and reprocessing operations.

Strategic resource management for sustainable energy systems

The working group deals with the topic of strategic resource concepts for sustainable energy systems. Apart from a pure economic assessment, technical feasibility, overall ecologic effects, social burdens, and innovation trends should be integrated into such an analysis. Accordingly, the research team comprises experts from natural sciences, management sciences, geography, geology, environmental sciences as well as experts from studies on resource management. Apart from the academic assessment, further knowledge from outside academia is required, for example, from NGOs and politicians that give insights into societal trends and into the feasibility of certain plans regarding their societal and political acceptance. In the following, we exemplify how the TMF supports the goal formation and the development of a mutual understanding as well as how it provides a comprehensive approach to problem solving.

Steps 1 and 2

At the beginning, apart from the lack of a mutual language, an overarching goal has to be derived from the fuzzy topic. Following the TMF, we develop a morphological box that unites the different understandings and perspectives on the topic (see Figure 3). It becomes obvious that the perception regarding sustainable energy systems varies widely among disciplines. While the management scientists are majorly aware of financial and economic effects of energy supply, other disciplines provide additional dimensions regarding environmental burdens, societal trends, and social factors to the discussion. Key questions range from "What is meant by the term energy system?" to "How can a sustainable energy system be characterized and what are appropriate metrics?" For instance, the term "energy system" is unclear as it may comprise supply, transmission, storage, and energy demand. After agreeing on assessing long-term energy supply systems, another topic for discussion concerns the focal energy supply sources. Here, all supply systems, fossil-based, advanced fossil-based, and renewable systems, are considered and further distinguished in subcategories. Knowledge about potentially critical materials (e.g., dysprosium, rare earth elements), which may pose future bottlenecks as well as societal and environmental issues are integrated into the analysis. The challenge of rising energy demand and technological limitations due to scarcity of functional raw materials is defined as a distinctive focus of the project. Overall, the working group sets the scope of the project by using the morphological box (see Figure 3) resulting in the following research question:

> *Define a mix of energy supply technologies that suffices economic, ecologic, and societal efficiency in the long-run considering the whole life cycle of focal technologies at the same time.*

Step 3—Identification of relevant activities

In accordance to the TMF, an identification of relevant activities is made by means of a work-breakdown structure (see Figure 4). The generic processes are derived from an approach named "Material pathways," a methodology that depicts material life cycles, which is commonly used by resource strategists (Achzet et al. 2011). Five relevant processes describe the value chain for each energy supply technology: Mining, refining, production, usage, and recovery. A distinction between partial value chains for raw materials and for technologies is necessary. This means that partial value chains for each relevant raw material consisting of the processes of mining and refining are developed. Accordingly, we define value chains that comprise production, usage, and recovery for each technology. In a subsequent step, technology value chains are connected to corresponding upstream raw material value chains based on the technology's bill of materials. A more detailed view on distinct value chains is achieved by decomposing generic processes to technology-specific activities and operations.

Step 4—Identification of inter activity relationships

Afterward, a flow chart for each raw material and technology is developed. Here, the activities that are identified within Step 3 are used. If a raw material is used for the production of a technology, the raw material flow chart and the technology flow chart are connected. Finally, this structure gives a starting point for the eventually developed OR model and helps to identify areas of disciplinary and interdisciplinary input. These first results of the TMF are formalized by means of a descriptive mathematical model (see excerpt of model in Table 2). This prototype integrates all perspectives, depicts relevant interdependencies, and serves as a basis for discussion.

The objective function minimizes economic (2, 3, 5), ecologic (5), social (4), and societal costs (7) that are induced by the respective energy supply mix. Thereby, it determines the installed capacity p_t [kW] per each supply technology (1). Relevant constraints are about the minimal supply requirements, base and peak loads, maximal risk of supply disruption, maximal acceptable violation of social standards, etc. Regarding the multicriteria

Figure 3: Morphological box for future energy systems (excerpt).

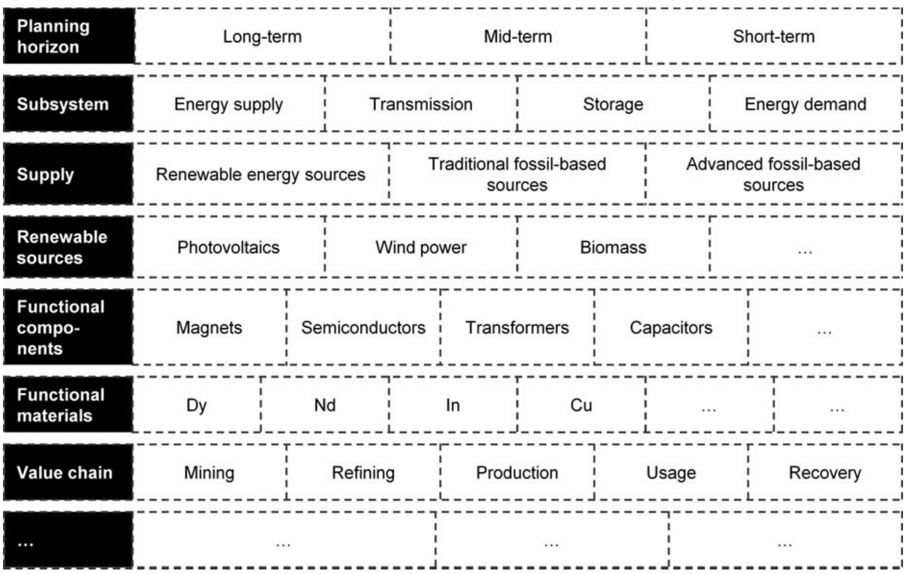


Figure 4: Simplified work-breakdown structure for energy supply technologies.

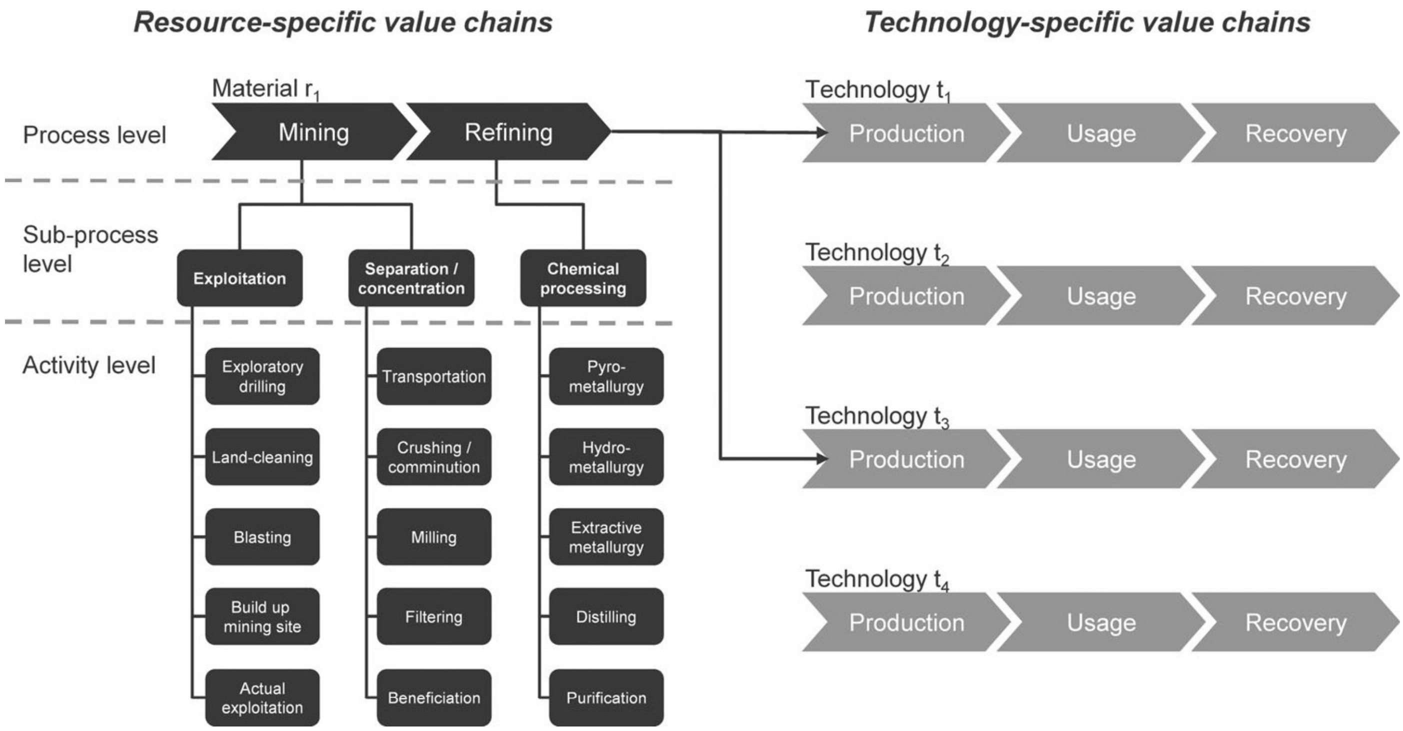


Table 2: Descriptive mathematical prototype (excerpt)

Objective function	Description	Leading discipline	
$\sum_{t=1}^{T} p_t($			(1)
$\alpha \cdot \sum_{r=1}^{R} C_r \cdot q_{r,t} + C_t$	Material and manufacturing costs	Management Sciences, Engineering	(2)
$+\beta \cdot \sum_{r=1}^{R} i_r \cdot q_{r,t}$	Risk of raw material availability	Geology, Resource Strategy	(3)
$+\gamma \cdot \sum_{r=1}^{R} (S_r^m \cdot q_{r,t} + S_r^r \cdot q_{r,t})$	Violation of social standards	Resource Strategy, Sociology	(4)
$+\delta \cdot \sum_{r=1}^{R} (e_r^m \cdot q_{r,t} + e_r^r \cdot q_{r,t}) + e_t^p + e_t^u$	Emissions in mining and refining, production, and usage	Geology, Environmental Sciences, Physics, Chemistry	(5)
$+\varepsilon \cdot d_t$	Spatially and temporal risk of supply disruption	Geography	(6)
$-\vartheta \cdot g_t \ldots$	Societal acceptance	Sociology, Politics	(7)

Notes: t, technology t of index T; r, raw material r of index R; p_t, installed capacity of technology t in kilowatt (kW) per hour; c_r, acquisition price for raw material r; $q_{r,t}$, quantity of raw material r needed for production of 1 kW installed capacity of technology t; c_t, costs for manufacturing of 1 kW installed capacity of technology t; i_r, risk rate i for raw material r; S_r^m, rate of social standards violation s in mining of raw material r; S_r^f, rate of social standards violation s in refining of raw material r; e_r^m, emission e in mining of raw material r; e_r^f, emission e in refining of raw material r; e_t^p, emission e in production of technology t; e_t^u, emission e in usage of technology t; d_t, risk rate d for supply disruption of technology t; g_t, rate of social acceptance g of technology t; α, β, γ, δ, ε, ϑ, weighting factors.

objective function, we see certain areas for mutual discussion. On one hand, the weights (α, β, γ, etc.) within the decision model have to be determined. This task hits the discourse on sustainability at its heart as it deals with the balancing of the triple bottom line. On the other hand, certain parameters within most parts of the objective function have to be developed, including metrics and approaches for measurement. We note that these parameters may result from functions, which are not necessarily linear. Especially standardized metrics, like the availability risk rate r_r or the social acceptance ratio g_t, leave room for discussion. Regarding the availability risk rate, first results are documented in Achzet et al. (2011) and Achzet and Helbig (2013).

Step 5—Identification of information and decisions
This step concentrates on gathering relevant information and determination of potential decisions. Former mainly concerns the determination of parameter values used in the mathematical model. The eventually used information in the quantitative model is high level, mostly on the process level. Nevertheless, the data are acquired on the more detailed level of activities. These granular data are subsequently aggregated to certain input parameters for the model. This way, it is possible to gather relevant parameters regarding mining, refining, production, usage, and recovery in accordance to their source. These data can be classified as local information as they are attached to distinct activities. Global information is mostly used in the set of constraints (e.g., minimal supply requirements, peak loads, maximal risk of supply disruption). As a consequence of this data gathering procedure, the data basis is traceable, reliable, and comprehensive. Moreover, it is possible to assess the influences of certain activities regarding performance measures on different hierarchical levels.

The area of decision making is given by the index of supply technologies. It is to mention that the term supply technology is understood in a very detailed way. For example, we do not only distinguish between photovoltaics and wind power, but also differentiate variations of either photovoltaic or wind technology. As the project is long-term oriented, we also take innovative technologies, for example, based on materials that are in laboratory stage, into consideration.

Summing up, we exemplify how the TMF supported the project team in revealing the diverging perspectives on the topic and in developing a descriptive mathematical model that enables the integration of participating perspectives and definition of subordinate working groups. Moreover, the structured approach of identifying certain operations, interrelating them, and assessing them regarding input–output relations supports a reliable gathering of data independent of the disciplinary focus.

Assessment of a CLSC in the plastics and polymer industry

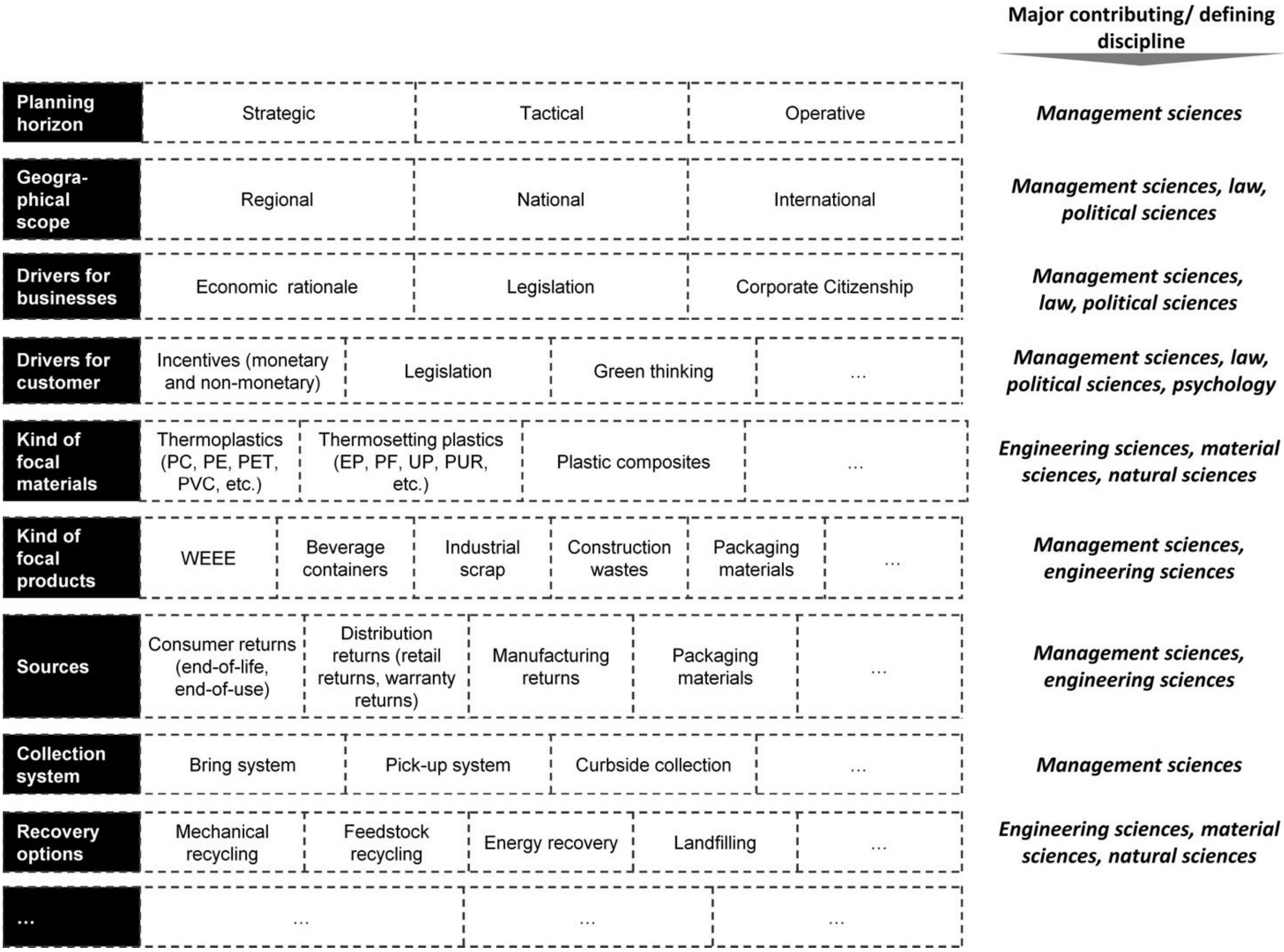
CLSCs are "sustainable supply chains almost by definition" (Quariguasi Frota Neto et al. 2010, 4463) and are a major enabler for implementing sustainability in production systems. In addition, CLSC research is already moving toward collaborative research (Agrawal and Toktay 2009) as circular systems show an increased complexity and additional uncertainties compared to traditional supply chains. This makes TDR approaches even more suitable.

Step 1—Definition of key concepts and paradigms
Within the first step of the project, a mutual understanding of key concepts is developed. A striking example of diverging perceptions is the wording and understanding of the terms recovery, recycling, and adjacent concepts. They require clarification as a broad spectrum of definitions on recovery options exists. This matches the observation of Stindt and Sahamie (2014) who show that central concepts of recovery are not adequately defined even within the single-discipline business literature. The same holds true among participating researchers in our projects. For instance, management scientists commonly refer to the recovery options presented by fellow researchers like Thierry et al. (1995) or de Brito and Dekker (2004). These concepts are hardly transferable to continuous goods recovery because they pertain to discrete goods that consist of components and modules. Hence, we need to redefine recovery options in order to match the requirements of plastics and polymer reprocessing. Throughout a brainstorming session, terms and understandings from each discipline regarding the definition of central concepts, for example, the definition of recovery options, are collected in a long list and the corresponding perceptions are recorded. Throughout the subsequent Delphi process, it was possible to converge the understandings and to develop a mutual basis for communication. It proved that the agreed definitions are very close to the recovery options for continuous goods (e.g., tertiary or chemical recovery), which are common in engineering sciences. Apart from the recovery options, manifold other terms need clarification. Some of them are mentioned in Figure 5 in form of dimensions and attributes. Indeed, we could observe that those terms and concepts derived from the collaborative project are hardly considered in this depth in management sciences literature. Finally, the agreed terms and concepts are documented in a central directory which is distributed among all team members.

Step 2—Scoping and framing
In order to define the frame and domain, we develop a morphological box mainly grounded on insights from Step 1, enriched with findings from discipline-specific literature, like Steven (2010), Stindt and Sahamie (2014), Schultmann et al. (2006), and Brandrup et al. (1996). In addition, the Reverse Supply Chain Planning Matrix, a generic planning structure for recovery operations, which was developed within a TDR project, is used for further refinement of the problem (Nuss et al. 2015). Eventually, a broad multifaceted picture of the topic of plastics recovery is provided, comprising certain dimensions of the problem and the according attributes. These initial boxes are integrated and discussed. The resulting morphological box provides a frame of the field of interest and enables users to delimit the research topic along the dimensions. Certain attributes of each dimension may be considered or ignored throughout the project. An excerpt of the resulting morphological box is exemplified in Figure 5. In addition to overall practitioners input, the academic disciplines that majorly contribute to certain dimensions or define attributes within the according dimension are presented.

Step 3—Identification of relevant activities
After defining key concepts, converging paradigms as well as setting a scope, the project turns an eye on the more detailed structure of the system. Hence, relevant operations are identified within a three-level hierarchical structure. Figure 6 shows an excerpt of this structure that delineates the process of reprocessing operations. The processes at the top equal the processes that we find in the Reverse Supply Chain Planning Matrix (Nuss et al. 2015). As stated earlier, the granular activities are industry sector specific. For instance, compacting or the overall reprocessing operations are typical for continuous goods recovery. Further clarification of terms is needed as, for example, the operations of separation and sorting cause some ambiguity. This represents an iteration to Step 1. Separation describes the process of splitting different material groups, like plastics, metal, and glass. Sorting denounces further differentiation between materials within one group, for example, sorting out polyvinyl chloride from a mixed

Figure 5: Morphological classification scheme (excerpt).



plastics stream. Other operations are more generic like disassembly or storing.

Step 4—Identification of interactivity relationships
Subsequently, all operations detected throughout the hierarchical structure are put into an organizational and temporal order by means of a substance flow chart (see Figure 7). Activities are depicted as rounded boxes. Resulting states of material are drawn as rectangles and arrows represent flow of substances, including the focal material, by products, wastes, and emissions.

Energy, water, and other substance flows enter the model through a detailed look into the single operation nodes as these flows are connected to them and depend on the implemented technology and its modes of operation. This information has to be gathered for every single node subdivided for each potential technology and according modes. This task primarily gathers knowledge from engineers as well as natural and environmental scientists who evaluate emissions and harmful coproducts of each operation. Considerable knowledge about real-world patterns of operations is given by practitioners. Further understanding of the overall system patterns among all participants can be emphasized by factory visits or other real-world observations. Depending on focal aspects of the system, certain input should emanate from other disciplines, like law, sociology, or political sciences. Accordingly, further information, like legislative requirements regarding minimal yield or maximal permissible values, enter the chart. Overall, the flow chart enables project teams to develop a mutual and visualized map of the system comprising interdependencies.

Step 5—Identification of relevant information and decisions
The flow chart is supplemented by assigning missing information ("I" in Figure 7) and decision alternatives (rhombuses in Figure 7) to distinct areas of the map. Relevant information may range from the amount of recoverable goods, composition of return flows, yields of operation units, potential technology choices, use of auxiliary supplies to working materials, and input−output relations. The latter depend on the implemented technology in each node and the according modes of operations. Those modes impact important aspects of the system regarding yields, emissions, wastes, and by products. Hence, we use a coefficient matrix or mathematical functions for every potential

Figure 6: Simplified work-breakdown structure for plastics and polymer recovery.

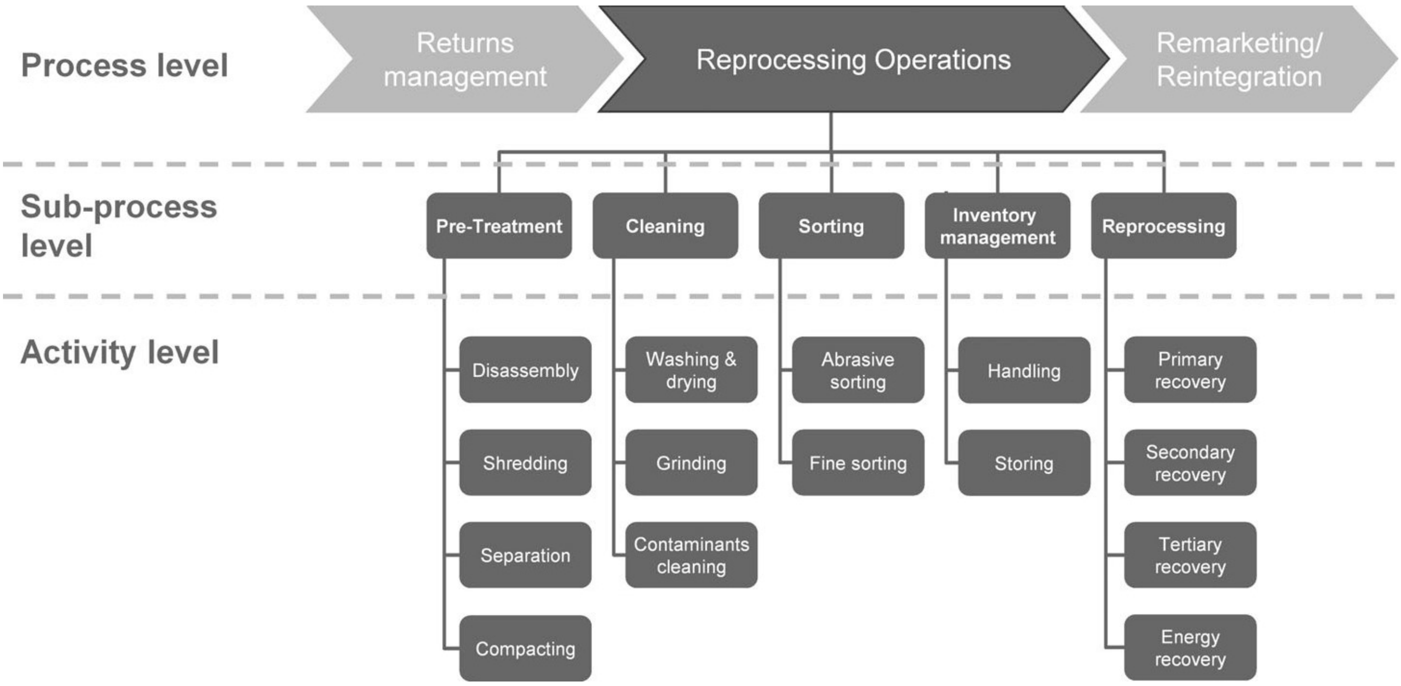
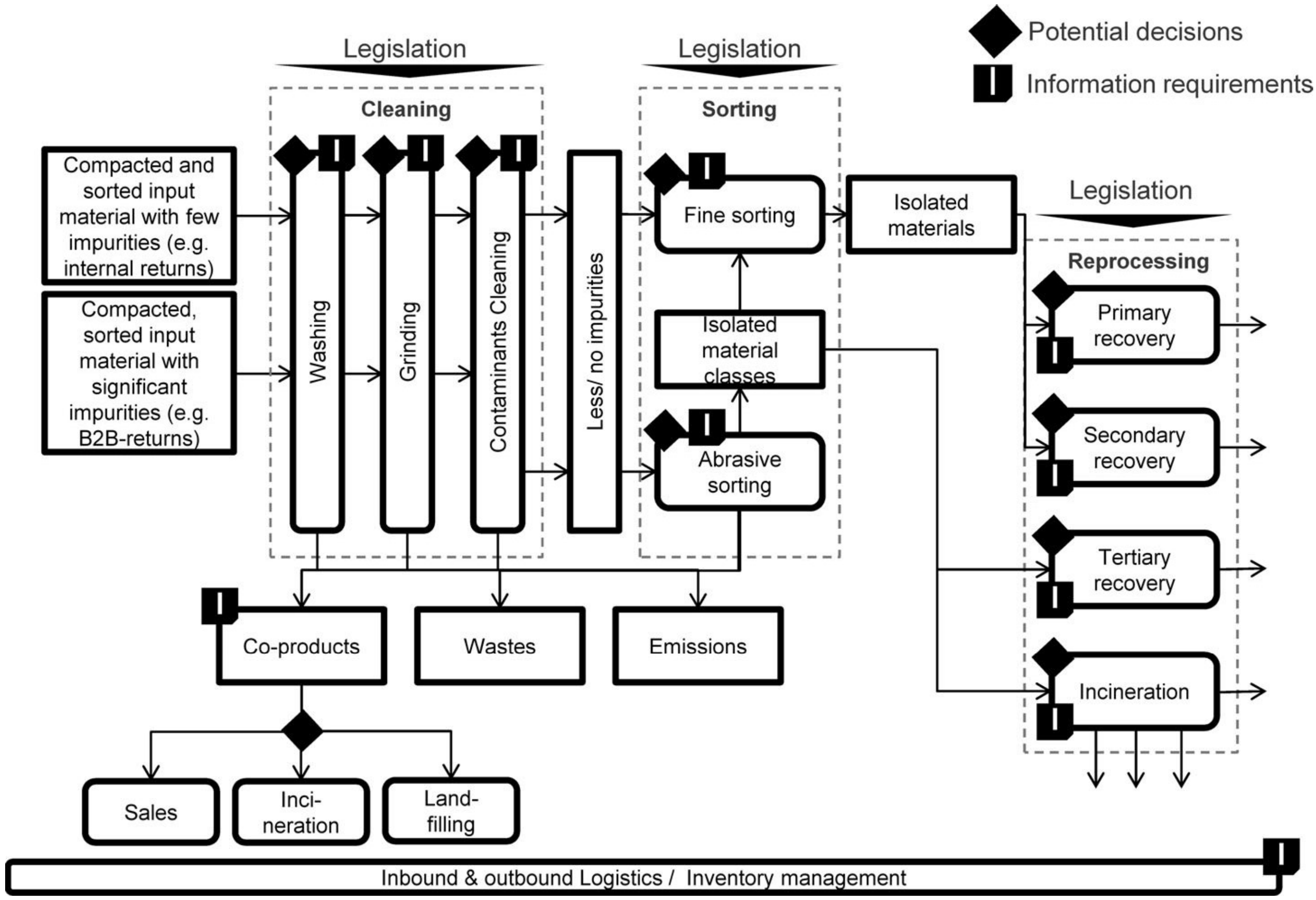


Figure 7: Substance flow chart (excerpt).



technology that provide information about input–output relations. Much of this information is not instantly available. Certain nodes require further research or qualified assumptions from according disciplines. Figure 8 provides an example for in-depth analysis of a single node. Local information regarding the input flows has to be determined considering quantity and quality depending on preceding activities. Moreover the output flows are determined by means of mathematical functions, which depend on the respective technology and the respective operating procedure (mode and process parameters). The local decisions within this excerpt are about selecting the most efficient technology and mode, aiming on balancing economic and ecologic dimensions. Especially the involvement of practitioners and technically oriented disciplines may avoid some common pitfalls of pure management scientists' assessment. Prominent examples are the modeling of simplified linear relations instead of nonlinear production coefficients and consideration of variations of yield and lead time depending on quality and mixture of reprocessed goods (Schultmann et al. 2004).

Further areas of decision making are determined by rhombuses within the flow chart. Here again, we differentiate between local decisions and global decisions. For each decision, a decision card is designed which is derived from the detailed substance flow analysis (see Figure 8). These cards subsume the topic of decision, the potential choices on the vertical axis as well as the influence of each choice on other areas of the system. Both preceding and succeeding operations are enumerated on the horizontal axis.

Summing up, based on the insights generated through the TMF approach a technology path is derived, which connects decisions regarding one technology to other decision areas (Figure 9). This way, we reveal which technology combinations are generally implementable and which combinations may eventually enable to reach a certain goal. As the TDR-oriented approach of the TMF integrates knowledge from multiple disciplines and backgrounds, the technology paths are fully assessable regarding economic, environmental, or legislative factors. Moreover, the continuous involvement of practitioners guarantees that the derived decisions are not just theoretically possible but also practically feasible.

Discussion of cases

Up to this point, we could demonstrate the application of the TMF to two cases that stem from the broad field of SSCM. As these cases show significant differences, they underline the value of the TMF as a generic methodology for collaborative SSCM problem solving. Table 3 gives an overview regarding major differences between the projects as well as the specific contribution of the TMF to each project.

First of all, *major drivers* that necessitate a TDR organization differ. In the first case, translating the sustainability paradigm into concrete measures and implementable goals poses a major challenge. Here, we experienced that fundamental definitions and the general structure of the energy system as well as influencing factors that impact the achievement of project goals are highly disputable or even unclear in some cases. Contrasting this, the overall patterns of the system are basically known within the second case. Here, domain experts are needed as the main uncertainty stems from the side of adequate parameter definitions and proper data acquisition. In addition, each problem structure requires a varying number of *involved disciplines* which show a problem-specific level of heterogeneity. Due to these project characteristics, the *fuzziness* is perceived as high in Case I and as medium in Case II.

Implementation difficulties concerning TDR are strongly connected to the observed problem fuzziness. In Case I, challenges regarding problem understanding, aims, and preferred solution approaches widely vary among the participating project stakeholders. Accordingly, disputes arise concerning fundamental definitions, goals formation as well as assessment and measurement methodologies. Within the second case, the involved researchers quickly agreed on the overall patterns of the focal system. In addition, the usage of quantitative modeling techniques is common for all participants. Hence, the challenges inherent to the first case are less crucial within Case II. The difficulties rather arise regarding the definition of the relevant system boundaries (e.g., which technology choices need to be included in the examination) and regarding the depth of relevant data. Especially the trade-off between very granular data requirements demanded by

Figure 8: Deduction of decision cards from local information and decisions.

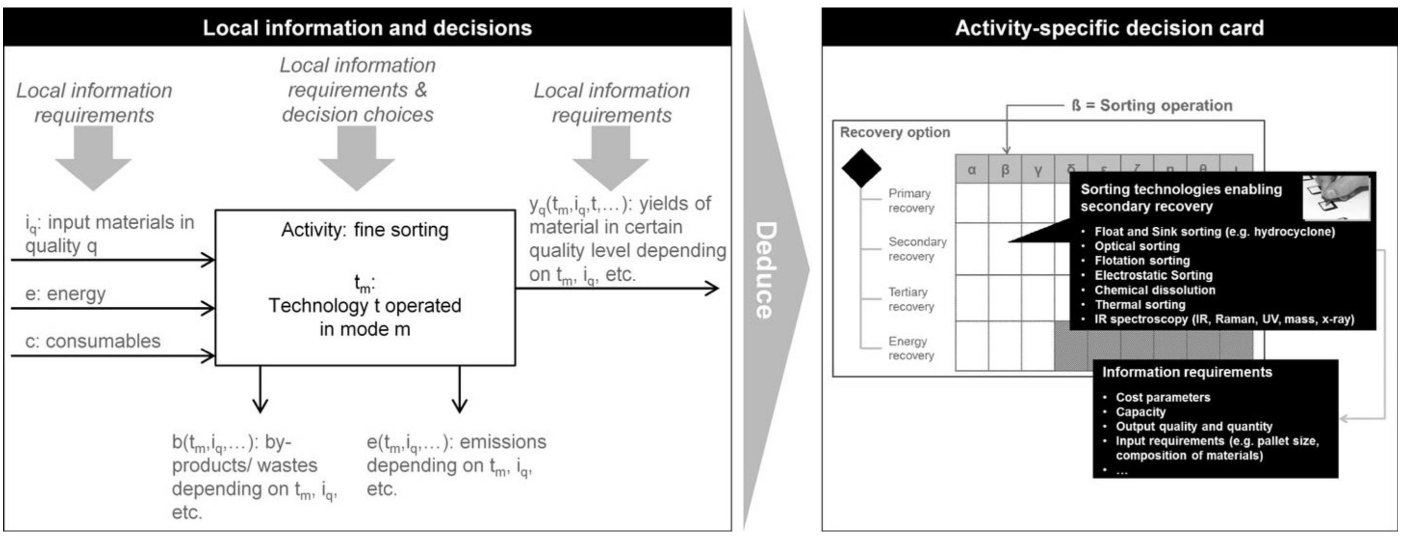


Figure 9: Interconnected technology path.

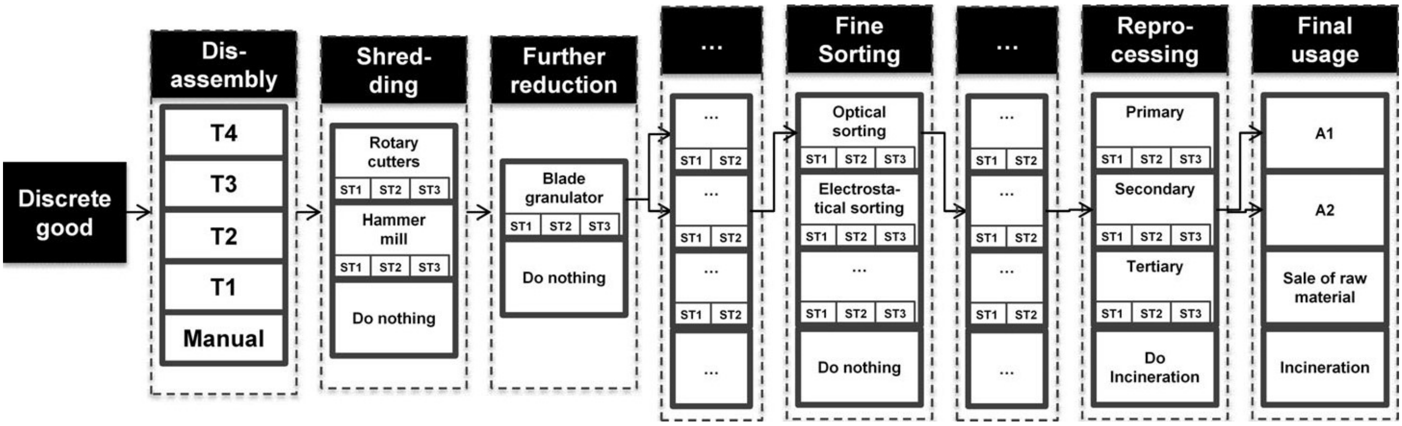


Table 3: Comparison of case studies

	Case I: "Strategic Resource Management"	**Case II: "CLSC in the plastics and polymer industry"**
Major drivers for TDR project organization	Uncertainty regarding definitions and disciplinary perceptions of context-specific sustainability	Data uncertainty: Quantity, quality, and timing of product returns and reprocessing yields
Involved disciplines	Management sciences, engineering sciences, natural sciences, material sciences, environmental sciences, geology, geography, sociology, communication sciences, political stakeholders, corporate experts	Management sciences, engineering sciences, natural sciences, material sciences, computer sciences, corporate experts
Problem fuzziness	High	Medium
Sources of implementation difficulties	Differences in problem understanding and preferred solution approaches	Definition of system boundary and granularity of both examination and data requirements
Major contribution of TMF	Identification of problem structure, mutual problem understanding and goal formation	Adequate definition of parameters and according data acquisition as well as identification of cause-and-effect relationships
Improvements of OR model	General structure of objective function and restrictions	Appropriate definition and instantiation of parameters
Users of results	Political decision makers and according economies	Industrial corporations

Note: CLSC, closed-loop supply chain; OR, operations research; TDR, transdisciplinary research; TMF, transdisciplinary modeling framework.

natural scientists and more manageable data sets requested by management scientists became obvious.

The *major contribution of the TMF* to the project corresponds to the respective implementation difficulty. The TMF enabled stakeholders to mutually define the problem and its characteristics in Case I. This way, a common understanding of sustainability in the context of renewable energy systems was developed. Regarding the second case, the TMF supported the participants in setting influencing parameters and gathering reliable and valid data. In terms of *improving the respective OR models* within the first case, the general structure of the multicriteria objective function and relevant restrictions are derived from a systematic approach that was guided by the TMF. The main challenge of Case II corresponds to data issues. Here, the TMF helps to overcome discipline-dependent biases in data acquisition and the use of over simplifying assumptions. This ultimately increases the transferability of results to the real-world problem. These results are eventually utilized by diversified *users*, depending on the case at hand.

Summing up, both cases well illustrate how the TMF supports the process of agreeing on goals and patterns of a problem, which "is perhaps the most significant contribution an operational researcher can make" (Eden and Ackermann 2013, 9). It helps "becoming aware of important feedback mechanisms that would not be discovered if the approach of each discipline was presented in isolation" (Krehbiel et al. 1999, 186). Based on our experiences, the TMF leads to improvements regarding both general aspects of collaboration (e.g., shared problem ownership, mutual language) and OR-based decision making (e.g., goal formation, data validity). The two projects show significant differences regarding their key characteristics (see Table 3), which illustrates the applicability of the TMF to a wide variety of problems in SSCM.

CONCLUSION AND FURTHER RESEARCH

The TMF helps to overcome the stated shortcomings of OR. It provides a methodological framework for structured collaboration of

TDR teams facing problems in SSCM. As SSCM can be seen as a subdiscipline of SCM, we believe that the proposed framework would be also beneficial in this broader research field. In line with the suggestion of Baumgärtner et al. (2008), the framework includes both forms of modeling: Generic modeling that can be applied to a large number of different systems. At the same time, it provides the flexibility to implement structures that represent a specific application case. Hence, the framework connects a structured and rather abstract generic model with distinct methodologies for case-specific implementation. We believe that the TMF is highly viable for practical usage as it relies on known methods that show a high ease of use. We could prove the practicability and benefits within the demonstration cases that integrate researchers and practitioners from different backgrounds. As both cases show very different patterns, we believe that the TMF is a suitable framework for further projects in SSCM and adjacent areas.

While the single techniques are not novel, the composition and the utilization for supporting holistic and more appropriate evaluations of SSCM systems provide a contribution to both TDR and OR. The TMF increases effectiveness and efficiency of collaboration by structuring and facilitating convergence processes in TDR teams. While supporting the goal of developing an appropriate model of the focal system, the TMF enables research teams to implement extensive transdisciplinary collaboration by reaching a state of mutual understanding and, thereby, provides a fundament for further research and modeling.

Through such integration of manifold expertise, holistic evaluations of focal system are possible. Especially in SSCM environments, technical, environmental, social, and societal peculiarities as well as interdependencies are taken into account, for example, through data specification and goal-oriented data acquisition as well as, if still necessary, realistic definition of assumptions. Moreover, the proposed research cycle meets the basic principle of OR modeling, which states that the problem determines the data requirements. Pidd (2008, 94) underlines the importance to put the process of defining data requirements in front. It seems that regarding the actual utilization of decision models, this logic is often turned upside down. Hence, the research cycle helps to compile the model development in the "right order." Indeed, the structured approach avoids numerous iterations within the problem-solving process (see Figure 1) and supports transferability to the real world. This way, resources are saved.

Although the TMF enables to derive a holistic picture of the focal system, it does not necessarily lead to a solvable mathematical model in terms of data requirements, ease of implementation, and computational efforts. Nevertheless, we believe that mathematical models better address real-world problems when a comprehensive verbal model is drawn upfront, which gives transparency to the complexity of the problem. This transparency enables researchers to balance the trade-off between completeness of the problem and the requirements of a mathematical model. This way, the mathematical model may be properly adapted to solvability taking the actual real-world problem structure into account, instead of mainly focusing on mathematical issues. Considering the criticism on the OR discipline, we believe that results and transferability are improved.

Concerning further research, please note that using the framework is not limited to SSCM. It may also be applicable for related problems of SCM decision making where the involvement of heterogeneous disciplines is suggested. We depict promising SCM research fields to implement TMF-guided collaborations in Table 4. An application to these SCM topics may be subject of upcoming research. Moreover, certain parts of the TMF are generalizable for non-OR problems. For instance, corporations may benefit from using the TMF within intracompany collaboration projects crossing functional areas (Frankel et al. 2008) or intercompany collaboration (Zacharia et al. 2009). This is especially true for Steps 1–3. However, the goal of the framework is to identify cause-and-effect relationships that are ultimately translated into quantitative models, which is the focus of Steps 4 and 5.

While we focus on quantitative modeling techniques as focal research methodology, the TMF may also be beneficial for other types of research employed by SCM scholars. Several aspects of the TMF may help to increase rigor and transferability of research that uses empirical survey, observations, action research, experiments, or other behavioral studies. Especially, Steps 1–3 of the TMF help to identify and assess potentially relevant factors of the analyzed system and, hence, formulate adequate hypotheses. Moreover, errors concerning internal validity (failures in detecting causal relationships) can be prevented by building

Table 4: Promising SCM research fields for further application of TMF

SCM research stream	Potentially involved disciplines	Example publications
Health care operations management	Physicians, Management Sciences, Sociologists, Economists, Politics	Hagtvedt et al. (2009), Simon (2009), Vanberkel et al. (2012)
Disaster operations management	Medical Experts, Logistics, Meteorologists, Geography, NGOs	Tomasini and van Wassenhove (2009)
Ecologically sound product design	Environmental Sciences, R&D, Production Management, Service Operations Management	Chung and Wee (2008)
SC coordination	Management Sciences, Computer Sciences, Economics, Corporate Actors, Psychology	Walther et al. (2008), McCarter and Northcraft (2007)
SC disruptions	Financial Experts, Meteorologists, Sociology, IT Experts, SCM Researchers	Tang (2006)

Note: IT, information technology; NGOs, nongovernmental organizations; R&D, research and development; SC, supply chain; SCM, supply chain management; TMF, transdisciplinary modeling framework.

structured TDR organizations for analyzing complex systems. Even integrative or theoretical literature studies may be improved as the variety of relevant research fields and according journals that need to be covered can be better determined and analyzed within a collaborative setting. The importance of transdisciplinary views on a single topic is shown by Stindt and Sahamie (2014) as well as Sahamie et al. (2013). The application and adaptation of the TMF to research using methodologies other than OR is a logical next step of research. Finally, the implementation of the TMF may lead to integration and adjustment of methodological toolsets from more remote scientific disciplines (e.g., natural sciences) to SCM research.

In conclusion, the TMF raises awareness for aspects of a system that are often neglected by hard OR. This ranges from the definition of the problem itself (e.g., what is meant by the term sustainability and how can it be measured and reached) to the reliable acquisition of information as well as to the identification of interdependencies. Hence, it prevents researchers to use over simplified or even wrong assumptions. In total, by supporting transdisciplinary collaboration, the TMF addresses major shortcomings of OR-based decision making and, hence, improves the validity of according results, especially regarding contemporary (S)SCM issues.

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