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A causal map analysis of supply chain decentralization.

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A Causal Map Analysis of Supply Chain Decentralization

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ABSTRACT

We study the inclusion of loops in automated theory development based on causal logic. As an area of application, we formalize a model of learning, adaptation, and selection in supply chain management. Our methodological contribution is to analyze a causal network with propositional logic, explaining the difference between material and intentional causality and considering cumulative causality. In the application domain, we prove that the ability of a supply chain to attract resources in turbulent environments depends on its governance structures, the degree of decentralization, and learning incentives, while in stable environments, a supply chain fails to attract resources if a dominant firm appropriates the rents created by others or if it lacks the ability to replicate its own structure. Furthermore, in turbulent times, adequate resources and dynamic routines allow the supply chain to survive.

KEYWORDS

Causality; cognitive mapping; knowledge-based systems; organizational learning; supply chain decentralization

Introduction

Cognitive mapping techniques obtain subjective knowledge from individuals and groups and represent it graphically.[1–6] They have been applied in different problems, including, among others, operational risk modeling using Bayesian networks,[7] measuring entrepreneurial orientation,[8] customer loyalty management,[9] and bankruptcy analysis.[10]

Causal maps, more specifically, have been used to study, for example, risk elicitation in the context of project management,[11] organizational ecology,[3] and supply chain performance measurement.[12] There are two major features of these maps, unique to the social sciences, which challenge the way logicians have looked at causal relationships: the first is intentional causality and the second is the presence of causal loops.

Intentional causality arises when we use rationality to assert the relationship between observed outcomes, which Hodgson[13] calls teleological causality and which has its origins in Aristotle's philosophy. Intentional causality has not yet receiving the acknowledgment it is due in economics and management, where the concept of *equilibrium* tends to prevail. Intentional causality is also absent in physics, which considers material causes only. As explained by Hodgson,[13] the relationship between intentional and *material causality* is crucial to understanding what the social sciences are about. Whereas causal dualism maintains the distinction between material and intentional causality to endow people with free will, causal monism asserts that all causality is material in nature. Accordingly, even the decisions made by people are, at a certain level, the result of matter at work. This concept is summarized in Figure 1. A third approach is *emergentist causal monism*, which regards intentions as emergent properties of matter, as proposed, among others, by Diderot, Darwin, and Veblen (Figure 1).[13]

Another important concept in the analysis of social systems is *feedback loop*, which, when associating decisions with respective effects, can be described as *causal loop*. From a methodological perspective, the problem we address in this article is based on the actual meaning and possibility of causal loops. The name itself is an issue. If there is a causal loop, it means that a decision at time t has an impact on the same decision at time $t + 1$. For example, how will a promotion in March impact pricing and sales in April? There is a clear relationship between the two pricing decisions and a feedback loop (and therefore a causal loop).

Additionally, these causal loops are important from a philosophical perspective. As described by Veblen, cumulative causation views the causal relationship as continuous, always changing and transitory, but cumulative between cause and effect.[13]

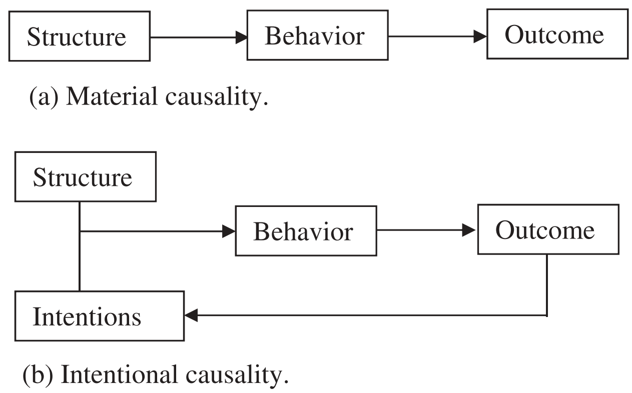

Figure 1. Causal graph of material vs. intentional causality.

So, from policy, practical, and philosophical perspectives, it is well known these causal loops exist and are central to the social sciences in general. Nonetheless, from a logical perspective, causal loops are problematic due to the understanding that one decision will lead to another and so on in an infinite loop. As a methodological contribution, we propose the formalization of causal loops using propositional logic. Propositional logic has been used in management science to analyze, among other issues, collaborative decision-making where different agents confront diverse arguments about a given topic that may be contradictory or not supported by facts.[14] The main advantage of such formalization is in allowing the complex dynamic behaviors to be described as a set of simple rules that interact with each other, enabling a better understanding of the relationship between cause and effect when describing a theory.

We apply propositional logic to theory development in supply chain management (SCM) for three main reasons. First, these are complex distributed systems constituted by organizations that exhibit interdependent behavior with non-linear performance,[15–17] the analysis of which requires knowl-edge from different areas of management. Second, as suggested by Hitt,[18] there is a need for a better integration of research in strategic management with SCM, more specifically in the areas of resource-based view, transaction cost economics, organizational learning, and social capital. Third, there is an increasing movement from centralized to decentralized supply chains facilitated by platform technology as the basis of the sharing economy and, for example, including peer-to-peer rental car and ridesharing[19–21] and more recently by the blockchain, in which individuals are viewed as auton-omous agents and part of an organizational ecology with self-evolving structures organized around smart contracts.[22–24]

We specifically formalize supplier relationship manage-ment as it is still an underdeveloped part of SCM: for example, 87% of companies in the P*w*C survey report having no established system to do it.[25] Even though supplier relationship management is essential for integrating suppliers in the business planning and in product and service innovation,[26] due to "lack of goal congruence, commitment, and trust," there are still potential barriers for increasing integration[1,27] and learning,[28,29] limiting supply chain profitability.

For these reasons, we need to pay better attention to the governance mechanism as an important component of a supplier relationship management system.[28–33] This govern-ance mechanism together with the supply chain structure is crucial in determining the use of bargaining power (which translates into different degrees of hierarchical control) and the survival of the supply chain.

As a contribution to this discussion, we apply automated methods to formalize a theory on the interaction between learning, bargaining power, and survival of the supply chain, using causal maps. Automated methods have been used in the management sciences to study organizational ecology,[3,34] and digital records.[35] This article differs from the previous literature not only in terms of the application domain but also with regard to the specific problem of developing a causal theory with loops and in the description of the hierarchy between the different results derived from the analysis.

The remainder of the article is organized as follows: First, we summarize causal analysis and propositional logic. Second, we formalize a causal theory of learning, adaptation, and selection in supply chain ecologies, describing the base axioms of the theory. Third, we derive new results and insights into SCM. Fourth, we discuss the major results in supplier relationship management, and finally, we present our conclusions.

Literature review on theory formalization

Propositional logic

In order to describe how theory formalization works, let us start by recalling the basic principles of propositional logic.[36,37] We first define its basic components, the predicates, or clauses, which are the statements we make about the relationships between variables. The formulas of propositional logic are obtained recursively from the basic axioms through the use of connective symbols, which (in this article) are not ($\neg$), and ($\wedge$), causal implication ($\leftarrow$). We discuss this in detail in the next subsection. In propositional logic, each clause is assigned a truth-value (*true* or *false*). A clause is said to be consistent if it can be interpreted as *true* and inconsistent otherwise. A clause is said to be valid (also known as a tautology) if it is always interpreted as *true*.

Automated theory development is undertaken in the context of an axiomatic system, also known as a proof theoretical system, which consists of a set of axioms and a set of inference rules (we use Modus Ponens, which states that if x and ($y \leftarrow x$) are theorems, then y is a theorem). A derivation, or proof, of a theorem is a sequence of axioms, inference rules, and previously obtained theorems required to prove that theorem. A vital requirement of an axiomatic system is *soundness*: every theorem must be a valid clause, i.e., a sound axiomatic system cannot generate a formula and its negation.

In this article, the theories are written in the clausal form, as proof procedures for this type of formula are simpler. As in earlier work,[4,38] we use *Horn clauses*, which for reasons of efficiency of the proof system can contain at most one positive literal, $Q_i \leftarrow P_1 \wedge \ldots \wedge P_m$, for all i.

Causal implication

As described earlier, we use causal implication ($\leftarrow$) in a rule-based system to derive causal relationships.[3,4,39–41] The main reason for this choice is the clarity of the rules derived and formalized and to enable us to describe a theory as close as possible to the one intended by the authors of the original studies.

In scientific research, we very often look for cause–effect relationships; however, the informal use of the word *cause* leads us to employ it with different meanings. As described by Copi et al.[36], it may stand for necessary or sufficient conditions, depending on the context. They explain the importance of this distinction whereby cause can be inferred from the effect when it is used as a necessary condition, while the effect can be inferred from the cause when the latter is used as a sufficient condition. The interpretation of causality as a necessary condition is not in the mainstream. Nonetheless, whereas sufficiency is the main feature used in theory development and interpretation, necessary conditions tend to be the focus of empirical work.[42]

Typically, in scientific theory development, we aim to infer the consequences from observing the causes. In this context, causality is interpreted as sufficiency, and this is the meaning we will attribute to causality in our theory.

Moreover, it is true that in empirical research we very often talk about the variables being associated or correlated instead of imposing a causal relationship because the latter assumes some additional knowledge of the problem under study. Nonetheless, causality is always a theoretical construct first, even when tested empirically.

Additionally, and most importantly, the main reason for using causal implication in automated theory development is the observation that many theoretical articles commit mistakes in using material (classical) implication. The errors arise from the difficulties in dealing with material implication. In causal implication, the relationship described is *a causes b*, and then observing a is enough to conclude that b is true (causality as a sufficient condition). This is not the case in material implication. The proposition *a implies b* is harder to interpret (when a is false, the proposition is always correct, independently of the truth value of b). This is what is known as a negative definition, in which the implication holds true until there is some evidence showing otherwise, i.e., an observation in which b is false but a is true.[37,43,44]

Therefore, we focus on causal implication as some of the axioms in the original studies only make sense if interpreted under a causal framework. Interpreting the axioms using material implication changes the inference sequence, and we may end up confusing cause and effect when, in reality, the material implication cannot impose any of these views. Consequently, for the sake of transparency, we have chosen to use causal implication.

Finally, very often cause is something that " …*tends* to have a causative role in the production of certain outcomes"[36(p455)] which is more often than not the meaning given to causality or the relation-ship between two variables in management sciences. In summary, we use the operator causal implication ($\leftarrow$) to convey the meaning "tends to have" or "increases the likelihood that some effect will arise."

Table 1. Basic concepts.

Concept	Description
Supply chain	Collection of organizations with coordinated routines institutionalized by formal and informal contracts.[15,46]
Resources	People, knowledge, machinery, real estate, marketability, and also information sharing or connectivity. The unique position an organization develops in comparison to its competitors through the routines employed to manage its resources (i.e., competitive advantage).[17,29,32,45,47–51]
Survival	A supply chain survives if it continues to operate year after year.[30,52,53]
Inertia	Structural inertia is the inability of an organization to modify its institutionalized routines.[52]
Institution	Represents an organization that has crystalized.[52]
Reliability and accountability	Reliability is the capability to produce collective outcomes of a given quality repeatedly. Accountability is the documentation of how resources are used and the reconstruction sequences of decisions and actions that lead to a particular result.[52]
Reproducibility	An organization can continuously repeat the same routines, under similar conditions, with similar output.[52]
Stable	A business environment in which there is no significant (structural) change.[52]
Routines	Routines are constituted by the informal and formal procedures regulating the interactions within the supply chain between flows of information, goods, and money.[31,45,54]
Knowledge	The formal and informal routines embedded in people and in formal policy.[29,31,45,50,51,53,54]
Institutionalization	The process of embedding learning by individuals and groups into the systems, structures, procedures, and strategies of an organization.[17,28,29,45,49–51]
Learning	The process of accumulating and modifying knowledge, which enables adaption to environmental changes, allowing the development of the capabilities valued by customers.[17,28,29,45,49–51]
Exploration	The creation of new knowledge and opportunities.[55–57]
Exploitation	The use and refinement of existing knowledge.[55–57]
Adequate learning incentives	The intellectual property rights reside in the supply chain and the innovator firm tends to appropriate the related benefits.[17,19,31]
Operational routines	These are the activities of exploitation carried out by the supply chain.[16]
Dynamic routines	The formal and informal processes defining the way the organization acquires new knowledge. These are also known as knowledge management capabilities.[32,51]

Table 2. Concepts for supplier relationship management.

Concept	Description
Pooled and standardized	Each supply chain member gives a contribution to the whole, is supported by the whole, and uses standard procedures.[21,23,50]
Sequential and planned	One member's task must be accomplished before another member's task starts, and the coordination mechanism is planning, as schedules and plans are essential to ensure coordination between agents.[21,23,50]
Reciprocal and mutualism	The members' tasks are interdependent and they use supply chain management tools, such as integrated project development teams, to achieve coordination between the agents in the supply chain.[21,23,50]
Master	A supply chain has a channel master if one firm in the chain owns an important resource over which it has a concentrated control or if it is a large firm in comparison to its partners.[16,17,30–33]
Bargaining power	The master's ability to impose its will on the supply chain partners due to the control of key resources.[16,17,30–33]
Exercise max power	The channel master appropriates all SCM gains plus a part of the pre-SCM profits.[16,17,30–33]
Exercise low power	The channel master appropriates all SCM gains but not the pre-SCM profits.[16,17,30–33]
Forbear power	The channel master shares the SCM gains with the other members of the supply chain.[16,17,30–33]
Hybrid governance structures	A sufficient condition for the development of hybrid governance structures is the presence of high and reciprocal transaction costs when vertical integration is not viable and there are knowledge sharing routines in the supply chain.[28,29,49,50]

Application domain: supply chain management

Basic concepts

The main concepts in our application domain are summarized in Tables 1 and 2. The theory can be described in a few paragraphs. The objective of the supply chain is to survive by being profitable and accumulating resources, toward which they develop operational routines to allow the exploitation of current knowledge and become *reliable & accountable*. However, these routines, created by a process of institutionalization, lead to the development of inertia, preventing the supply chain from adapting to structural disruptions.

Consequently, long-term survival involves the ability to learn and adapt, for which the supply chain, therefore, needs to institutionalize the dynamic routines that enable learning through exploration and resource accumulation in times of disruption. These dynamic routines are difficult to implement, as they require constant investment of resources and the implementation of adequate learning incentives.

A formal theory of organizational ecology and learning

The development of qualitative theories is likely to be incomplete and/or contain contradictions due to space constraints, language ambiguity, and issues with exposition. Most importantly, it is difficult to derive new results from a qualitative summary. For this reason, we now proceed by formalizing our theory using propositional logic and causal networks.

The first step in the formalization of a theory is the description of its basic axioms, which are summarized in the Appendix, Table A1. We consider a concept as exogenous to the theory if the latter cannot explain the former and the concept is, instead, a feature of the supply chain. We add the prefix $\neg$ to each one of these predicates to represent the respective negation. We start by identifying the reinforcement loop represented by the coevolutionary relationship between selection, adaptation, and learning in axioms A1 to A17, shown in Figure 2. The nodes are concepts (predicates) and the arrows represent causal relationships and are named after the respective axioms. We will now focus on Figure 2, instead of Table A1, to facilitate understanding of the theory in its completeness.

In Figure 2, we adapt the original theory on structural inertia using causality.[52] An alternative formalization of organizational inertia can be found in Peli et al.,[34] for example. We postulate that independently of the level of the business environmental instability, supply chains that accumulate resources have a higher probability of survival (axiom A1), and those that deplete resources exhibit a lower probability of survival (axiom A2) because resource accumulation protects against environmental shocks, thus increasing the probability of survival. The continuous accumulation (depletion) of resources is, therefore, a sufficient condition for survival (collapse). For this reason, our analysis focuses on resource accumulation and depletion.

Moreover, reliability and accountability tend to increase the probability the supply chain is able to attract resources: a *reliable & accountable* supply chain has a higher probability of attracting resources (axiom A3), whereas a supply chain that is not *reliable & accountable* has a higher probability of failing to attract resources (axiom A4). Axioms A3 and A4 are an adaptation of Hannan and Freeman's[52] theory to include the use of resources.

Furthermore, using concepts from organizational ecology, we postulate that supply chains with institutionalized operational routines, if possessing reproducible structures, tend to have a higher probability of being *reliable & accountable* (axiom A5).

However, supply chains that cannot reproduce the same level of performance have a higher probability of not being *reliable & accountable* (axiom A6). Furthermore, when there is an environmental change, inert supply chains have a higher probability of not being reliable (axiom A7). Additionally, axiom A8 declares that if the business environment is stable, the existence of institutionalized operational routines is suffi-cient for increasing the probability of reproducibility of supply chain routines. This axiom is new as it proposes a causal explanation for reproducibility, which is absent in Hannan and Freeman's[52] original theory.

Axiom A9 introduces the interaction between structural inertia and learning by considering that supply chains with a reproducible structure, but only those practicing exploitation, have a higher probability of developing structural inertia. A9 refines Assumption 3 in Hannan and Freeman[52] by explaining the role of exploitation in the creation of inertia. Furthermore, extending Hannan and Freeman's[52] theory, A10 explains the institutionalization of operational routines, which are a direct consequence of survival.

Axiom A11 postulates that supply chains that survive become crystalized into institutions. This axiom is relevant for what it does not declare. It does not assert that institutions tend to survive or fail, but quite the opposite: institutionalization is the result of a successful adaptation process.

We now formalize the learning part of our theory by incorporating interactions with organizational ecology and the development of dynamic routines. Organizations may choose different learning strategies, such as exploration and/or exploitation. It has been shown that these methods are indeed complementary, and some organizations pursue both under different conditions to implement ambidextrous learning. To reflect this perspective, axiom A12 postulates that a supply chain failing to attract resources tends to implement exploitation but not exploration, as exploration is resource intensive.

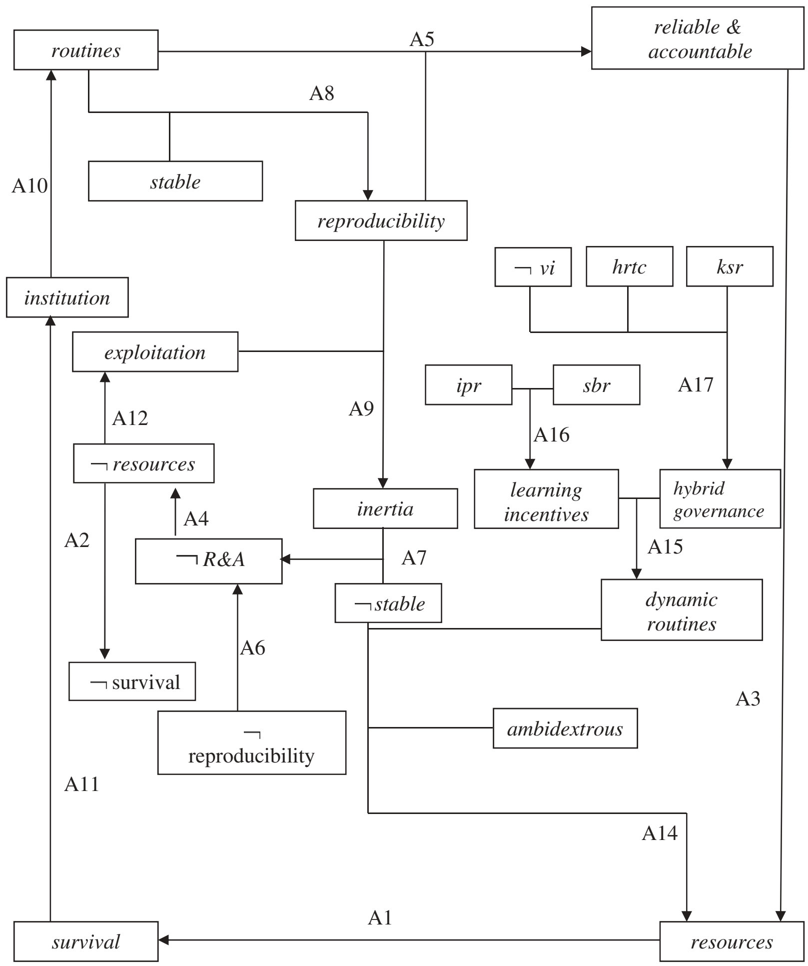

Figure 2. This causal graph represents the relationships between axioms A1 to A17.

Moreover, axiom A13 declares that ambidextrous learning tends to occur in supply chains with the resources and dynamic routines essential for continuous innovation. Exploration has a cost in terms of the structures involved in the maintenance of learning abilities, which need to be constantly renewed. When a supply chain is able to achieve ambidextrous learning and has the dynamic routines that enable the transformation of knowledge into adaptation of its structure, it has a higher probability of attracting more resources (axiom A14) if there is a change in business environment, as it can profit from the new opportunities and avoid potential threats.

Furthermore, we postulate that a supply chain has a higher probability of having developed dynamic routines (agility, adaptability, and alignment) if it has implemented adequate learning incentives and a hybrid governance structure (axiom A15). Additionally, adequate learning incentives tend to be implemented in the supply chain (axiom A16) when the intellectual property rights (*ipr*) reside in the supply chain and the innovator firm appropriates the related benefits (*srb*). Both the *ipr* and the *srb* are exogenous to the theory. These learning incentives are crucial for the supply chain as the firm creates knowledge that is difficult to imitate through using the interactions with the other supply chain members.

In axiom A17, we present the sufficient conditions for increasing the probability of developing hybrid governance structures, which are based on three concepts (high and reciprocal transaction costs, *hrtc*, vertical integration is not viable, ¬ *vertical integration* (¬ *vi*), and the presence of knowledge sharing routines, *ksr*), all of which are exogenous to the theory.

All these axioms are based on *material causality*. Even though there are human decisions underlying each one of these causal relationships, we actually describe them in terms of the structure of the industry, as structure leads directly to outcome through a set of implicit decisions that are completely determined by underlying conditions. This is typical of the approach followed in economics and management, where, given the rationality of the agents, if we can describe the rules or structure of the system, the outcome follows.

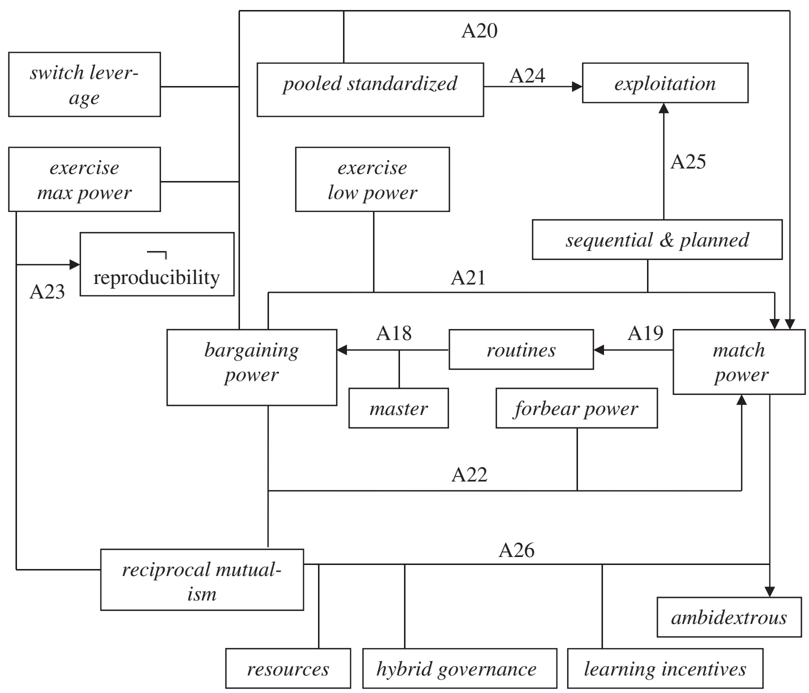

Figure 3. This causal graph represents the relationships between axioms A18 to A26.

A formal theory of supplier relationship management

We now formalize the theory on supplier relationship management using the concepts summarized in Table 2.[30–33] We start the description of this part of the theory by analyzing how the channel master interacts with the other members of the supply chain. The channel master can use bargaining power to appropriate a larger share of the supply chain profits, the optimality of which depends on the specific structure of the supply chain. If used unduly, this appropriation may destroy learning incentives and value, reducing supply chain profitability and ability to cope with change. For this reason, the development of dynamic routines also assumes the implementation of hybrid governance structures, which determine what Wilhelm and Sydow[58] call the coopetition capabilities that allow the firms in the supply chain to continue a fruitful cooperation and, at the same time, manage the tensions created by competition. These governance structures are particularly important when some tasks, such as cooperation among firms, cannot be imposed by authority or ownership arguments.[17] It follows that these dynamic routines enable the supply chain to be agile, adaptable, and aligned with its customer needs.[21,59–61]

We postulate the axioms presented in Figure 3 (and supported by Table A2 in the Appendix). Based on Crook and Combs[30] and Theodorakopoulos et al.,[33] we postulate that the optimal strategy depends on the type of task interdependency. If there is a channel master and operational routines in a supply chain, the channel master tends to have *bargaining power* (axiom A18).

Additionally, following Crook and Combs,[30] we postulate that the way bargaining power is exercised should match the supply chain structure, which we describe as *match power*. When a supply chain matches its organizational structure to the corresponding power relationship, this increases the probability of routine institutionalization (axiom A19). Axioms A19 to A22 are also based on supply chain alignment, as by power matching the channel master ensures the firms align the interests of the supply chain with their own interests. If there is a *pooled & standardized* structure, the channel master should appropriate all SCM gains and all the other firms in the supply chain should attempt to build switching costs for the channel master, leveraging the membership outside the chain and reducing profit uncertainty by being in the chain, described as *switch leverage reduce*. This is the optimal alignment between structure and behavior (axiom A20). If the structure is sequential, the channel master should appropriate all SCM gains but not the pre-SCM profits, exercising low power (axiom A21). Finally, if the structure is reciprocal and if there is a channel master (which does not have to be the case), it should share the SCM gains with the other members of the supply chain (axiom A22).

Furthermore, we postulate that when the channel master appropriates all SCM gains, even in a reciprocal structure, the supply chain has low reproducibility as the weaker firms have no incentives to remain in the chain (axiom A23). This axiom reinforces the basic theory that there needs to be alignment between structure and behavior for the supply chain to be sustainable.

Additionally, there are some links between supplier rela-tionship management and learning theory. Axioms A24 and A25 declare, respectively, that pooled and sequential supply chains have a higher probability of implementing exploitation. This arises first because the leader fails to align the objectives of the supply chain members. Second, as most of the interactions between firms are regulated by contracts, there are fewer opportunities for knowledge creation, and the learning activities, therefore, tend to be directed to improving efficiency via small changes in processes.[62]

Furthermore, axiom A26 postulates that if a reciprocal supply chain matches power, ensures the alignment of its members' objectives, has adequate learning incentives, and implements a hybrid governance structure, it has a higher probability of developing ambidextrous learning. It underlines the importance of alignment between the objectives of firms in the supply chain.

The axioms in Figure 3 require some further explanation, as even though attempting to replicate the original theory, the causal implication used in this part of the theory is not simple. The optimization process imposes causality, i.e., through, for example, the rationality of the channel master who attempts to increase the long-term profit by aligning its behavior with the supply chain structure. The theory of supplier relationship management is based on intentional causality as it explicitly considers the way bargaining power is used and whether or not it is adequate for a given supply chain structure. Therefore, the structure does *not* directly determine the outcome. Instead, there is a mediating effect of the bounded rationality conditioning the final outcome. Consequently, we need to know management *intentions*, which are *not* determined by the structure of the supply chain, to assert what the final outcome of the causal relationships will be.

As can be seen from Figures 2 and 3, there are a few causal loops that result from the interaction between the axioms. These loops are fine from a business logic perspective, and all of them are consistent in logical terms. Nonetheless, in order to prevent infinite loops in the inference cycle, we restrict the results to include only the most interesting theorems and assert the following concepts as *building blocks: bargaining power, match power, routines, resources, learning incentives, hybrid governance*, and *reproducibility*. These *building blocks* are important as they provide the foundation on which the deductive reasoning is built into causal explanations, avoiding the deductive infinite cycle that would be created otherwise.

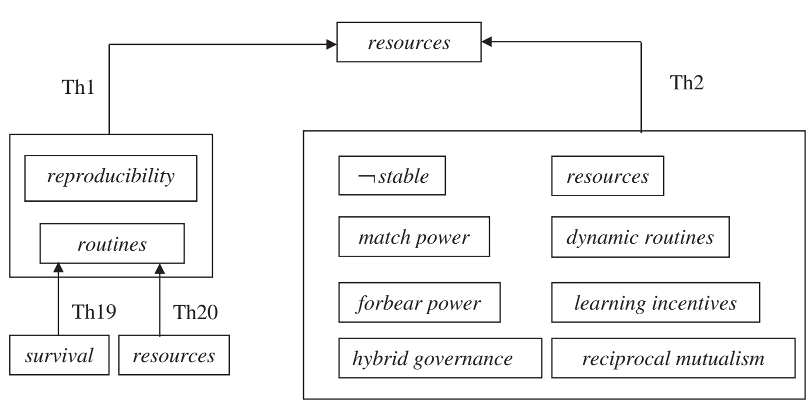

Figure 4. Derivation of the *resources* related theorems.

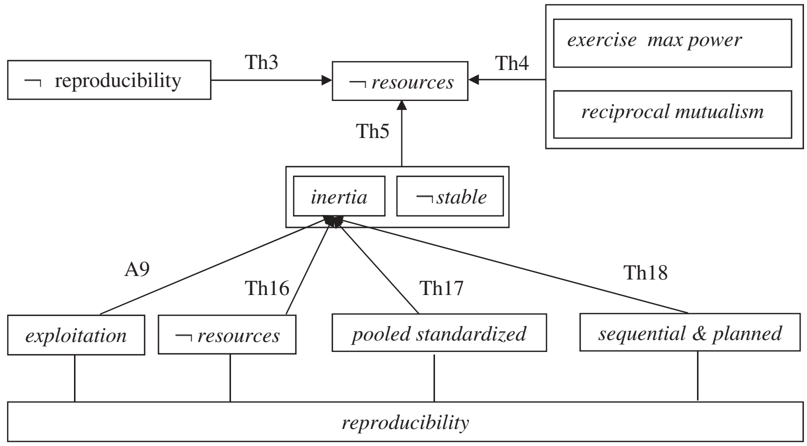

Figure 5. Derivation of the ¬ *resources* related theorems.

Major results in supply chain management

We have derived 20 theorems (Th1 to Th20), as described in the Appendix, Table A3 (which also summarizes the axiomsused to prove each theorem). There are two major concepts we try to explain, resources and : resources. Furthermore, there are a few minor concepts we analyze as well, namely *inertia, routines, institutionalization*, and ¬ *reliable & accountable* (an important one, nonetheless). Figure 4 summarizes the relationships between the theorems involved in proving the conditions under which a supply chain accumulates resources.

The two main theorems are Th1 and Th2. Supply chains with institutionalized operational routines and reproducible internal structures exhibit a higher probability of accumulating resources (Th1). Reciprocal supply chains in which the dominant firm forbears power (and in which there are hybrid governance structures and incentives to learn) tend to attract resources in turbulent environments (Th2). These theorems are in line with the resource orchestration perspective, which holds that the accumulation of resources requires sustainable learning and the dynamic abilities to sustain this process over time.[29] The supporting theorems Th19 and Th20 describe the institutionalization of operational routines, such that reproducible supply chains with a high probability of survival (Th19) or abundant resources (Th20) tend to have reproducible routines.

In Figure 5, we analyze resource depletion. The main theorems are Th3, Th4, and Th5. Th3 shows that supply chains that do not have reproducible processes tend to have lower *reliability and accountability*, leading to a higher probability of resource depletion. Th4 explains how reciprocal supply chains tend to deplete resources when the channel master appropriates all SCM gains plus a portion of the pre-SCM profits. Th5 shows that in unstable environments supply chains with high inertia have a high probability of depleting resources.

Table A3 includes a few additional theorems (Th6 to Th9) to explain resource depletion, but these are refinement of axiom A9 and the supporting theorems Th16 to Th18, which explain structural inertia. (The theory can be better understood by focusing on these instead.)

As shown in Figure 5, even when the supply chain structure is reproducible, when coupled with exploitation (A9), with depleted resources (Th16), or with inadequate organizational structures (pooled, Th17, or sequential, Th18), the supply chain has a high probability of being inert. When there is a structural change in the business environment, this inertia leads to resource depletion (Th5).

Therefore, pooled and sequential supply chains are not adequate for industries where a structural change is likely, and moreover in any situation that involves a change, these supply chains will struggle. But why is that? In order to adapt to environmental change, the supply chain is required to explore new solutions and implement ambidextrous learning. However, both these types of supply chain tend to use exploitative learning. As a result, they fail to discover new ways to be successful after an environmental change and, for this reason, have a high probability of depleting resources.

Furthermore, we formalize Th10, a theorem on supply chain institutionalization (Table A3), which shows that supply chains survive by accumulating resources (axiom A1) and develop a power structure in the relationships between the different firms that crystalizes over time.

Additionally, we automatically derived a few theorems, the proof of which is depicted in Figure 6, on ¬ *reliable & accountable* (¬ *R&A*), which is the central concept leading to resource depletion, as stated in axiom A4. Th11 proves that the abuse of bargaining power by a channel master in the context of a reciprocal supply chain tends to lead to low reliability and low accountability, as the structures of these networks are not reproducible. This is the process at the base of Th4 – the theorem used to prove resource depletion (but with one less inference step).

In all other theorems on low reliability and low accountability (Th12 to Th15, Table A3), the cause includes an environmental change faced by a supply chain that even though characterized by a reproducible structure, uses exploitative learning abilities (Th12), has depleted resources (Th13), or possesses a pooled (Th14) or sequential (Th15) structure. It is evident from this analysis that the main explanation for this lack of reliability and lack of accountability is structural inertia and exploitation in the context of an unstable environment. For this reason, in Figure 6, we represent the derivation process using axiom A9 and theorems Th16 to Th18.

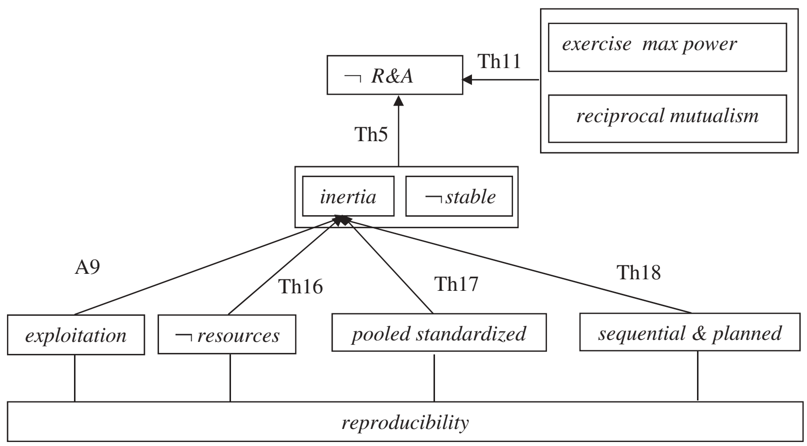

Figure 6. Derivation of the ¬ *reliable & accountable* related theorems.

Discussion on supplier relationship management

In summary, we derived the following results on supplier relationship management. First, we have described the interaction between supply chain structure, bargaining power, and the ability of the organization to cope with change. Second, we have explained the causes of lack of reliability and reproducibility of the supply chain structure, which we show are crucial aspects for predicting the likelihood of survival. Third, we have studied the conditions under which the supply chain becomes institutionalized with its own routines. Finally, we have described the major causes of resource accumulation and depletion in the supply chain and, additionally, explained the causes of the emergence of structural inertia.

More specifically, we have shown that the probability of attracting resources increases if, in stable environments, the supply chain has reproducible routines. Moreover, we conclude that a reciprocal supply chain has a higher probability of attracting resources in unstable environments if the dominant firm forbears power, and if there are learning incentives, together with a hybrid governance structure and dynamic routines.

In stable environments, the appropriation of all SCM gains plus a portion of the pre-SCM profits by a channel master (in a reciprocal supply chain) tends to lead to a loss of resources and to low *reliability and accountability*. Moreover, in the case of stable environments, the low reproducibility of the supply chain structure has a higher probability of leading to resource depletion.

In turbulent environments, a reproducible supply chain that (a) implements exploitation or (b) has a pooled or a sequential structure has a higher probability of resource depletion and tends to exhibit low *reliability and accountability*. In a reproducible supply chain, (a) structural inertia is caused either by exploitation or by pooled or sequential structures; and (b) resource accumulation causes the institutionalization of operational routines.

In practical terms, this analysis of supplier relationship management and supply chain decentralization helps in better understanding how learning abilities, resources, and power structure need to fit customer requirements, taking into account the likelihood of a structural disruption, in order for the organization to survive.

Conclusion

The feedback loop is an important concept for analyzing supply chain dynamics. Nonetheless, to date, the philosophical and computational problems associated with these loops remain misunderstood and underexplored. Additionally, in order to properly account for the centrality of causality to decision-making in management sciences, we need to better explain the difference between material and intentional causality, taking into consideration how *cumulative causation* (working in causal loops) influences the long-term behavior and logical connections between the decisions at different stages.

In this article, we apply propositional logic to represent these causal relationships when integrating population ecology with supplier relationship management and analyze how this methodology can represent loops and the intricacies of causality in dynamic settings. We describe how population ecology and the learning parts of the theory are explained based on material causality and how the analysis of supplier relationship management requires the inclusion of intentional causality.

Given the significant push for supply chain decentralization, based on the sharing economy and the decentralized autonomous organizations emerging with the blockchain, we expect cumulative causation, and the interplay between structure and intentions, to be at the core of the creation of new types of organizations able to survive in these new and challenging industries.

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Appendix

Table A1. Axioms of supply chain selection and learning theories in propositional logic.

A1: *survival* *resources*
A2: ¬*survival* ¬ *resources*
A3: *resources* *reliable & accountable*
A4: ¬ *resources* ¬ *reliable & accountable*
A5: *reliable & accountable* *routines* ∧ *reproducibility*
A6: ¬ *reliable & accountable* *routines* ∧ ¬ *reproducibility*
A7: ¬ *reliable & accountable* ⟵ *inertia* ∧ ¬ $_{stable}$
A8: *reproducibility* ⟵ *routines* ∧ *stable*
A9: *inertia* *reproducibility* ∧ *exploitation*
A10: *routines* *institution*
A11: *institution* ⟵ *survival*
A12: *exploitation* ¬ *resources*
A13: *ambidextrous* ⟵ *resources* ∧ *dynamic routines*
A14: resources ¬ *stable* ∧ *ambidextrous* ∧ *dynamic routines*
A15: *dynamic routines* *learning incentives* ∧ *hybrid governance*
A16: *learning incentives* *ipr* ∧ *sbr*
A17: *hybrid governance* *hrtc* ∧ ¬ *vertical integration* ∧ *ksr*

Table A2. Axioms of supply chain bargaining theory in propositional logic.

A18: *bargaining power* *routines* ∧ *master*
A19: *routines* *match power*
A20: *match power* ⟵ *pooled & standardized* ∧ *bargaining power* ∧ *exercise max power* ∧ *switch leverage reduce*
A21: *match power* *sequential & planned* ∧ *bargaining power* ∧ *exercise low power*
A22: *match power* *reciprocal & mutualism* ∧ *bargaining power* ∧ *forbear power*
A23: ¬ *reproducibility* *reciprocal & mutualism* ∧ *exercise max power*
A24: *exploitation* *pooled & standardized*
A25: *exploitation* *sequential & planned*
A26: *ambidextrous* *reciprocal & mutualism* ∧ *match power* ∧ *learning incentives* ∧ *hybrid governance*

Table A3. Theorems.

Theorems	Ant. Axioms
Th1: *resources* ⟵ *routines* ∧ *reproducible*	A3, A5
Th2: *resources* ⟵ ¬ *stable* ∧ *resources* ∧ *reciprocal mutualism* ∧ *match power* ∧ *learning incentives* ∧ *hybrid governance* ∧ *dynamic routines*	A14, A26
Th3: ¬ *resources* ¬ *reproducibility*	A4, A6
Th4: ¬ *resources* *reciprocal & mutualism* ∧ *exercise max power*	A4, A6, A23
Th5: ¬ *resources* ¬ *stable* ∧ *inertia*	A4, A7
Th6: ¬ *resources* ¬ *stable* ∧ *reproducibility* ∧ *exploitation*	A4, A7, A9
Th7: ¬ *resources* ¬ *stable* ∧ *reproducibility* ∧ ¬ *resources*	A4, A7, A9, A12
Th8: ¬ *resources* ¬ *stable* ∧ *reproducibility* ∧ *pooled & standardized*	A4, A7, A9, A24
Th9: ¬ *resources* ¬ *stable* ∧ *reproducibility* ∧ *sequential & planned*	A4, A7, A9, A25
Th10: *institution* ⟵ *resources*	A1, A11
Th11: ¬ *reliable & accountable* *reciprocal & mutualism* ∧ exercise max power	A6, A23
Th12: ¬ *reliable & accountable* ¬ *stable* ∧ *reproducibility* ∧ *exploitation*	A7, A9
Th13: ¬ *reliable & accountable* ¬ *stable* ∧ *reproducibility* ∧ ¬ *resources*	A7, A9, A12
Th14: ¬ *reliable & accountable* ¬ *stable* ∧ *reproducibility* ∧ *pooled & standardized*	A7, A9, A24
Th15: ¬ *reliable & accountable* ¬ *stable* ∧ *reproducibility* ∧ *sequential & planned*	A7, A9, A25
Th16: *inertia* reproducibility ∧ ¬ *resources*	A9, A12
Th17: *inertia* reproducibility ∧ *pooled & standardized*	A9, A12, A24
Th18: *inertia* reproducibility ∧ *sequential & planned*	A9, A12, A25
Th19: *routines* *survival*	A10, A11
Th20: *routines* *resources*	A1, A10, A11