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Making a Transition toward more Mature Closed-Loop Supply Chain Management under Deep Uncertainty and Dynamic Complexity: A Methodology

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Received: 1 March 2019; Accepted: 14 April 2019; Published: 17 April 2019



Abstract: This article develops a methodology to empirically study and cope with deep uncertainty and dynamic complexity when the actors in a traditional supply chain make a transition toward more mature closed-loop supply chain (CLSC) management. The methodology addressed calls for innovative research and decision-making approaches in this field. Mature, in this context, refers to moving operationally and mentally away from a stochastic, one-dimensional and static approach to CLSC management, towards an exploratory, multi-dimensional and dynamic approach. To empirically study and cope with deep uncertainty and dynamic complexity in a CLSC context, a conceptual framework and related methodological toolbox are developed, together called the ‘closed-loop integration: collective keystones methodology’ (hereinafter CLICK methodology). The conceptual framework entails six maturity stages, which have been defined based on the well-known capability maturity framework and the concept of double-loop learning. Based on the conceptual framework, methods to equip the toolbox have been systematically identified and evaluated. The study identified 31 potentially appropriate methods, varying from non-participatory methods, to the active engagement of actors and stakeholders, and from analytical methods to evaluation/assessment methods.

Keywords: closed-loop supply chain management; deep uncertainty; dynamic complexity; methodological approach; CLICK methodology; decision making

1. Introduction

The concept of a ‘closed-loop supply chain’ (CLSC), which refers to supply chains that serve the ‘circular economy’, has attracted the attention of researchers and practitioners, especially because developments such as climate change and resource scarcity have become serious issues in global politics. A CLSC integrates a forward supply chain with a reverse supply chain, and aims to maximize economic, ecological and societal value creation over the entire (technical) lifecycle of a good with a dynamic recovery of value after each usage cycle [1]. At present, most supply chains do not bear this ‘circular’ character yet. To make a transition towards a CLSC, various interventions for change need to be developed, decided upon, implemented and monitored; hence, explicit CLSC management is necessary. In practice, during these interventions supply chain actors must cope with complexity and many uncertainties. Changing regular practices when aiming to become a CLSC triggers questions regarding, e.g., whether goods from the reverse supply chain can be transformed into valuable resources for the forward supply chain, especially when it comes to goods with a long lifecycle and unknown quality,

and how end-users will respond to recovered goods. Furthermore, persistent disagreement may exist regarding which CLSC interventions to implement now and which in the future. Moreover, uncertainty tends to increase because of the dynamics related to market structures, for example, that dynamically change over time, geographical scales, and competitors also making changes to their business, as well as new regulations that change the rules of the (market) game. Recent research claims that a transition towards CLSC management is hampered by the effects of such uncertainties, notably the so-called deep uncertainties (also labelled as the 'known unknowns' and 'persistent disagreement') and diverging responses to dynamic complexity [2,3]. This article aims to develop an innovative methodology that allows to empirically study and address such uncertainties and complexity, by exploring the literature and by combining existing decision-making and management theories to the following question: How to empirically study and deal with deep uncertainty and dynamic complexity in a transition towards more mature CLSC management?

Studies of real-world practices in (closed-loop) supply chains suggest that a transition towards CLSC management follows a process characterized by a succession of so-called 'maturity stages'. While some supply chain actors already implemented and adjusted to some CLSC interventions, e.g., introducing material recovery or closed-loop logistics, others may not have implemented any CLSC interventions yet. For example, van der Heijden et al. [4] studied the apparel supply chain in-depth and observed substantial differences between various supply chain actors with regard to the issue of closing the loop. Some actors appear to be in a 'business-as-usual' stage, questioning the urgency of making a transition towards a CLSC. Others already appear to have adopted CLSC-oriented goals and/or developed CLSC interventions and even have implemented one or multiple CLSC interventions, such as recycling cotton, or leasing rather than selling jeans. It can also be observed that some CLSC interventions are more successful than others are. The analysis of the apparel supply chain showed that dimensions such as timing, geographical scale, and the organizational level play a major role in this matter. The same applies to the construction supply chain, with many actors with divergent and sometimes conflicting goals and interests and different levels of knowledge in relation to CLSC management. Residents want to live comfortably at an acceptable rent, and sustainability comes in second, if not third, place. Awareness of circularity is on average low, implying that there is a huge challenge to link the housing needs to the need for sustainability and circularity [5]. A preliminary conclusion based on these observations is that different stages of maturity should be anticipated in different echelons of the supply chain when making a transition towards CLSC management.

Theoretical and practical insights regarding a transition towards more mature CLSC management have led to the question of which knowledge gaps exist with respect to (studying and coping with) deep uncertainty and dynamic complexity in that context. To find an answer to this question, Coenen et al. [6] performed a systematic literature review. In this review, the authors evaluated the approaches used in (64) relevant articles. Based on this review, the authors identified the following three knowledge gaps: conceptual gaps, a process gap and methodological gaps. A major conceptual gap is the lack of an elaborate conceptual framework to investigate transitions towards more mature CLSC management under deep uncertainty and dynamic complexity. The process gap refers to a lack of understanding of how to systematically involve supply chain actors in the pursued transition. A major methodological gap is the lack of methods to empirically study and cope with deep uncertainty and dynamic complexity simultaneously, and in relation to CLSC management. The majority of the studies focused on studying stochastic or fuzzy uncertainty, or on dynamic complexity without taking into account (deep) uncertainty [6]. On this basis, it was concluded that an adequate conceptual framework and a related toolbox for empirically studying and coping with deep uncertainty and dynamic complexity in a transition towards more mature CLSC management seems to be missing. Therefore, this article takes up the challenge to find an answer to this lack and propose ways to study and cope with this issue.

This article proposes a conceptual framework and the contours of a related toolbox, together referred to as the 'CLICK methodology'. The elaboration integrates three ideas. First, focus is placed on closing the earlier mentioned conceptual gap by adopting ideas related to the so-called Capability

Maturity Model [7] and the concept of double-loop learning [8]. These concepts will be further elaborated upon in Section 2. Second, the focus is on closing the methodological knowledge gap. It involves a systematic study of appropriate methods that enable studying and coping with deep uncertainty and dynamic complexity in a transition towards CLSC management. Third, an attempt is made to close the process-gap. It concerns a qualitative assessment of the duration, degree of participation and methodological expertise required for the application of the methods concerned.

The article consists of five sections. Section 2 elaborates on the conceptual framework. The third section describes the methodology used to extensively search for and assess appropriate methods. The fourth section presents the findings of the research, i.e., an overview of appropriate methods for the CLICK methodology. Section 5 presents the conclusions and a discussion of the CLICK methodology and provides directions for future research.

2. CLICK Methodology: A Conceptual Framework

As indicated in the systematic literature review by Coenen et al. [6], a major challenge is to develop a coherent conceptual framework and a related toolbox to study and improve the supply chain actors' abilities to cope with deep uncertainty and dynamic complexity in their attempt to make a transition towards more mature CLSC management. They found that CLSC management papers pay limited attention to the development of future-based transition pathways consisting of different CLSC interventions and the implementation, operation and monitoring of these pathways. Furthermore, as mentioned earlier, very limited attention has been paid to studying and coping with deep uncertainty and dynamic complexity simultaneously in the management process. The main focus in current approaches, found in a systematic literature review, are on the development/modelling and selection of CLSC interventions under stochastic or fuzzy uncertainty or (dynamic) complexity [6].

The term deep uncertainty refers to a situation in which actors do not know (i.e., known-unknowns) or cannot agree (i.e., persistent disagreement) upon the appropriate system models, such as CLSCs, to describe interactions among aspects such as the system's (exogenous and endogenous) variables, the probability distributions to present uncertainties regarding key parameters in the models, and/or how to value the desirability of alternative outcomes [9,10]. Exogenous variables are variables whose values are independent from the states of other variables in a complex system model and are determined by variables outside the system under study [11]. For instance, access to certain raw materials might be dependent upon geopolitical developments (e.g., related to the grand challenges). Endogenous variables are (economic, ecological and/or societal oriented) variables whose values are determined by the states of other variables in a complex system model [12]. For example, the price of wood is determined by global availability and regional or local demand for wood over time. In the case of deep uncertainty, especially when it comes to the known-unknowns, it is possible to enumerate possible representations of a system, plausible futures and relevant outcomes of interest without being able to rank-order these aspects in terms of likelihood [13]. The notion of dynamic complexity in a supply chain implies that changes in the output of a chain are perhaps not proportionally related to changes in its input over time (short to long term), geographical scales (local to global) and/or organizational levels (an individual organization to a network of organizations). Dynamic complexity can be explored by first tracing the nonlinear relationships between variables and the (reinforcing and balancing) feedback loops, and then simulating these relationships and feedback loops over time, over geographical scales and/or over organizational levels. These simulations provide insight into the dynamic behavior of (deeply uncertain) systems, such as certain forms of CLSCs. The dynamic behavior may be chaotic or show bifurcation. Dynamic behavior also refers to emerging patterns, which can only be explored through simulations.

Having specified deep uncertainty and dynamic complexity, this section elaborates an appropriate conceptual framework for studying and coping with these concepts in a transition towards mature CLSC management. The novelty of this conceptual framework lies in both operationally and mentally breaking away from the dominating stochastic, one-dimensional, and static approach to CLSC management

to an exploratory, multi-dimensional and dynamic approach towards complex CLSC management. CLSC management is based on deciding between alternative interventions and can thus be perceived as a continuous decision-making process. Therefore, elaborating an appropriate conceptual framework should start with evaluating decision-making frameworks that have been developed over the past fifty years, in attempts to better understand complex management and policy decision-making. The early frameworks were based on breaking down a policy-making process into several discrete stages, from problem definition, via generating and evaluating alternative interventions, to making a rational choice and implementing the related strategy. These frameworks had a linear and internal logic, implying that monitoring the feedback towards a system or policy and studying external/environmental influences on such a system or policy received very limited attention. As a result of increased contextual uncertainty since the last decades of the previous century (due to, e.g., globalization, and geopolitical and oil crises) and the apparent limitations of trend extrapolation models, the decision-making frameworks started to shift towards more cyclic frameworks to express the real-world dynamics experienced in strategic decision-making [14,15]. These decision-making frameworks have triggered an increasing amount of, often case-based, empirical studies on complex decision-making processes. In turn, these studies led to the coining of new concepts that explicitly aim to study and cope with (deep) uncertainty, (dynamic) complexity and adaptive planning and management. The concepts are, among others, 'assumption-based planning', 'dynamic adaptive planning', 'robust decision-making' [9], 'dynamic adaptive policy pathways' [16] and 'anticipative and adaptive steering' [17]. Also typical for these frameworks is a dominant focus on making logical management steps, often starting with the formulation and analysis of goals or problems and/or the design of initial interventions. However, it may be the case that the initial interventions cannot be formulated because of deep uncertainty (i.e., grand challenges) and dynamic complexity in the environment. In that case, actors first need to gain awareness regarding how the system which they are part of responds to the changes related to the grand challenges. This awareness may stimulate the actors to improve their understanding of the possible threats and opportunities they might face in the (near) future. Awareness, thus, forms a basis for problem identification, goal setting and the development of interventions. Next, it can be observed that decision-making frameworks, in the past, but even today, tended to focus on finding the best or most suitable interventions given specified conditions, often with little attention for the characteristics of the process. Notably, these frameworks paid limited attention to the positions and interactions of the involved actors and, in a context of transitioning towards a CLSC, the need for adjust their approaches to cope with the complexity of this challenge. Especially in the case of such a transition, a fundamental change in the way decision making and management is performed is not only related to the operational business process and practices but also to developing and internalizing a new mindset [17].

To develop the conceptual framework that facilitates the operational shift, the capability maturity Model of Paulk et al. [7] is used as a source of inspiration, implying that the authors present their own interpretation of this model. The capability maturity model describes and refines business process development, operations and monitoring processes, and is composed of various degrees of maturity. Each degree of maturity consists of capabilities and a cluster of related activities needed to achieve the specific capabilities. The elaboration of these thoughts resulted in the conceptual framework (i.e., maturity stages, capabilities and activities) depicted in Figure 1 and operationalized in Table 1 in terms of maturity levels and questions expressing the focus of the related analyses. The conceptual framework of the CLICK methodology consists of six maturity stages. Each maturity stage consists of a capability describing the expected result that can be achieved by the involved supply chain actors when performing a cluster of related management activities or interventions. For instance, in Maturity Stage 1, supply chain actors need to be able to gain an awareness of how the complex business-as-usual (BAU) supply chain might behave in response to the grand challenges (e.g., global resource scarcity). To achieve this capability, various management activities must be carried out such as the specification of the most important exploratory scenarios regarding the grand challenges

(see further explanation in Section 2.1). To be able to perform a certain management activity, the highest level of maturity of the specific management activity should be achieved. Based on the literature on deep uncertainty and dynamic complexity, three subsequent maturity levels are identified. Maturity Level 1 refers to the recognition of the supply chain actors that they are unaware of the information needed for the execution of a certain activity given deep uncertainty and/or dynamic complexity. Maturity Level 2 indicates that the involved actors have identified and are aware of the information that might be helpful to execute that management activity, while the actors still disagree on the most important elements of that activity. Maturity Level 3 refers to awareness and acceptance of the decision by the actors on the most important elements of that management activity. Acceptance of the decision by the actors may imply 'agree to disagree' or 'agreement'. In the latter case, deep uncertainty is being reduced. To support supply chain actors in the achievement of the highest maturity level (i.e., Maturity Level 3), various analytical and evaluation questions (see Table 1) need to be answered by researchers in collaboration with the participating supply chain actors. For specific management activities, one can only transition from Maturity Level 1 to Maturity Level 2, because these management activities only refer to the understanding of and the coping with the known unknowns and dynamic complexity, and do not require actors to agree on the activities. The questions formulated in Table 1 support supply chain actors in achieving the maturity levels and therefore to execute the different management activities.

Apart from the operational shifts as expressed in the capability maturity model, the concept of double-loop learning is adopted [8] to emphasize the required mental shifts among supply chain actors towards a more exploratory, multi-dimensional and dynamic approach towards complex CLSC management. A mental shift implies that the involved actors internalize this approach. The concept of double-loop learning is fundamental to the concept of maturity growth, as expressed in the literature on capability maturity model since its first publication [18]. By consistently following the CLICK methodology, the mental models of the involved supply chain actors change, and as a result, CLSC management becomes more mature. The underlying rationale of the CLICK methodology is that the better supply chain actors can cope with deep uncertainty and dynamic complexity during different stages of closing the loops in a supply chain, the more mature the CLSC management process will be. The six maturity stages, associated capabilities, and management activities of the conceptual framework are described in the following subsections (see also Figure 1). The operationalization of the conceptual framework is presented in Table 1.

2.1. Maturity Stage 1: Understanding Responses to Grand Challenges

In Maturity Stage 1, supply chain actors have developed the capability to gain an awareness of how the complex BAU supply chain might behave in response to the so-called grand challenges. A grand challenge acts as an inherently uncertain development in the environment of the supply chain that could stimulate a transition towards CLSC management. Grand challenges could be long-term developments such as decreasing global natural and economic resource availability or shifting taxes from labor to CO₂ emissions within the European Union. Grand challenges could also be medium-term developments such as public policy strategies regarding improving sustainability and circularity in different geographical areas. The term 'behave' specifically refers to the dynamic economic, ecological and societal behaviors (e.g., bifurcation, oscillation, chaos) of a BAU supply chain over different time horizons, geographical scales and/or organizational levels.

To develop this capability, three types of management activities need to be addressed. Activity 1a involves specifying the most important exploratory scenarios in relation to the grand challenges. Exploratory scenarios answer the question 'what could happen?' and have long time-frames and multiple perspectives, varying from worst-case scenarios to best-case scenarios [19]. Exploratory scenarios can be divided into framed and unframed scenarios. Framed scenarios consider driving forces, which serve as guidance for their development, but which also limit the breadth of plausible futures that can be explored. Unframed scenarios also consider other factors, actors

and sectors, in addition to driving forces, as guidance for their development [19]. Activity 1b implies the identification of causal structures of the relevant BAU supply chain in relation to the grand challenges, from economic, ecological and/or societal points of view. Hence, this activity results in identifying and understanding the multiplicity of nonlinear relationships and interacting feedback loops between the grand challenges and the BAU supply chain system models. Activity 1c involves the exploration of plausible (near) future types of dynamic behavior of the BAU supply chain in response to the grand challenges, as well as investigating which combinations of deep uncertainties cause different types of dynamic behavior. This activity results in many plausible scenarios of the economic, ecological and/or societal behavior of a BAU supply chain over different time horizons, geographical scales and/or organizational levels.

2.2. Maturity Stage 2: Ambition to Change

In Maturity Stage 2, supply chain actors have developed the capability to gain awareness of, to develop, and be able to accept a set of multidimensional—and possibly conflicting—goals to maximize multidimensional value creation over the entire lifecycle of the goods they are dealing with. In general, a goal can be defined as “an observational or measurable organizational outcome to be achieved within a specified time limit” [20]. ‘Multidimensional’ refers to economic, ecological and/or societal goals formulated from geographical, organizational and/or temporal perspectives. For instance, an ecological goal that includes the organizational and temporal dimensions could be that all relevant actors of a construction chain jointly maximize the reduction of the CO₂ emissions of the chain by 2025. The various actors in a supply chain, however, may have different and sometimes conflicting economic, ecological and societal goals. They may also have different perceptions regarding the time horizon, geographical scales and/or organizational levels of the goals. Coenen, van der Heijden and van Riel [6] argue that in many of the reported model-based studies on supply chains, the goals are primarily specified by the researchers and not by the supply chain actors. Furthermore, the goals are considered as conflicting or non-conflicting and are integrated into a CLSC model with the primary aim of finding the optimum solution or compromising solutions. Very little attention has been given in these studies to the process of CLSC goal setting itself, especially in situations of deep uncertainty and dynamic complexity. Therefore, as part of this maturity stage, the following management activities are proposed. Activity 2a refers to the development of a shared understanding of the most important possible threats and opportunities perceived by the different supply chain actors, using the alternative plausible future scenarios explored in Maturity Stage 1. Given this understanding, Activity 2b is about setting multidimensional (possibly conflicting) goals wherein each party’s interests are respected.

2.3. Maturity Stage 3: No-Regrets Interventions for Change towards a CLSC

In Maturity Stage 3, supply chain actors have developed the capability to gain awareness, to develop, and are able to accept the developed no-regrets CLSC interventions. No-regrets interventions are interventions that pay off, regardless of what happens [21]. Hence, the focus is on maximizing positive and minimizing negative outcomes for the supply chain actors involved. To develop this capability, the following management activities are required. Activity 3a includes the specification of various potential CLSC interventions and related deep uncertainties, to reconcile the diverse and possibly conflicting goals defined in Maturity Stage 2. The CLSC interventions derive from the various key business decision domains suggested by Schenkel et al. [22] and previously published in Coenen et al. [6], i.e., product design, product-as-a-service concepts, procurement and logistics, production and recovery procedures, marketing, integrated supply chain partnerships, and information technology (see Table S1). Activity 3b involves the conceptual integration of the potential CLSC interventions into the structure of the BAU supply chain developed in Activity 1b, leading to alternative causal CLSC system models with inherently uncertain model structures, parameters, nonlinear interactions, and outcomes. Activity 3c includes the exploration of plausible types of dynamic behavior of the BAU supply chain over time, at geographical scales and/or organizational levels, in response to the potential CLSC interventions,

as well as which uncertainties cause the different types of dynamic behaviors. The results are used to perform Activity 3d, i.e., identifying which CLSC interventions can be considered as potentially no-regrets interventions, to reconcile the specified (conflicting) goals.

2.4. Maturity Stage 4: Transition Mapping towards a CLSC

In Maturity Stage 4, supply chain actors have developed the capability to gain awareness of, to develop, and are able to accept the developed transition map towards a CLSC. A transition map consists of a set of transition pathways, indicating the avenue to transform an existing BAU supply chain into a CLSC. At the same time, they allow for flexibility, because during the process new knowledge, changing circumstances and unexpected effects must be dealt with. A single pathway consists of a sequence of preferred no-regrets CLSC interventions, signposts and trigger values. A signpost refers to the variables related to a single (CLSC) activity that need to be tracked, while triggers are the values of those variables that would trigger a response [23]. Hence, the following management activities should be performed: decision making regarding (i) the preferred no-regrets CLSC interventions that supply chain actors can, and are willing to implement now, (ii) the no-regrets CLSC interventions that supply chain actors can and are willing to postpone, and (iii) the signposts and trigger values of the implemented no-regrets interventions.

2.5. Maturity Stage 5: Jointly Anticipative and Adaptive Steering of a CLSC

In Maturity Stage 5, supply chain actors should have developed the capability to gain awareness of, to develop, and be able to accept, the plan with which the transition towards a CLSC can be monitored in an anticipative and adaptive manner. From a transition theory perspective, anticipative steering refers to the continuous development and adjustment of potential (CLSC) interventions in response to new developments and changes inside and outside a CLSC. Hence, here, it concerns a repetition of the management activities described in Maturity Stages 1 to 3. Adaptive steering implies the continuous monitoring of the signposts and trigger values of the transition pathways and the choice of alternative no-regrets CLSC interventions in case the existing interventions in the transition pathways are no longer beneficial. This implies a repetition of the management activities described in Maturity Stages 3 and 4. The concepts of anticipative and adaptive steering show many similarities with the classic concept of the 'early warning system', which stresses the collection of information to obtain early warning signals for taking actions or for the reassessment of an ongoing development. Hence, as part of this Maturity Stage, the following management activity is proposed: decision-making regarding investments in time, people, money and basic rules for a structural process of anticipative steering and adaptive steering.

2.6. Maturity Stage 6: Mature CLSC Management

In Maturity Stage 6, supply chain actors have developed the capability to systematically (i) identify and scrutinize different sources of deep uncertainty in CLSC management, (ii) more or less fully understand the multidimensional dynamic behaviors of CLSCs, and, (iii) systematically integrate the process of anticipative and adaptive steering in normal business. The aim is multiple value creation of the entire life cycle of goods and related services with a dynamic return of value over the different usage cycles. This maturity reflects the earlier mentioned 'double-loop learning', which implies that the supply chain actors learn not only to make an operational transition towards a CLSC from an exploratory, dynamic and multidimensional perspective, but that they also internalized this in a fundamentally changed mindset. The underlying rationale is that the continuous practice of the earlier specified capabilities and activities in Maturity Stages 1 to 5 are required to achieve the three capabilities of Maturity Stage 6 and, thus, express double-loop-learning capability.

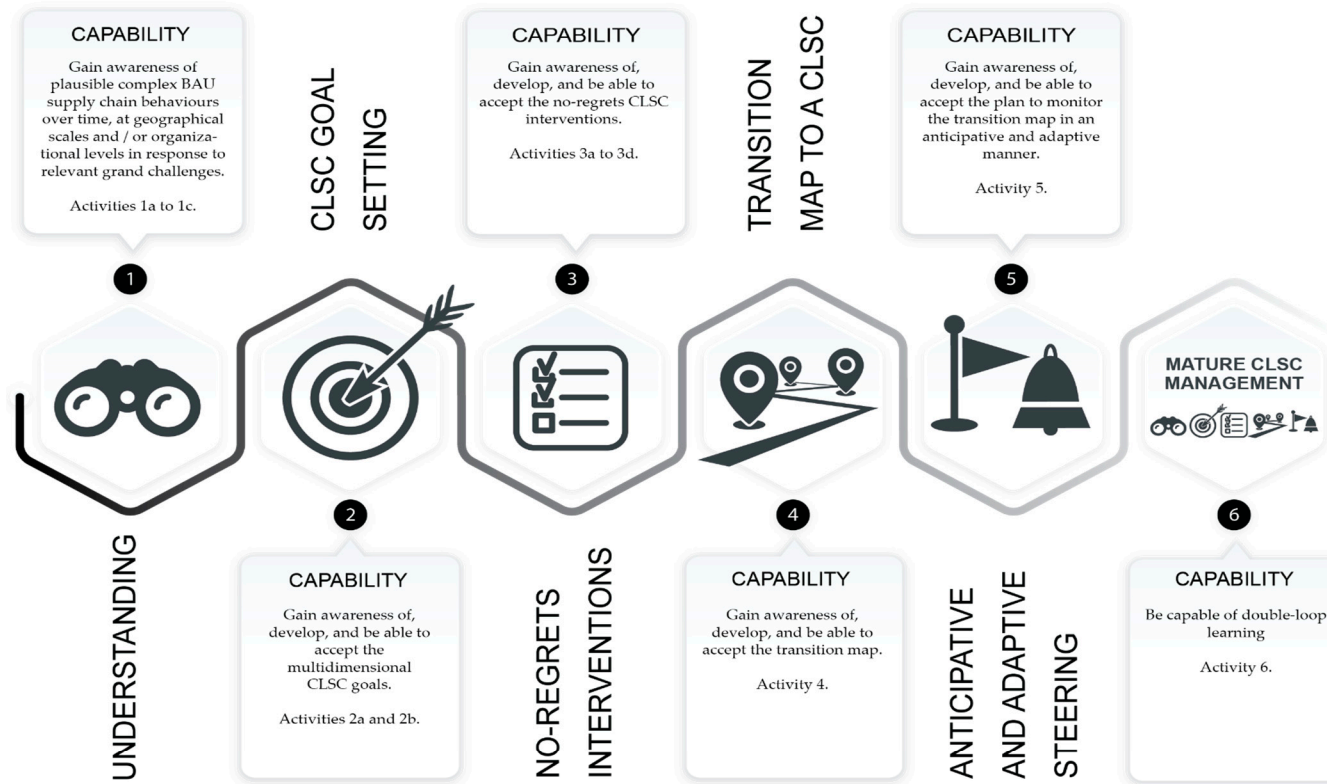


Figure 1. The conceptual framework of the CLICK methodology.

Activities to achieve capabilities

- 1a: Specification of the most important exploratory scenarios of different grand challenges.
- 1b: Developments of the causal structures of linked grand challenges-BAU supply chain system models.
- 1c: Specification of the different types of dynamic behavior of the BAU supply chain in response to the grand challenges.
- 2a: Identification of the relatively most important possible threats and opportunities in the BAU supply chain stimulating change toward a CLSC.
- 2b: Setting the relatively most important multidimensional CLSC goals.
- 3a: Identification of the relatively most important potential CLSC interventions.
- 3b: Identification of the causal structures of the adapted BAU supply chain system models.
- 3c: Specification of the types of dynamic behavior of BAU supply chain in response to potential CLSC interventions.
- 3d: Identification of no-regrets CLSC interventions.
- 4: Selection of the preferred transition map toward a CLSC
- 5: Selection of the relative preferences regarding investments in anticipative and adaptive steering of a CLSC
- 6: Go through Maturity Stages 1–5.

Table 1. Management activities, levels of maturity and questions helping to reach a higher maturity level.

Activity	Levels of Maturity	Analytical and Evaluation Questions to Answer to Reach a Higher Maturity Level
1a	1 Ignorance about the exploratory scenarios of the grand challenges.	Analytical questions 1. Which grand challenges could trigger a transition towards a CLSC for the SC actors involved? 2. What are the variables and driving forces of the grand challenges? 3. What are the relationships between the variables and driving forces of a single grand challenge and those among the grand challenges? 4. How can grand challenges unfold over time, at geographical scales and/or organizational levels?
	2 Gained awareness on and being able to identify the exploratory scenarios of the grand challenges, but persistent disagreement on the relatively most important grand challenges to focus on.	
	3 Aware and agree or agree to disagree upon the relatively most important exploratory scenarios of the grand challenges for further exploration.	
1b	1 Ignorance about the causal structures of the linked grand challenges-BAU SC system models.	Analytical questions 6. What are the boundaries of the BAU supply chain system model in terms of geographical scale(s), time horizon and organizational level(s)? 7. What are the activities, endogenous and exogenous variables of the BAU supply chain system model? 8. What are the nonlinear interactions and feedback loops among the endogenous and exogenous variables of the BAU supply chain system model? 9. What are the ranges of uncertain parameters in relation to the most important causal structures?
	2 Gained awareness on and being able to identify the causal structures of the linked grand challenges-BAU SC system models.	
1c	1 Ignorance about the different types of dynamic BAU supply chain system behaviors in response to the grand challenges.	Analytical questions 10. How does the BAU supply chain system model economically, ecologically and/or societally behave over time, at geographical scales and/or organizational levels in response to the grand challenges? 11. Which combinations of deep uncertainties cause the many different types of dynamic BAU supply chain system behaviors?
	2 Gained awareness on and being able to identify different types of dynamic BAU supply chain system behaviors in response to the grand challenges.	
2a	1 Ignorance about the most important possible threats and opportunities.	Analytical question 12. Which threats and opportunities in the supply chain can occur over time, at different geographical scales and/or organizational levels, from the economic, ecological and/or societal perspective? Evaluation question 13. What are the relatively most important possible threats and opportunities for the SC actors involved to focus on over time, at different geographical scales and/or organizational levels, from the economic, ecological and/or societal perspective?
	2 Gained awareness on and shared understanding, yet persistent disagreement on the most important possible threats and opportunities.	
	3 Shared understanding and agree or agree to disagree on the most important possible threats and opportunities.	
2b	1 Ignorance about the set of multidimensional goal setting.	Analytical question 14. Which economic, ecological and/or societal CLSC goals need to be formulated to tackle the relatively most important threats and opportunities in the supply chain over time, at different geographical scales and/or organizational levels? Evaluation questions 15. What are the relatively most important CLSC goals for the SC actors involved to tackle the relatively most important threats and opportunities in the supply chain over time, at different geographical scales and/or organizational levels?
	2 Gained awareness on and being able to set multidimensional goal, yet persistent disagreement on the different goals.	
	3 Multidimensional goal setting and agree or agree to disagree upon the different goals.	

Table 1. Cont.

Activity	Levels of Maturity	Analytical and Evaluation Questions to Answer to Reach a Higher Maturity Level
3a	1 Ignorance about the possible CLSC interventions. Gained awareness on and being able to specify possible CLSC interventions,	Analytical question 16. Which CLSC interventions can be specified to reconcile the CLSC goals and tackle the threats and opportunities in the supply chain? 17. What are the uncertainties in relation to the divergent CLSC interventions?
	2 yet persistent disagreement on the relatively most important CLSC interventions.	
	3 Able to specify possible CLSC interventions and agree or agree to disagree upon the relatively most important CLSC interventions.	Evaluation question 18. What are the relatively most important CLSC interventions for the SC actors involved to reconcile the CLSC goals and tackle the threats and opportunities in the supply chain?
3b	1 Ignorance about the causal structures of the adapted BAU SC system models.	Analytical questions 19. What are the variables and parameters of the relatively most important CLSC interventions and related deep uncertainties? 20. What are the nonlinear interactions and feedback loops among the endogenous and exogenous variables of the linked CLSC interventions - BAU supply chain system models? 21. What are the ranges of uncertain parameters and structural variations in the adapted BAU supply chain system models?
	2 Gained awareness on and being able to identify the causal structures of the adapted BAU SC system models.	
3c	1 Ignorance about the different types of dynamic BAU supply chain system behaviors in response to the CLSC interventions.	Analytical questions 22. How does the BAU supply chain system model economically, ecologically and/or societally behave over time, at geographical scales and/or organizational levels in response to the CLSC interventions? 23. Which combinations of deep uncertainties cause the many different types of dynamic BAU supply chain system behaviors in response to the CLSC interventions?
	2 Gained awareness on and being able to identify different types of dynamic BAU supply chain system behaviors in response to the CLSC interventions.	
3d	1 Ignorance about the no-regrets CLSC interventions.	Analytical question 24. Which CLSC interventions can be defined as no-regrets CLSC interventions?
	2 Gained awareness on and being able to identify the no-regrets CLSC interventions.	
4	1 Ignorance about the transition map towards a CLSC.	Analytical question 25. What are the signposts and triggers of the no-regrets CLSC interventions? 26. Which transition maps can be developed based on the no-regrets CLSC interventions and the related signposts and triggers?
	2 Gained awareness on and being able to indicate individual preferences, yet persistent disagreement on the relative preferences of the transition map towards a CLSC.	
	3 Agree or agree to disagree on the relative preferences of the transition map towards a CLSC.	Evaluation question 27. Which transition map has the relative preference of the supply chain actors involved?
	1 Ignorance about the investments in anticipative and adaptive steering of a CLSC.	Analytical questions 28. What are the individual preferences regarding the person(s) that should perform (i) anticipative steering and (ii) adaptive steering? 29. What are the individual preferences regarding the time and budget to be spent on (i) anticipative steering and (ii) adaptive steering? 30. What are the individual preferences regarding the basic rules for (i) anticipative steering and (ii) adaptive steering?
	2 Gained awareness on, yet persistent disagreement on the investments in anticipative and adaptive steering of a CLSC.	

Table 1. *Cont.*

Activity	Levels of Maturity	Analytical and Evaluation Questions to Answer to Reach a Higher Maturity Level
3	Aware and agree or agree to disagree on the investments in anticipative and adaptive steering of a CLSC.	Evaluation question 31. What are the relative preferences regarding the person(s), time, budget and basic rules for the implementation of anticipative steering and adaptive steering?
6	1 Ignorance about double-loop learning in relation to CLSC management under deep uncertainty and dynamic complexity.	Go repeatedly through Questions 1 to 31 for each change process.
	2 Capable of double-loop learning in relation to CLSC management under deep uncertainty and dynamic complexity.	

The briefly described characteristics of the CLSC methodology have been translated into maturity levels and research questions in Table 1, that give direction to the analytical and evaluation challenges for each of the described stages, capabilities to achieve, and activities to perform. The maturity levels and research questions support the exploration of the most appropriate supportive methods in the remainder of this paper and, hence, constitute a starting point for filling the toolbox related to the conceptual model underlying the CLICK methodology.

3. Selecting Appropriate Methods: The Research Methodology Applied

To identify appropriate methods to support a transition towards more mature CLSC management under deep uncertainty and dynamic complexity, two research steps were performed. Step 1 is an extensive literature review. Therefore, online databases (e.g., Web of Science, Business Source Complete, and Science Direct) and handbooks in the field of (change) management and systems analysis and decision making under deep uncertainty and/or dynamic complexity were considered. To collect the relevant studies related to the conceptual framework of the CLICK methodology, the following keywords were used: ‘scenario development’, ‘goal-setting’, ‘problem identification’, ‘exploratory system modelling/multi-scale modelling’, ‘strategic-robust option development/optimization’, ‘multi-criteria decision-making’, and ‘adaptive monitoring’. Regarding the databases consulted, the search was narrowed down by selecting only papers that mentioned one or multiple keywords in the abstract and introduction, and by eliminating duplication. The relevant studies and handbooks constituted a basis for the execution of Step 2, i.e., analysis of the reported methods (see Section 4.1) and a qualitative assessment of their advantages and disadvantages for the CLICK methodology (see Section 4.2). The qualitative assessment is based on three process-based criteria, i.e., (i) participation of supply chain actors, (ii) duration of the application of the method concerned, and, (iii) required methodological expertise needed for the application of the method concerned. The participation of the supply chain actors is subdivided into ‘non-participation’, ‘passive consultation’ and ‘active engagement’ [24,25]. Non-participation means that the researcher only performs the application of the method. Passive consultation refers to supply chain actors only providing information as input for the application of the analysis. Active engagement means there is a two-way exchange of information between the supply chain actors and researcher as equal partners within the context of the application of the method. Duration can be subdivided into ‘short’, ‘medium’ and ‘long’. Required methodological expertise can be subdivided into ‘non-essential’, ‘supports and accelerates’ and ‘essential’ for the application of the method.

4. CLICK Methodology: An Overview of Appropriate Methods

The following sub-sections discuss the methods through which the analytical and evaluation questions of the CLICK methodology can be answered (Section 4.1), and the suitability of the reported methods in relation to the earlier mentioned assessment criteria (Section 4.2).

4.1. Appropriate Methods to Answer the Questions and Achieve the Maturity Levels

The literature study yielded at least 31 different qualitative and quantitative methods that appear suitable to fill the toolbox of the CLICK methodology. When applying the CLICK methodology, the relevant supply chain actors for the different maturity stages should be selected and analyzed in terms of their position in the network, preferences, resources, interactions, etc. It might be that different or new actors are required in Maturity Stage 2 versus those who were required in Maturity Stage 3, or that because of persistent disagreement, actors choose to collaborate with a different actor. Therefore, the stakeholder analysis methods mentioned by, e.g., Reed et al. [26] might be of added value. The remaining 30 methods are briefly analyzed and reported in the following paragraphs.

4.1.1. Activity 1a of Maturity Stage 1: Specification of the Relatively Most Important Exploratory Scenarios of the Grand Challenges

To specify the relatively most important exploratory scenarios of grand challenges that could trigger a transition towards a CLSC (Question 5), the supply chain actors must first become aware of and identify the characteristics of the grand challenges and how they can unfold over time, at geographical scales and/or organizational levels (i.e., exploratory scenarios). Therefore, Questions 1 to 4 need to be answered first. The following methods could be applied:

Questions 1 to 4: For the specification of the grand challenges and the exploratory scenarios of the grand challenges, environmental scenario development can be applied [27–29]. Environmental scenario development in this context aims at constructing coherent storylines describing (i) the variables of the grand challenges and the uncertain driving forces behind the grand challenges, (ii) the relationships between the variables of a single grand challenge or the variables between multiple grand challenges, and, (iii) the way grand challenges can unfold over time, at geographical scales and/or organizational levels. For the first issue, the researcher can employ individual interviews with the supply chain actors and other experts (e.g., trend watchers), as well as perform a literature study to gain in-depth knowledge regarding the grand challenges mentioned by the actors and other experts. Through evidence from the interviews and literature, the researcher can carry out a first ordering of the variables and driving forces. For the last two issues, (digital) workshops can be applied where those same actors apply brainstorming techniques [19,30]. Evidently, the data originating from the literature research and individual (expert) interviews can also serve as input for the workshops.

Question 5: Although it is important to preserve sufficient exploratory scenarios to cover the potential (large) variety of different future projections for further exploration, it might be necessary, for the sake of the feasibility of the study, to focus on those grand challenges that are perceived ‘most important’ by the involved supply chain actors. However, a serious challenge exists when the supply chain actors cannot agree upon which grand challenges are perceived as most important to study in relation to a BAU supply chain, i.e., there is deep uncertainty. The extensive literature review shows that three different methods can be used separately, or in combination to cope with persistent disagreement. The first method involves ‘(fuzzy) multi-criteria decision-making’ [31,32]. Traditional multi-criteria decision aid methods do not systematically and explicitly take into account the uncertainty associated with human judgements, including preferences, which are often vague and cannot be estimated with an exact numerical value [33]. To overcome this problem, fuzzy theory is integrated with various multi-criteria decision aid methods, implying that linguistic assessments are used instead of numerical values. This type of assessment accepts that the ratings and weights of criteria related to a decision problem should be treated as scores on nominal or ordinal scales. The second method that could be used is Delphi. A Delphi inquiry is a structured expert consultation method that “uses a series of successive questionnaires, where, in each questionnaire after the first, the respondents receive feedback information about the outcome of the acknowledge for further study the preceding round” [34]. Because of the survey-approach, the method guarantees anonymity so that (field) experts can freely express their opinions. At the same time, Delphi is highly sensitive to design characteristics such as panel expertise, panel composition, question clarity, and possible distractions between question rounds [35]. The Delphi method results in an overview of ideas and expectations regarding, e.g., the nature and the plausibility of the grand challenges, and consequently indicates where the experts agree upon, and on which issues they fundamentally disagree. The third method that can be used is a workshop in which supply chain actors use various brainstorm techniques. This method is useful when the group of actors is relatively small (3–7 members).

4.1.2. Activity 1b of Maturity Stage 1: Development of Causal Structures of (parts of) a Linked Grand Challenge—BAU Supply Chain System Model

To identify the causal structures of the grand challenges in relation to the BAU supply chain and the ranges of uncertain parameters to further study (Question 9), the supply chain actors must

first become aware of the elements and plausible causal relationships between these elements that constitute the causal structures. Therefore, Questions 6 to 8 need to be answered first.

Questions 6 and 7: The generic structure of a complex system model consists of endogenous and exogenous variables. The grand challenges defined in Activity 1a can be considered as a configuration of exogenous variables. To classify the relevant endogenous and exogenous variables, the boundaries of the system model must be determined, depending on the geographical, organizational and temporal perspective taken by the actors. Regarding the temporal dimension, in a construction supply chain, e.g., the raw materials, building components and the building may have different life cycles. As for the organizational and geographical dimensions, the number and density of actors and stakeholders in, e.g., a building industry may differ geographically. To classify the boundaries and specify the endogenous and exogenous variables of a BAU supply chain system, the researcher can employ interviews with the supply chain actors involved and other experts, and/or (digital) workshops where the actors use brainstorming techniques.

Question 8: The literature research shows that the causal structures of complex system models, in terms of nonlinear interactions and feedback loops, can be specified using participatory methods such as group model building or mediated modelling [36]. These methods aim to achieve a common understanding regarding the structures and behavior of system models. Both group model building and mediated modelling build upon the principles of system dynamics. The methods do not differ from each other, except for the fact that mediated modelling focuses primarily on environmental applications [37]. In system dynamics, a complex system model is subdivided into interlinked sub-models. For instance, a global wood production sub-model relates to a series of sub-models for the global wood biomass energy production, CO₂ emissions, the national demand, the construction sector, and the energy sector. The sub-models can consist of stocks (state variables) and flows (rate variables), which are illustrated via a stock-flow diagram. For example, in a demand sub-model, the stocks may involve the demand for wood for construction and the demand for wood for biomass production. The flows may involve the external change rate, which is affected by variables such as the local or global wood and energy needs. In this example, the focus is on economic variables. From a sustainability perspective, however, one might argue that it is also important to focus on societal variables, such as relative poverty, and ecological variables, such as CO₂ emissions or waste production. The causal structures of, and between, sub-models can be illustrated qualitatively via causal loop diagrams in terms of nonlinear interactions and reinforcing and balancing feedback loops [38]. One of the disadvantages of system dynamics is that the method does not pay attention to the differences between organizations. Individuals or items in a stock, e.g., consumers with a demand, are considered as homogenous decision makers, meaning that they do not have individuality and, thus, behave in the same way [39]. To integrate the organizational dimensions more explicitly, companion modelling can be employed [40]. Companion modelling is a participatory method in which actors jointly develop an agent-based model and use the model to explore, among others, the behavioral heterogeneity of the agents in a (supply chain) system [41]. An agent-based model consists of different agents (e.g., individuals, business units, vehicles, and products), applying different decision heuristics, direct and indirect nonlinear interactions between these agents, and systematic links to contextual dynamics (the environment). To specify agent behavior, state charts can be employed. State charts allow different states of agents, deeply uncertain changes between the states, grand challenges and events that trigger those changes, the timing, and the actions that an individual agent may make during its lifetime to be captured graphically. Whether group modelling, mediated modelling or companion modelling is chosen, the data originating from Question 7 serve as an input for Question 8.

Persistent disagreements may exist between the actors' mental models of the underlying (causal) structure(s) of the linked grand challenges-BAU supply chain system model that cannot be resolved through group model building or mediated modelling [42]. In that case, the researcher should retain these differences and explore the implications of these differences on the model outcomes (see Activity 1c).

Question 9: Because the grand challenges are deeply uncertain themselves, the causal structures are deeply uncertain as well. The causal structures consist of parametric variations. To specify the uncertain parameters and their ranges (e.g., categorical, integer-based, parametric), focus groups can be employed, especially because the topic is defined clearly and there is a focus on enabling and recording the interactive discussion between supply chain actors on the parameters. If there are several dominant actors, one can also choose to perform individual interviews. The information retrieved from Questions 6 to 8 can be used as input for focus groups or individual interviews.

4.1.3. Activity 1c of Maturity Stage 1: Specification of (i) the Different Types of Dynamic System Behaviors of a BAU Supply Chain System Model in Response to the Grand Challenges and (ii) the Uncertainties Causing the Dynamic Behavior

This activity aims to specify how the grand challenges affect the dynamic economic, ecological and/or societal behavior of (parts of) a BAU supply chain over time, at different geographical scales and/or organizational levels. To be able to reach that purpose, the supply chain actors first need to gain awareness on and identify which behaviors may occur and which deep uncertainties are the result. Therefore, Questions 10 and 11 need to be answered. ‘Behavior’ refers to distinct (near) future types of dynamic behavior, such as exponential growth, exponential decay, oscillation, bifurcation, and chaos that emerges from nonlinear interactions and feedback loops between the grand challenges and a BAU supply chain.

Question 10: In the literature, various methods have been proposed to explore different types of dynamic behavior of a complex system model, notably, (i) ‘exploratory system dynamics modelling and analysis’ (ESDMA), (ii) ‘exploratory agent-based modelling and analysis’ (EAMA) [43], and, (iii) ‘experiential model-based serious gaming’ [44]. Regarding ESDMA and EAMA, the researcher can use the system models and ranges of deep uncertainties generated in Activity 1b to simulate and explore the different types of dynamic behavior in linked grand challenges-BAU supply chain models, across various uncertainties. In other words, computational experiments are performed with the aim of exploring plausible future worlds. For the application of the computational experiments, various operational modelling and simulation decisions have to be made, see for instance, and Pruyt and Islam [45]. The results/data from the computational experiments need to be clustered and classified based on the types of (economic, ecological and/or societal) dynamic behavior, such as an exponential increase of CO₂ emissions in the production stage of the supply chain, or an exponential decline in employment further along the supply chain. Therefore, data clustering methods and behavior-based classification methods can be employed by the researcher [46]. To ensure that the supply chain actors understand the different types of system behaviors over time, at geographical scales and/or organizational levels, interactive visual analytics techniques (e.g., multi-plots, 3D graphs, animations, and info graphics) can be applied to present the results. Regarding the third method, i.e., experiential model-based serious gaming, (supply chain) actors involved can, via system dynamics models or agent-based models and flight simulation, pre-experience a changed environment and system, and the plausible behavioral effects of a changed environment on a system [44]. Experiential model-based serious gaming and exploratory modelling and analysis can also be mutually beneficial; the former introduces a more participatory approach to the latter.

Question 11: To identify which combinations of deep uncertainties cause the many different types of dynamic behaviors, machine learning methods can be employed, such as the ‘patient rule induction method’ (PRIM) [47]. With PRIM, clusters in uncertainty in the parameter values can be identified within which the values of the output variables are considerably different from their average values over the entire domain. PRIM is part of the exploratory modelling and analysis research methodology. The results of PRIM can be enhanced by pre-processing the data with (nonlinear) principal component analysis [48]. The results can be presented to the supply chain actors by using interactive visual analytics techniques.

4.1.4. Activity 2a of Maturity Stage 2: Identification of the Relatively Most Important Threats and Opportunities in a BAU Supply Chain, Stimulating Change towards a CLSC

To identify the relatively most important threats and opportunities stimulating change towards a CLSC (Question 13), the supply chain actors must first become aware of and achieve a shared understanding of the possible threats and opportunities. Hence, Question 12 must be answered first. In this context, 'plausible' refers to threats and opportunities the actors believe may occur, based on the current understanding of how the BAU supply chain model could respond to grand challenges over time, at geographical scales and/or organizational levels. Hence, no statement can be made about the probability of an occurrence of the threats or opportunities.

Question 12: To understand what threats and opportunities can occur affecting the behavior of the supply chain, focus groups can be arranged. The visualizations developed by the researcher in Activity 1c, serve as the input for the discussions. A less participatory and more analytical and precise method that can be used is multi/many-objective optimization (e.g., NSGA-II) [42]. In this context, the aim of using many-objective optimization algorithms is to search for the worst (i.e., threats) and the best (i.e., opportunities) that could happen given the uncertainties. Here, too, the system models developed in Activity 1c can be used as an input, and the results can be visualized using interactive visual analytics and can be presented to the supply chain actors involved.

Question 13: Although there might be awareness and a shared understanding of the possible threats and opportunities in the relevant BAU supply chain among the supply chain actors, the actors may not be able to agree which threats and opportunities the most important ones are to focus on. After all, given known unknowns inside and outside a BAU supply chain, it is not possible to rank-order the threats and opportunities based on likelihood. Nevertheless, it could be argued that the assessment of the threats and opportunities in terms of importance depends on (i) the strengths and weaknesses of the various supply chain actors involved and (ii) dimensions, such as time, geographical scale, and the economic, ecological and/or societal nature of the threats or opportunities. To identify the relatively most important threats and opportunities, methods such as a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis and confrontation matrix can be employed [49]. To explore the general strengths and weaknesses of the supply chain actors involved, individual interviews can be used. Then, a confrontation matrix could be used to further analyze the output of the SWOT analysis. The confrontation matrix allows supply chain actors to study each different combination of strengths, weaknesses, opportunities and threats, with the aim of identifying the most important threats and opportunities to tackle. For the execution of the confrontation matrix, focus groups or workshops where the actors apply brainstorming techniques can be organized.

4.1.5. Activity 2b of Maturity Stage 2: Setting the most Important Multidimensional CLSC Goals

To be able to agree or agree to disagree on the relatively most important CLSC goals, the supply chain actors must first be able to become aware of and formulate the CLSC goals. Therefore, Question 14 must first be answered, followed by Question 15.

Question 14: A CLSC goal can be formulated in terms of many different dimensions. In the context of CLSCs, the dimensions are economy, ecology, society, time, the geographical scale and the organizational level. To structure the goals on the different dimensions, the supply chain actors can employ a 'goal-tree analysis', which is a systematic thinking process method describing the logical links between a goal, interventions in achieving the goal and the necessary conditions to implement the interventions [50]. For instance, a goal is to decrease CO₂ emissions. An intervention could be to reduce the amount of transportation in a supply chain significantly. A condition for this intervention is a tight collaboration between the supply chain actors. The goal-tree analysis can be performed via focus groups. The supply chain actors can use the information related to the most important threats and opportunities selected in Activity 2a as an input.

Question 15: Multidimensional goal setting can be deeply uncertain: there might be persistent disagreement among the supply chain actors on the determination of the relatively most important

goals. Various methods have been suggested in the literature that could be applied to support goal setting under a situation of persistent disagreement. For instance, Crabbé et al. [51] propose deliberative democratic evaluation, which is a process-based method with the aim of achieving mediation between (supply chain) actors with diverging and conflicting interests, values and opinions. The researcher or evaluator draws conclusions based on the different arguments. The evaluator plays a central role in the process. In other words, the evaluator must (i) avoid allowing certain supply chain actors to have a dominant influence on the determination of the relatively most important goals, (ii) prevent interests, values and opinions from being misinterpreted or be neglected, and, (iii) accurately evaluate the arguments for and against of the different goals. Two others, more individual, ways to collect and examine the diverging (and even conflicting) interests in relation to the goals and their relative importance, is to organize one or multiple electronic meetings (e.g., Group Decision Room) or to employ the Delphi inquiry. In electronic meetings, the supply chain actors provide their individual preferences regarding the goals and see each other's preferences while maintaining anonymity. This prevents certain actors from becoming dominant in the decision-making process.

4.1.6. Activity 3a of Maturity Stage 3: Identification of the Relatively Most Important CLSC Interventions

To be able to identify the relatively most important potential CLSC interventions (Question 18), the supply chain actors must first gain awareness and be able to specify (i) which CLSC interventions are possible to reconcile the multidimensional CLSC goals (Question 16) and (ii) the deep uncertainties in relation to the divergent CLSC interventions (Question 17).

Questions 16 and 17: The possible CLSC interventions are derived from the earlier mentioned seven CLSC decision domains (e.g., product design, product-as-a-service concepts, production and recovery procedures) (see Table S1) and can differ in geographical scale (e.g., local or regional oriented intervention) and organizational level (i.e., intervention implemented by one or multiple supply chain actors). Decision making on the potential CLSC interventions depends on the threats and opportunities explored in Activity 2a and the goals specified in Activity 2b. Various potential CLSC interventions may introduce new sources of deep uncertainty. For instance, achieving successful closed-loop logistics depends, among others, on the unknown quality, quantity and timing of product returns [52]. To specify potential CLSC interventions and related deep uncertainties, combinations of methods, such as evidence from the literature, brainstorming techniques, morphological analysis, and analysis of interconnected decision areas (hereinafter AIDA) can be employed. In this context, morphological analysis starts with splitting up the CLSC decision domains into different dimensions. Then, the dimensions are presented in the form of a matrix, with the cells suggesting the possible functions or aspects of each dimension. For the specification of the possible functions/aspects, the supply chain actors can use brainstorming techniques and evidence from the literature. Based on the matrix, different combinations of possible interventions can be generated by linking a function/aspect from one dimension to a function/aspect from each other dimension. The AIDA method is, to a substantial degree, based on the same ideas as the morphological analysis, but AIDA concentrates on the exploration of inconsistent or incompatible (CLSC) interventions. This way, several interventions can be excluded, and within the remaining, possible interventions, portfolios can be generated. Both morphological analysis and AIDA enable the supply chain actors to explore intervention portfolios that might normally be overlooked. To specify the deep uncertainties in relation to the CLSC interventions, brainstorming and evidence from the literature can again be used.

Question 18: The process of specifying possible CLSC interventions may produce so many interventions that it is too costly (because or required in time and resources) to examine all of them thoroughly. Consequently, it is desirable to screen out the inferior possibilities. In other words, the challenge is to reduce the intervention set to the—for the supply chain actors—most important CLSC interventions. In the case of persistent disagreements between supply chain actors regarding which CLSC interventions are the most important ones, the researcher could choose to apply multi-criteria decision methods to support the actors in this selection process [53,54]. The selection

criteria are based on the goals formulated in Activity 2b. One could also choose to employ a Delphi inquiry or perform a deliberative democratic evaluation. Another method that could be applied is a voting procedure. For instance, Kallis et al. [36] describe a voting procedure with the aim of selecting the most relevant ideas. First, the group of actors is divided into sub-groups with the aim of separately generating a multitude of ideas. Based on the generated ideas, each sub-group votes for the most relevant ideas from their point of view. The ideas with the most votes are selected. Next, these selections are discussed in the whole group.

4.1.7. Activity 3b of Maturity Stage 3: Identification of the Causal Structures of Adapted BAU Supply Chain System Models

To identify the causal structures of linked CLSC interventions-BAU supply chain system models (Question 20) and the ranges of uncertain parameters and structures (Question 21), the supply chain actors should first become aware of and be able to specify the variables and parameters of the CLSC interventions and related deep uncertainties identified in Activity 3a. Therefore, Question 19 needs to be answered first.

Question 19: To specify the variables and parameters of the most important CLSC interventions and related deep uncertainties, the actors can apply methods, such as interviews with the supply chain actors involved and other experts and/or brainstorming techniques. Data originating from Questions 16 to 18 can also serve as input for answering Question 19.

Question 20: The variables and parameters of (combinations of) CLSC interventions and related deep uncertainties need to be integrated into the existing structure of the BAU supply chain system (see Activity 1b), leading to divergent plausible system models. To develop these models and explore the causal structures in collaboration with the supply chain actors involved, group model building, mediated modelling or companion modelling can be employed. Regarding the former two, the supply chain actors could build causal loop diagrams and stock-flow diagrams, displaying the nonlinear interactions and feedback loops of the CLSC interventions, uncertainties, and the existing structure of the BAU supply chain system. Regarding companion modelling, the supply chain actors can build state charts displaying products or actors with properties that are different from each other in relation to the CLSC interventions. These state charts serve as input for the exploration of dynamic system behavior (see Activity 3c).

Question 21: The causal structures of various adapted BAU supply chain system models consist of parametric and structural variations. In the case of deep uncertainty, the range of uncertain parameters should be as large as possible. After all, one does not (and sometimes cannot) know how certain developments inside and outside a supply chain unfold. To specify the uncertain parameters, system model structures, and their ranges, focus groups, a literature study and/or individual interviews can be applied. The data retrieved from Questions 19 and 20 and the literature study may serve as inputs for the focus groups and individual interviews.

4.1.8. Activity 3c of Maturity Stage 3: Specification of (i) the Different Types of Dynamic Behavior of the BAU Supply Chain System Model in Response to Potential CLSC Interventions and (ii) the Deep Uncertainties Causing the Dynamic Behaviors

To be able to define which deep uncertainties cause the different types of dynamic economic, ecological and/or societal behavior of (parts of) a BAU supply chain over time, at different geographical scales and/or organizational levels (Question 23), supply chain actors first need to become aware of and identify which types of dynamic behaviors can occur (Question 22).

Question 22: For the exploration of the different types of dynamic behavior, the same methods could be applied as in Activity 3c, i.e., ESDMA, EAMA, and/or experiential model-based serious gaming.

Question 23: Machine learning algorithms (e.g., PRIM, PCA-PRIM), which are part of the exploratory modelling and analysis, can be used to reveal the combinations of uncertainties that cause the different types of dynamic behavior.

4.1.9. Activity 3d of Maturity Stage 3: Identification of No-regrets CLSC Interventions

Question 24: According to the literature, various methods can be applied to explore which potential CLSC interventions can be defined as no-regrets CLSC interventions, such as many-objective robust (and nonlinear) optimization and a direct policy search. The first method can be employed to find the worst and the best that could happen in a supply chain, given the CLSC interventions and related uncertainties identified in Activity 3c. The method is also applicable for the achievement of (conflicting) goals defined in Activity 2b. Therefore, different types of algorithms can be used, such as genetic algorithms, many-objective evolutionary algorithms or artificial neural networks [55,56]. To make sure that the knowledge of the BAU supply chain behaviors in response to the various CLSC interventions is systematically used for feedback to inform decision-making at each stage, a ‘closed-loop control method’ can be applied by the researcher, which is also called the ‘direct policy search’ in the literature [57]. A direct policy search simulation model can be coupled with many-objective evolutionary algorithms to directly optimize the attainment of the goals formulated in Activity 2b. Interactive visual analytics can be used to visualize the trade-offs (i.e., Pareto) curve and makes the results derived from robust optimization and direct policy search understandable for the supply chain actors involved, by for example using (3D) graphs [58].

4.1.10. Activity 4 of Maturity Stage 4: Selection of the Preferred Transition Map towards a CLSC

To select a preferred transition map (Question 27), the supply chain actors must first become aware of and be able to indicate the signposts and triggers of the no-regrets CLSC interventions (Question 25) and to build various alternative transition maps based on the CLSC interventions (Question 26).

Question 25: Signposts and triggers serve as early warning signals that the goals and objectives may not be achieved anymore through underperformance and that a form of adaptive reaction is required [59]. To identify signpost variables and trigger values, the researcher can use data retrieved from the application of Activity 3d, which are the plausible scenarios in relation to the no-regrets CLSC interventions. The researcher can study which variables trigger changes and discusses the results with the involved supply chain actors. For the presentation of the signposts and triggers of each of the CLSC interventions to the supply chain actors involved, the researcher can apply one of the earlier mentioned interactive visual analytics techniques.

Question 26: Based on the no-regrets CLSC interventions identified in Activity 3d and the related signposts and triggers, different transition maps can be built by the supply chain actors. A transition map consists of various pathways. A single pathway consists of a sequence of CLSC interventions that are appropriate to implement within a certain time horizon. A transition map also consists of alternative no-regrets CLSC interventions that can be implemented or adjusted in case the existing intervention is underperforming. To construct different transition maps, workshops can be organized where the supply chain actors sort the no-regrets CLSC interventions in the different decision domains and order the interventions by time horizon, geographical scale and organizational level. However, decision making on when to implement which CLSC intervention does not only depend on the robustness of the intervention in terms of no-regret but also on the required financial investment, at least for the CLSC interventions that can be implemented immediately or in the short run. Therefore, a ‘cost-benefit analysis might be appropriate. A point of criticism, however, could be that in this method the distribution of costs among the different actors is not considered. Another method that could also be used is a ‘cost-effectiveness analysis’, in which, in comparison to cost-benefit analysis, costs do not have to be expressed in monetary terms [51]. In cost-effectiveness analysis, however, only alternative CLSC interventions with the same goal or objective can be weighed against each other. This is not the case with cost-benefit analysis, where alternative CLSC interventions with different goals or objectives can be weighed against each other, if they are expressed in monetary terms.

Question 27: When the supply chain actors have gained awareness on and built various alternative transition maps, it may be that the actors involved cannot agree upon the relatively most important transition map. In that case, the earlier mentioned voting procedure might be appropriate to employ

with the aim of achieving an agreement on the collectively preferred transition map. As mentioned before, however, the result could also be an agreement to disagree.

4.1.11. Activity 5 of Maturity Stage 5: Selection of the Relative Preferences regarding Investments in Anticipative and Adaptive Steering of a CLSC

To be able to agree or agree to disagree on the relative preferences regarding the investments in anticipative steering and adaptive steering of a CLSC (Question 31), the supply chain actors must first become aware of and be able to clarify their individual preferences (Questions 28 to 30).

Questions 28 to 30: The supply chain actors may have different, or even conflicting, preferences in relation to the appropriate actors to include, to set basic rules (e.g., who communicates what with whom, confidentiality) and to spend time and money on (i) tracing developments and changes inside and outside the relevant CLSC and (ii) the monitoring of the signposts and trigger values of the selected transition pathways. To identify the different preferences, brainstorming techniques, electronic meetings and/or individual interviews can be applied.

Question 31: To minimize the risk of indecisiveness, it is proposed to apply methods such as voting procedures and multi-criteria decision aid methods. The latter might be appropriate to select the preferred actors from a field of multiple candidates. The former might support decision making on the preferred basic rules, time and money to spend on tracing developments and changes and monitoring the signposts and trigger values. The data retrieved from Questions 28 to 30 serve as input for the application of the methods.

4.2. Qualitative Assessment of the Methods from a Process Perspective

In Section 4.1, a large range of different methods has been mentioned and some substantive advantages and disadvantages of the selected 31 methods have been reported. This subsection presents a qualitative assessment of these methods in terms of (i) the degree of participation of supply chain actors, (ii) the expected duration, and, (iii) the methodological expertise that is assumed to be needed for the application of the method concerned. Table 2 presents the results of this assessment.

4.2.1. Required Degree of Participation of Supply Chain Actors for the Application of the Methods Concerned

Most methods require an active engagement of the supply chain actors in the collection of data and the analysis and/or decision making based on the results of the analysis. This finding may seem obvious, because one of the aims of this study was to search for methods that can support actors in coping with, or even reduce persistent disagreement (i.e., a form of deep uncertainty). However, as noted by Coenen et al. [6], many CLSC management and decision-making studies that focus on uncertainty do not focus on reaching an agreement or dealing with persistent disagreement and, therefore, do not include participatory methods, such as environmental scenario development, brainstorming techniques, or voting procedures. In other words, most of the studies are non-participatory or require passive consultation. However, to cope with the known unknowns and persistent disagreement simultaneously, a connection should be made between methods that are non-participatory, or based on passive consultation, and methods that assume active engagement of the actors.

4.2.2. Duration of the Methods Concerned

Most of the methods have a medium or long runtime. For instance, (exploratory, prospective) scenario development is time consuming, mostly because data from different sources have to be collected and interpreted by the different actors and experts involved [60]. Nevertheless, sharing ideas and beliefs regarding the various grand challenges might improve and broaden the awareness of the actors on the plausible course of the grand challenges. Methods such as ESDMA, EAMA, many-objective robust (and nonlinear) optimization, system dynamics modelling and agent-based modelling are also time consuming, especially in the case of large system models. Brainstorming

techniques, however, are not time consuming [61]. Methods such as morphological analysis, Delphi, data clustering methods and (behavior-based) classification methods generally have a medium duration. However, regarding the morphological analysis, the actual duration depends on the depth of the interventions desired and if there is computer support (i.e., software), among other aspects [62]. With respect to the clustering and classification methods, the actual duration depends on the algorithm that is being used.

4.2.3. Required Methodological Expertise needed for the Application of the Method Concerned

With most methods, it is important to involve/consult methodological expertise. For example, methods such as ESDMA and EAMA require considerable expertise in modelling and computation. Multi-criteria decision aid methods require expertise in selecting the criteria, assigning weights, applying decision rules, and performing sensitivity analyses, especially when uncertainty is present. In addition, it is important to communicate the choice of assigning weights to criteria in a transparent manner. Otherwise, manipulation may occur. Therefore, it is important to involve an independent methodological mediator [51]. For a proper application of the Delphi inquiry method, professionals and experts who are knowledgeable in their field within the supply chain must be invited to participate. For instance, a CEO of a clothing brand firm who has substantial knowledge of the grand challenges in and surrounding (parts of) the clothing supply chain. Experts might also include trend watchers or branch organizations. In addition, as a consequence of the (digital) surveying approach, Delphi offers the freedom to select experts based on their closeness to, or experience with, an issue without being limited by geography or narrow expert definitions [34]. (Exploratory, prospective) scenario development also requires the involvement of experts with a deep understanding and knowledge of the grand challenges in question [60]. Involving experts can also ensure that weak-signals and disruptive events are better recognized as such. With respect to the deliberative democratic evaluation method, an evaluator is needed. The evaluator aims to draw justified conclusions. The evaluator might be the researcher or another independent expert who is able to supervise the process, to keep the initiated dialogue going and to elaborate summaries and conclusions [51]. All actors involved must absolutely recognize the neutrality of the evaluator. Doubts about the evaluator may be a reason for the actors not to participate in the evaluation process or to question the evaluation results [51].

In some methods, the involvement of methodological expertise is not required, but it could support or improve the application of the method concerned. For instance, in the case of a morphological analysis, which is a rather straightforward method, the involvement of a facilitator and/or computational support is not necessary, but might contribute to the process of specifying possible CLSC interventions [62].

In the case of methods such as brainstorming, SWOT analysis and voting procedures, the presence of methodological expertise is not required. However, one might argue that to guarantee the qualitative and/or quantitative productivity of these methods, it is important that the participant/actor groups are not too large (5–10 members).

Table 2. Qualitative assessment methods for the CLICK methodology.

Method	Criteria								
	Nature of Participation SC Actors			Duration			Required methodological Expertise Needed for the Application of the Method Concerned.		
	<i>Non-Participation</i>	<i>Passive Consultation</i>	<i>Active Engagement</i>	<i>Short</i>	<i>Medium</i>	<i>Long</i>	<i>Not Required</i>	<i>Supports and Improves</i>	<i>Required</i>
Environmental (framed, unframed) scenario development			X			X			X
System dynamics modelling		X			X				X
Agent-based modelling		X			X				X
Exploratory system dynamics modelling and analysis		X				X			X
Exploratory agent-based modelling and analysis		X				X			X
Experiential model-based serious gaming (PCA)-PRIM	X	X				X			X
Brainstorming techniques			X	X					X
Many-objective robust (and nonlinear) optimization	X					X			X
(Evolutionary, multi-objective) direct policy search	X					X			X
Multi-criteria decision aid methods		X			X				X
Morphological analysis			X		X			X	
Delphi inquiry		X			X				X
Voting procedure			X	X			X		
Deliberative democratic evaluation			X		X				X
Cost-benefit analysis		X				X			X
Cost effectiveness analysis		X			X				X
Group model building			X			X			X
Mediated modelling			X			X			X
Companion modelling			X			X			X
Interactive visual analytics techniques	X				X				X
Goal tree analysis			X	X			X		
AIDA			X		X			X	
Literature research	X				X		X		
Individual (expert) interviews		X			X				X
Data clustering techniques	X				X				X
Electronic meetings (e.g., Visa Skills lab)			X		X				X
(Behavior-based) classification techniques	X				X				X
SWOT analysis		X		X			X		
Confrontation matrix			X		X			X	
Stakeholder analysis methods		X			X		X		

5. Conclusions and Discussion

The analysis in this paper was triggered by calls for innovative research and decision-making approaches to study and cope with deep uncertainty and dynamic complexity in a transition towards more mature CLSC management. A conceptual framework was built consisting of six maturity stages and a related toolbox was specified (jointly referred to as the CLICK methodology). Maturity Stages 1 to 5 are about gradually increasing the supply chain actors' capabilities to gain awareness of, as well as understand, develop, and accept a series of decisions regarding the following: (i) the plausible behavioral effects of the relatively most important grand challenges such as global resource scarcity, climate change or CO₂ reduction plans on a BAU supply chain (Maturity Stage 1), (ii) the actors' ambitions to make a transition towards a CLSC (Maturity Stage 2), (iii) the no-regrets interventions for transitioning towards a CLSC (Maturity Stage 3), (iv) the transition map (Maturity Stage 4), and, (v) the actors' plan for anticipative and adaptive steering of a CLSC (Maturity Stage 5). In Maturity Stage 6, it is suggested that the actors have reached a level of mature CLSC management under deep uncertainty and dynamic complexity. This implies that supply chain actors at this stage have both operationally and mentally moved away from a stochastic and static way of acting and thinking towards an exploratory and dynamic way of acting and thinking. For the empirical study of and coping with deep uncertainty and dynamic complexity, 31 appropriate methods have been found to fill the toolbox and support the achievement of the various maturity stages of the CLICK methodology. These methods vary from non-participatory to active engagement and from analytical methods to evaluation/assessment methods. Despite the thorough research into appropriate methods for the CLICK methodology, the authors do not rule out that other methods or variations on the methods exist which may be useful in practice. The included selection refers to a set of methods with which experience has been reported in literature, offering background information for the decision in the context of practical applications of the CLICK methodology to apply the methods. Future evaluations of practical experience with the suggested methods in the context of CLSC management will be helpful for eliminating from or adding other methods to the toolbox.

Furthermore, the number of maturity stages in the conceptual framework is based on a logical sequence of general management activities, i.e., problem identification activities, goal and intervention development activities, implementation and operation activities, and monitoring activities. To this end, new management activities (Activities 1a–2a) are developed and added to the conceptual framework. These management activities seem to be missing in the existing decision-making framework. However, there are many situations, especially when it comes to transitions, where goals, a plan or interventions cannot be formulated upfront because of deep uncertainty (i.e., grand challenges) and dynamic complexity in the environment. Although some maturity capabilities and activities could be merged, the order of the capabilities to be developed and the activities to be performed must be maintained, to create the best conditions for making a transition towards more mature CLSC management. The order of analytical and decision steps in the CLICK methodology offer (at least theoretically) a large added value in systematically increasing the understanding of the system's dynamic complexity, in helping to identify and structure relevant sources of uncertainty, and in enabling the selection of no-regrets CLSC interventions. Future research with practitioners in real-world contexts should provide the empirically evidence whether the proposed CLICK methodology can indeed provide the claimed support in such contexts.

The focus so far in the scientific debate on deep uncertainty has primarily been on the 'known unknowns'. Very little attention has been paid to (coping with) persistent disagreement among actors, which should also be recognized as a form of deep uncertainty. With the CLICK methodology, this form of deep uncertainty can be reduced, presuming an adequate formulation of the reasons for this disagreement and a choice for the application of supportive methods that matches the nature of these reasons with the aim of reaching an agreement. For instance, multi-criteria decision aid methods or a voting procedure could support supply chain actors in achieving an agreement on the relatively most important CLSC interventions to explore. In general, various authors claim

that participatory research methods support actors to improve system understanding, improve each other's perspectives and to cope with or even reduce conflicts/disagreement [63]. However, it may also be that, despite the proposed methods, the supply chain actors still cannot agree upon certain issues. In that case, one can choose to preserve the richness in preferences, interests or opinions for analysis for the next maturity stage, proposing that further analysis in that context might be helpful to (partly) reduce this richness and even to arrive at agreement. Hence, future research is needed on (the effectiveness of) of alternative methods that claim to support reaching agreement or reduce persistent disagreement in a decision-making process. Furthermore, non-participatory methods are essential for coping with the known-unknowns, especially because participatory methods do not seem to offer features to do so [64].

The data generated in simulations involving thousands of scenarios can be difficult for researchers to visualize to the relevant supply chain actors. However, to increase actors' commitment and to facilitate the learning experience, it is important to make the (scientific) data and research results accessible. Therefore, it is essential to link analytical techniques to powerful forms of communication that are simple in presentation form, flexible in use, are clear in terms of narrative, etc. Animations and (animated) info-graphics can help researchers to communicate data and research more effectively. The development and testing of such communication approaches also provides a challenge for future research.

Finally, various other avenues for future research can be identified. The gaining of practical experience with the elaborated approach seems to have the highest priority. The CLICK methodology should be considered as a guideline in that respect; hence, steps should be filled in with prudence and in interaction with the unique circumstances. Evaluating and sharing the experiences will bring the theory on and practice of CLSC management further. The authors of this study intend to contribute to this challenge soon.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/11/8/2318/s1>, Table S1: Domains relevant for closed-loop supply chain management.

Author Contributions: J.C., with the help of R.v.d.H. and A.C.R.v.R., conceptualized the paper and all three authors were involved in the methodology design; data collection and analysis were carried out by J.C.; R.v.d.H. and A.C.R.v.R. provided relevant feedback; J.C. developed the visualization and wrote the main part of the paper; R.v.d.H. and A.C.R.v.R. contributed to the discussion and editing.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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