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Building and testing necessity theories in supply chain management

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Abstract

This article contributes to the Emerging Discourse Incubator initiative by presenting how supply chain management scholars can contribute to theory development by means of necessity theories. These are unique theories that inform what level of a concept must be present to achieve a desired level of the outcome. Necessity theories consist of concepts that are necessary but not sufficient conditions for an outcome, where the absence of a single causal concept ensures the absence of the outcome. The theoretical features of necessary conditions have important implications for understanding supply chain management phenomena and providing practical applications. In 2016, Necessary Condition Analysis (NCA) became available for building and testing necessity theories with empirical data. However, NCA has not yet been used for the development of supply chain management theories. Therefore, we explain how necessity theories can be built and tested in a supply chain management context using necessity logic and the empirical methodology of NCA. We intend to inspire scholars to develop novel necessity theories that deepen or renew our understanding of supply chain management phenomena.

KEYWORDS

NCA, Necessary Condition Analysis, necessity theories, research methodology

INTRODUCTION

A central goal of scientific endeavors in supply chain management (SCM)[1] is to understand phenomena through theory development. The cyclic process of building and testing theories allows scholars to accumulate scientific knowledge that informs research, practice, and policy (Wacker, 2008). The 2020 Emerging Discourse Incubator highlighted emerging approaches for theory development and called for the development of supply-chain-specific theory (Flynn et al., 2020). To tackle this challenge, we present how SCM research can answer pressing theoretical questions about why things do not happen or why processes fail. For example, why do buyer–supplier relationships fail? What prevents organizations from creating sustainable supply chains? Why are some supply chains destined to never achieve a

[1]In line with the philosophy of the Journal of Supply Chain Management, this article refers to the discipline of supply chain management (SCM) in its broadest sense. Thus, the term SCM and also the target audience of this article encompasses all functions and processes related to the management of supply chains and the transformation of inputs to outputs, including operations, logistics, purchasing, and networks.

competitive advantage? Our central thesis in this article is that SCM scholars can advance the understanding of important phenomena by developing a unique type of theory that addresses these "sine qua non": necessity theories.

Necessity theories focus on predicting the absence of the outcome when a single causal concept (the necessary condition) is absent.[2] Necessary conditions follow the general theoretical logic "Y only if X" and are critical, essential, and must be present in all cases that desire the outcome. If absent, these necessary conditions are bottlenecks that prevent the outcome from existing: "without X no Y." Necessary conditions do not guarantee success if present but guarantee failure if absent and cannot be compensated by changing the level of other concepts (Dul, 2016). Necessity theories can be parsimonious; even a single necessary condition can prevent the outcome from occurring. They are also important for practice because all necessary conditions must be satisfied to avoid failure. For example, if commitment among the supply chain partners is necessary for a successful supply chain partnership, the partnership will not be successful when commitment is absent. Absence of commitment guarantees failure, which also means improving anything but commitment is a waste of time, money, and other resources.

Although much of the elegance of a necessity theory lies in its simplicity, thinking logically about necessary conditions has important implications for theory and methodology. Necessity theorizing can impact the concepts, relationships, domain, and predictions of theory (Wacker, 2008; Whetton, 2009). A theory that does not incorporate identified necessary conditions will fail to predict the outcome adequately. For example, an overlooked concept that is not the researcher's focal concept can be necessary and individually predict the absence of the outcome. Relationships between concepts are often described in terms of additive logic where concepts can compensate for each other when predicting the outcome, whereas necessary conditions should be described with "necessary but not sufficient" logic. Identified necessary conditions can often help define the theory's claimed domain of generalizability and applicability, as they define the context where the outcome is possible. Predictions made with necessity theories ("no Y without X") are fundamentally different from predictions that most common theories make ("X produces Y"). To develop a pure necessity theory or a necessity theory as an embedded part of an existing theory, empirical SCM scholars need to choose the appropriate methodology and find a theory–method fit. Theory–method fit is grounded in the basic premise that there are several types of theories and there is no universally right method that works for all types of theories (Gigerenzer, 1991; Gigerenzer & Marewski, 2015; Goertz & Starr, 2003). All methods are valuable, and no single approach is best. Therefore, the nature of the theory (e.g., additive or necessity) must fit the method for generating meaningful results.

To illustrate necessity theory and theory–method fit, first consider the theory consisting of additive logic relationships common within SCM (Melnyk et al., 2018). Additive theory follows the general logic "If $a + b_1X_1 + b_2X_2 + ... + b_nX_n + \varepsilon$, then Y, on average."[3] The suitable method for empirical testing of additive theories is regression (Ho et al., 2017). When regression-based tools are used, for example, multiple regression and structural equation modeling (SEM), scholars add variables to make predictions. Additive theories inform us about how a set of concepts add up in a certain way to increase (or decrease) the outcome on average and can compensate for each other in producing the outcome. Scientific hypotheses are built and tested in light of the available statistical tools (Goertz & Mahoney, 2013), and statistics is often taught as if there were only one logic of inference (Gigerenzer, 1991). Thus, the existing research tools have guided SCM scholars toward developing additive theories while neglecting necessity theories.

Necessity theories are fundamentally different from additive ones, and necessary condition hypotheses cannot be tested using regression-based methods. Instead, Necessary Condition Analysis (NCA) is the right method for building and testing necessity theories (Dul, 2016). NCA focuses on necessity and does not compete with any other method. It complements all other existing data analysis techniques available to SCM scholars. Just like regression-based methods are unsuitable for necessity theories, NCA is not appropriate for additive theories.

Necessity theories and NCA are useful for SCM scholars. First, a full understanding of SCM phenomena is impossible without developing necessity theories. A

[2]This article discusses both the properties of theories and the process of building and testing theories with empirical data. We therefore differentiate between theoretical and empirical terminology in the following way. Theoretical terminology includes concept, domain, proposition, and focal unit. Empirical terminology includes variable, scope, hypothesis, and unit of analysis. Further, the concepts of a theory can serve different roles in the theory (e.g., antecedent, consequence, mediator, and moderator). In this article, we introduce a new role that can be allocated to concepts: necessary condition. In NCA, the term condition is used to refer to a variable characteristic X of a focal unit of which the value (or its change) permits a value (or its change) of another variable characteristic Y (called the outcome) (Dul, 2020). In additive theories, the corresponding term is usually predictor or independent concept.

[3]Or other variants with added linear or nonlinear terms; a = intercept, b = slope, ε = error term.

conventional[4] SCM theory that aims to predict a desired outcome (e.g., good performance) but does not incorporate identified necessary conditions will fail to fully understand whether the outcome occurs or not. For example, if commitment among the supply chain partners is necessary for a successful partnership, then a theory that fails to incorporate this necessary condition will not be able to understand why success occurs in certain cases (where commitment is satisfied), but not in other cases (where commitment is not satisfied). Although statements about necessary conditions are widespread in SCM (Dul et al., 2010), testing them is rare, despite some examples of empirical exploration for potential necessity relationships (Stek & Schiele, 2021). This lack of evidence for necessary conditions limits the explanatory and predictive adequacy of current SCM theories. Exploring necessity relationships with NCA has also been done in various adjacent disciplines such as Psychology (Karwowski et al., 2016), International Business (Richter & Hauff, 2022), and Human Resource Management (Hauff et al., 2020), and Bergh et al. (2022) trace the methodological developments of NCA within management. This has led to suggestions for theory advancements through a better understanding of the causal effects for certain, desired outcomes (Aguinis et al., 2020). Second, necessity theories are both useful and usable to practice and therefore akin to the strong practical tradition of SCM. Necessary conditions are clear, practical, easy to understand and act upon, and inform practitioners that if the right level of the necessary condition is absent, the desired outcome will not occur in practically all cases, no matter the level of other concepts.

This article aims to support the development of necessity theories within SCM. To this end, we make four contributions to the SCM literature. First, we provide actionable advice to SCM scholars by outlining a set of suitable starting points for necessity theorizing and NCA testing. Second, we provide a literature review of the prevalence and theory–method fit for theoretical necessity statements within SCM. Third, we go into depth by defining necessity theories and describing their essential properties, as well as explaining how necessity theories can be built and tested in an SCM setting using NCA. Fourth, we conclude by providing four core recommendations to SCM scholars together with a checklist of best practices for building and testing necessity theories with NCA.

[4]In this article, we refer to "conventional" theories, relationships, and methods as based on other additive logic (usually tested with regression) or configurational logic (usually tested with QCA).

NECESSITY THEORIES IN SCM—WHERE DO WE START?

Developing a new theory using a different causal logic and an emerging data analysis technique might feel like entering uncharted waters for many SCM scholars. To support SCM scholars in getting started, we recommend two strategies for finding relevant research problems where necessity theorizing and NCA testing could generate novel findings: (1) starting from theory and (2) starting from evidence.

First, we recommend starting from theory, which entails three alternatives. The first is to initiate an entirely new necessary condition hypothesis based on the knowledge or experience that a certain concept is important for an outcome. If this concept is critical or essential for the outcome and cannot be compensated by other concepts, it can be substantiated against the backdrop of existing theory (e.g., by reviewing the literature and analyzing existing concepts and relationships) and formulated into a necessary condition hypothesis. For example, Fisher et al. (2021) describe how experience, curiosity, and conversations can be starting points for novel theorizing. Necessity logic provides a new perspective on phenomena.

The second alternative is to substantiate and test existing necessary condition statements in the literature, representing individual propositions that have not yet been incorporated in an established theory. In our literature review (Tables 1 and 2), we find 157 explicitly formulated statements between 2009 and 2019, the vast majority of which are untested or tested incorrectly. For example, "information technology is a necessary but not a sufficient capability for creating sustainable competitiveness" (McKone-Sweet & Lee, 2009, p. 5). It is also possible to identify implicitly formulated necessary condition statements (e.g., X is a prerequisite for Y) and test them. The necessity logic behind these implicit statements often becomes clear when reading and interpreting the context where the statement is introduced in the article (e.g., in the managerial implications section). For example, Ogden (2006) explored critical success factors for supply base reduction programs and observed that information systems were present in all successful cases. The author claims that "information systems are a prerequisite to effective supply base reduction programs" (p. 34). Because you only need two variables to test a necessary condition hypothesis, focusing on existing necessity statements offers a straightforward opportunity to extend knowledge on relevant SCM phenomena.

The third alternative focuses on existing theories that could be advanced by incorporating necessary conditions. General theories such as transaction cost economics (what kind of supply chain relationships enable economic efficiency?) and the resource-based view (are valuable, rare, inimitable, and non-substitutable resources necessary for sustained competitive advantage?) could benefit from necessity theorizing. However, we echo the call of Flynn et al. (2020) and advise scholars to focus on theories that are specific to the SCM domain. For example, the supply chain practice view (SCPV) examines how and why the adoption and use of specific practices within and across supply chains improve performance (Carter et al., 2017). A key facet of SCPV is the explicit notion to explain the entire range of individual and relational performance. This can be extended by necessity theorizing that incorporates individual supply chain practices that limit performance, where NCA identifies the "limiting range" that certain necessary practices impose on performance. In other words, NCA identifies the ceiling on performance implied by empty spaces, whereas conventional methods define the average range of performance implied by lines through the middle of the data. For example, basic supply chain practices may be necessary even for a low level of performance. The absence of such practices could predict why some organizations consistently underperform. More sophisticated supply chain practices may be necessary for a high level of performance and thus relevant for organizations that aspire to become top performers.

A supply-chain-specific phenomenon that can be understood better through theory development is the bullwhip effect, that is, the causes, countermeasures, and performance implications of increasing demand variation through a supply chain (Dooley et al., 2010). This effect is far more complex and nuanced than previously described in the literature (Mackelprang & Malhotra, 2015), and novel empirical examinations of this effect can thus have far-reaching implications for theory and practice (Yao et al., 2021). Here, necessity theorizing may contribute to this coveted nuance by identifying countermeasures that managers must put and keep in place at certain positions in a supply chain to avoid the bullwhip effect. For example, authors (Lee, 2010; Wu & Katok, 2006) have suggested that some levels of visibility, collaboration, communication, and training must be present to counter the bullwhip, but these propositions still need to be empirically tested with a necessity method. Thus, a promising avenue for NCA studies aiming to extend theory on the bullwhip effect would be to investigate the specific strategies and tactics used by supply chain members for taming the bullwhip.

Second, we recommend starting from evidence. Because most empirical SCM research uses conventional methods, the existing evidence is inherently based on a certain type of logic. When the methodological logic differs from the theoretical logic of the phenomena (i.e., theory–method misfit), researchers end up in situations where empirical findings do not match the theoretical backing or where replications fail to support the robustness and generalizability of propositions. Therefore, a suitable starting point is to investigate bodies of evidence that have inconclusive findings and where NCA could potentially solve the puzzle. Necessity theorizing and NCA testing could examine relationships that have theoretical backing but lack empirical support from conventional methods. These situations often occur when performance outcomes are disaggregated and when specific relationships are theorized with more nuance (Ketokivi & Mahoney, 2020). One such body of evidence is supply chain integration. At the aggregate level, dimensions of supply chain integration (internal, supplier, and customer) have been shown to correlate with performance in meta-analyses. However, many theoretically justified relationships are not empirically supported when disaggregated, leading to ambiguous and inconclusive findings (Ataseven & Nair, 2017; Leuschner et al., 2013). It is plausible that some of these disaggregated relationships represent necessity, and NCA could provide greater clarity. Moreover, internal integration is a "crucial building block" for full supply chain integration (Schoenherr & Swink, 2012), and practitioners are often advised to implement internal integration first before pursuing other dimensions of integration (Flynn et al., 2010). NCA could shed more light on this by assessing whether internal integration is necessary for supplier and/or customer integration and must be put and kept in place first.

NECESSARY CONDITIONS IN SCM—WHAT DO WE KNOW?

Every research area has important necessary conditions because they imply a special kind of cause: "If X is absent, Y will not occur" (Goertz & Starr, 2003). There are both explicitly formulated necessary condition statements (e.g., "X is necessary for Y") and implicitly formulated necessary condition statements (e.g., "X is a requirement for Y"). In 2010, Dul et al. explored the prevalence of explicitly formulated necessary condition statements in operations management. The authors performed a literature search in the following four journals: Journal of Operations Management (JOM), the International Journal of Operations and Production Management (IJOPM), Production and Operations Management (POM), and Manufacturing Service and Operations Management (MSOM). The search included the keywords "necessary condition," "necessary and sufficient

TABLE 1 Necessity statements in SCM journals

	JSCM		JOM		IJOPM		POM		MSOM		Total	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Individual necessity statements												
Necessity statement, not tested	53	87%	16	38%	18	49%	6	38%	1	100%	94	58%
Necessity statement, tested	8	13%	26	62%	19	51%	10	63%	0	0%	63	42%
Total	61	100%	42	100%	37	100%	16	100%	1	100%	157	100%
Articles with necessity statements												
Necessity statement, not tested	39	87%	9	50%	11	61%	5	50%	1	100%	65	69%
Necessity statement, tested	6	13%	9	50%	7	39%	5	50%	0	0%	27	31%
Total	45	100%	18	100%	18	100%	10	100%	1	100%	92	100%

Abbreviations: IJOPM, International Journal of Operations and Production Management; JOM, Journal of Operations Management; JSCM, Journal of Supply Chain Management; MSOM, Manufacturing Service and Operations Management; POM, Production and Operations Management.

condition," and "necessary but not sufficient condition" and covered the period from the launch of the journals to 2008. To provide a recent status on necessary condition statements and to include a more specific focus on SCM, we added the Journal of Supply Chain Management (JSCM) as the leading outlet for SCM research and analyzed the period from 2009 to 2019. We downloaded all articles that used any wording of necessity and searched for necessity statements in the full text of each article. We applied three exclusion criteria to ensure that the statements were formulated using necessity logic. Statements were excluded if they (1) did not formulate necessary condition statements in terms of necessity logic (e.g., simply using "necessary" as a synonym for "important"); (2) did not specify necessary condition statements for causal reasoning or to be empirically tested (e.g., explaining methodological procedures or referring to necessary/sufficient parameters in analytical models); or (3) did not refer to conditions necessary for an outcome (e.g., not specifying for what Y that X is necessary, or referring to moderation as a condition that is necessary for a covariational relationship[5]).

We differentiate and extend our review compared with Dul et al. (2010) by focusing on two main aspects: (1) the prevalence of necessary conditions across both journals and articles and (2) theory–method fit (i.e., the methods used to establish evidence about necessary conditions). Table 1 shows the prevalence of necessary condition statements in the five SCM journals (individual statements and articles) and whether the necessity statements were empirically tested or not. "Necessity statement, not tested" means that the statements were not intended to be empirically tested in the article. "Necessity statement, tested" means that the statements were empirically tested in the article, using methods that can or cannot test necessity. Table 2 presents a selection of necessity statements to highlight existing necessity theorizing in SCM.

We make four key observations in our review. First, SCM journals have published 92 articles with 157 explicit necessity statements (Table 1). JSCM has the most necessity statements (61 in 45 articles), followed by JOM (42 in 18 articles) and IJOPM (37 in 18 articles). However, the total number of necessity statements is much higher because necessary conditions can also be expressed in a variety of implicit ways (Dul, 2020). Second, necessity theorizing has been applied to various important SCM concepts, relationships, and domains (Table 2). The most common type of necessity statement in SCM includes one necessary condition and one outcome. For example, "supply chain visibility is a necessary, but insufficient capability for enabling supply chain responsiveness" (Williams et al., 2013, p. 543). Some statements include multiple necessary conditions for one outcome (Done et al., 2011; Knol et al., 2019; Oliveira & Roth, 2012; Silander et al., 2017). For example, "both internal and external collaboration are necessary to ensure performance" (Cao & Zhang, 2011, p. 168). Some authors also specify how different propositions (e.g., "necessary" and "not necessary") are expected to hold in separate theoretical domains (Dube et al., 2016). Others incorporate necessity statements in general theories such as absorptive capacity (Kim et al., 2015; Saenz et al., 2014) and the resource-based view (Fawcett et al., 2011; Hitt, 2011). This high prevalence of statements shows that necessity theorizing is important for SCM theory and practice.

[5]Moderation in regression refers to the idea that the magnitude of a covariational relationship between two variables depends on the level of a third variable (moderator). In special cases, a moderator is sometimes called "necessary" for the existence of a covariational relationship. The relationship exists when the moderator has a certain value, but not with another value. This is distinct from necessity logic in NCA that focuses on conditions that are necessary for an outcome.

TABLE 2 Explicitly formulated necessity statements in supply chain management (emphases added)

Source	Necessity statement
Williams et al. (2013)	"Supply chain visibility is a *necessary, but insufficient* capability for enabling supply chain responsiveness" (p. 543)
Brinkhoff et al. (2015)	"Trust [...] is *necessary but not sufficient for* supply chain project success" (p. 181)
Chen et al. (2013)	"Information technology integration has become a *necessary condition for* hospital supply chain integration" (p. 396)
Whipple et al. (2015)	"Internal collaborative process competence is *a necessary, but not sufficient, condition to* enhance operational performance in buyer–supplier relationships" (p. 17)
Reuter et al. (2010)	"Stable and high-class sustainable global supplier management processes are *a necessary condition to* achieve competitive advantage; however, they are *not sufficient to* maintain the buying firm's reputation in the long run" (p. 59)
Theißen et al. (2014)	"A suitable relationship base is *a necessary condition for* creating partnership-value" (p. 56)
McKone-Sweet and Lee (2009)	"Information technology is a *necessary but not a sufficient* capability *for* creating sustainable competitiveness" (p. 5)
Brandon-Jones et al. (2014)	"Information systems capabilities *are necessary in order for* an organization to utilize information technology effectively" (p. 57)
Cao and Zhang (2011)	"Both internal and external collaboration *are necessary to* ensure performance" (p. 168)
Kim et al. (2015)	"Absorptive capacity is considered as a critical and *necessary condition for* the recipient to exploit external knowledge" (p. 36)
Hitt (2011)	"Holding valuable and rare resources is *a necessary but insufficient condition for* achieving a competitive advantage" (p. 9)
Kumar et al. (2020)	"Awareness about the competitive landscape is *a necessary but not sufficient condition for* strategy formulation and implementation" (p. 19)

Third, the majority (60%) of all statements have not been tested (94 statements in 65 articles). These statements typically appear in qualitative studies aimed at theory building (i.e., formulation of theoretical propositions). This implies that SCM scholars can extend knowledge on various phenomena relevant to theory and practice by testing proposed necessary conditions. Fourth, if the statements are tested (63 statements in 27 articles), most are tested incorrectly with a method that cannot test necessity. Theory–method misfit is most visible in how necessary condition statements are often introduced in the abstract, introduction, theory, or hypothesis section, followed by an incorrect testing method. Most hypothesis testing uses regression-based methods, for example, two-stage least squares (2SLS) regression (Wang et al., 2016), covariance-based SEM (CB-SEM) (Cao & Zhang, 2011; Dobrzykowski et al., 2015), and partial least squares SEM (PLS-SEM) (Chen et al., 2013), which are not the correct approaches for testing necessary conditions. Another example is Brinkhoff et al. (2015), who conclude that "trust [...] is necessary but not sufficient for supply chain project success" (p. 181) while specifying the formal hypothesis as "Trust [...] has a positive effect on the success of supply chain projects" (p. 184). By using PLS-SEM for testing, there is no evidence for the necessary condition hypotheses (Richter et al., 2020). Such theory–method misfit between necessary condition hypotheses and empirical methods for testing them has resulted in a lack of empirical evidence for necessary conditions in SCM.

Although the general observation is that necessary conditions are not tested correctly, there are a few exceptions. Four articles test necessary condition statements correctly from the theory–method fit perspective, yet imperfectly because they use limited data analysis techniques. Done et al. (2011) used a contingency table approach (an implicit version of NCA), and Sousa and da Silveira (2017) visually inspected the data for indications of necessary conditions. Golini et al. (2016) used NCA but reported nothing about their procedure or results. Knol et al. (2019) used an earlier version of NCA without NCA's statistical test to reduce the risk of false positives. These studies indicate a promising development for enhancing theory–method fit. We also identified three articles in JSCM that used Qualitative Comparative Analysis (QCA) for testing necessity (Karatzas et al., 2016; Reimann et al., 2017; Timmer & Kaufmann, 2019). QCA is usually exclusively employed for testing sufficient configurations. Although these authors focus on developing theories of sufficient configurations, they still test which single variables could be dichotomously necessary for the outcome(s) as a part of the methodological procedures of QCA. One of the studies by these authors found necessary conditions, and two did not. QCA has limited possibilities for identifying necessary conditions. The key methodological point is that only tailored methods can appropriately test and provide evidence for necessary condition hypotheses (Goertz, 2017).

DEVELOPMENT OF NECESSITY THEORIES IN SCM

So far, we have outlined specific starting points for necessity theorizing and NCA testing, introduced the general idea of necessary conditions, how these are commonly formulated as theoretical statements in SCM, and have identified the mismatch between theory and methods in the SCM literature. In line with the 2020 Emerging Discourse Incubator, this section explains the development of necessity theories to support SCM scholars in their research efforts to build and test necessity theories. With theory development, we mean the empirical cycle of building and testing theories, where building consists of formulating theoretical propositions and testing consists of assessing whether the propositions hold in reality by using empirical data from that reality (Dul & Hak, 2008). We adhere to the generally accepted view (although with minor variations in terminology) that any theory comprises four essential properties: concepts, domain, relationships, and predictions (Wacker, 1998, 2008; Whetten, 1989; Whetton, 2009). Necessity theorizing can be applied to any level of theory (e.g., grand, mid-range, and local), any focal unit (e.g., individual, organization, dyad, and network), and is compatible with any philosophical stance (e.g., positivism and interpretivism).

We define *necessity theory* as "a theory that employs causal necessity logic for describing the causal relationships between all or a selection of the concepts of a theory." *Necessity theorizing* is formulating necessity theory using necessity logic when describing causal relationships between concepts. In other words, necessity theorizing is the process and necessity theory is the result. Necessity theorizing can provide a different theoretical lens on causal mechanisms and contribute to existing and newly developed theories.

We distinguish two types of necessity theories. First, SCM scholars can develop "pure necessity theories"—theories that only include necessity relationships. That is, all propositions of the theory are necessity relationships, where each relationship imply that the absence or a certain level of a single causal concept (the necessary condition) ensures the absence or a certain level of the outcome, independent of other causes. In other words, if the causal concept is absent or below a certain level, it is the bottleneck for the outcome. Note that a necessity theory can be as simple as having only one condition and one outcome because the necessary condition operates in isolation from the rest of the causal structure. Pure necessity theories are simple and predict the absence of the outcome when a single causal concept is absent. An empirical study to build and test pure necessity theories only uses a necessity method. A rare subcategory of pure necessity theories consists of necessary conditions that are also jointly sufficient for the outcome. For example, the Ability-Motivation-Opportunity (AMO) theory in high-performance work systems states that an organization's ability, motivation, and opportunity are individually necessary and jointly sufficient for an organization's performance (Van Rhee & Dul, 2018).

Second, SCM scholars can develop "embedded necessity theories"—theories that incorporate necessity relationships as an embedded part of conventional theories. That is, some of the propositions of the theory are necessity relationships whereas others are conventional relationships. Embedded necessity theories are complex and enrich conventional theories by focusing on the necessity effect of the cause. Each embedded necessity relationship implies that the absence or a certain level of a single causal concept (the necessary condition) ensures the absence or a certain level of the outcome, independent of other causes. An empirical study to build and test embedded necessity theories uses a necessity method and a conventional method. Thus, a multimethod approach is needed to ensure theory–method fit when testing such theories.

Necessity theories are both useful and usable to practice because they identify concepts that must be present to allow a desired outcome to exist and provide insights about actions that can be influenced to effectively improve the situation (i.e., avoiding guaranteed failure) (Aguinis & Cronin, 2022). Necessity theorizing can also alter the perception of complementary[6] and focal concepts in existing theories (Whetton, 2009). For example, concepts in additive theories that have weak empirical support (e.g., small regression coefficients) can be necessary conditions (Dul, 2016). Necessary conditions are also often theorized as contextual variables, and necessity theorizing can thus contribute to better

[6]A focal concept is the core of scholarly interest and act as the most memorable and interesting element of a theory. A complementary concept combines with a focal concept to form a proposition (Whetton, 2009).

specifications of theoretical domains. When a theory incorporates a necessary condition for an outcome, then the theory's ability to predict the outcome only applies to the theoretical domain where the necessary condition is satisfied. Table 3 summarizes the virtues of good necessity theories and how necessity theorizing can contribute to theory development in SCM. Developing good necessity theories (pure or embedded) that demonstrate these virtues would support the quest for more supply-chain-specific theory development called for by Flynn et al. (2020).

Because theories and empirics go hand in hand (Flynn et al., 2020), we now elaborate on building and testing necessity theories using the logic and methodology of NCA. We explain the conceptual logic of necessary conditions and describe how the theoretical features of necessary conditions translate to empirical data patterns. We also show how necessary conditions can be empirically tested with NCA, why existing methods cannot be used to test necessity, and how NCA can be combined with other methods.

Theory building using necessity logic

Building necessity theories start by acknowledging the unique theoretical features of necessity relationships—the conceptual relationships that link concepts in necessity theories. With theory building, we mean the formulation of theoretical propositions. In this article, we focus on using NCA in a deductive manner, where theory building consists of conceptually formulating necessary condition hypotheses using necessity logic. NCA can also be used in inductive studies where empirical data are explored without prior theory to formulate propositions, but this is beyond the scope of this article.

In theory building, necessity logic should not be confused with additive logic. For example, Brinkhoff et al. (2015) statement in Table 2 focuses on the relationship between trust and supply chain project success. Necessity logic implies that a minimum level of trust is needed for supply chain project success (no success without trust). Additive logic implies that the higher the level of trust, the more likely is supply chain project success (the more trust, the more success). Both types of hypotheses are important, but they are fundamentally different (Goertz & Starr, 2003).

Although the idea of necessity relationships might seem simple, the intricacies of necessity logic can be difficult to grasp. It can also take considerable time and effort to translate necessity logic to necessity predictions—the empirical data patterns produced by necessity relationships. A helpful way to understand necessary conditions is via constraints. When researchers use the idea that a concept X is a constraint, bottleneck, or barrier for an outcome Y, they predict that empirical observations should reveal regions with no data because X constrains Y (Goertz et al., 2013). Constraints and necessary conditions are conceptually and empirically closely related as both are concerned with the absence of outcomes—why things do not happen or why processes fail. A strong constraint cannot be violated as it is a necessary condition. As the necessary condition X decreases in value, the constraining effect on Y increases (Goertz, 2017). Note that constraints represent the "sufficiency of absence formulation" of necessary conditions (i.e., the absence of X is sufficient for the absence of Y). In contrast, in the "necessity of presence formulation," the necessary condition enables the outcome (i.e., the presence of X is necessary for the presence of Y) (Dul, 2016). Although the two formulations (X constrains Y and X enables Y) represent different ways of expressing necessity, they are logically equivalent (Dul, 2020). Still, it is not uncommon to treat them as distinct. For example, Silander et al. (2017) differentiate between "constraints" and "enablers" for modularizing specialized hospital services. Negatively valued necessary conditions are often called constraints, hindering factors, or inhibitors (e.g., goal conflict between supply chain partners). Positively valued necessary conditions are often called enablers or supporting factors (e.g., goal setting and rewards to support supply chain collaboration) (Pagell, 2004).

Empirically, necessary conditions predict a ceiling effect. This type of effect produces a data pattern comprising a border between data regions where cases are possible (below the ceiling) and regions where cases are not possible (above the ceiling). By definition, necessary conditions produce no-data zones, geometrically located in the upper-left corner of a Cartesian coordinate system (Dul, 2016).[7] Necessary conditions imply that we empirically want to know about ceiling lines that separate data zones from no-data zones (Goertz et al., 2013). A ceiling is "a value Y_c for a given value of X that observations rarely if ever exceed" (Goertz et al., 2013). That is, a lower ceiling has higher constraints (Goertz, 2017). In essence, necessary conditions ask the question to the data analyst: "Where are there no observations?" (Goertz et al., 2013).

Necessary condition hypotheses can be expressed in kind (qualitatively) and in degree (quantitatively)

[7]No-data zones in the upper-left corner presume a "+ nc +" relationship where a "high value of X is necessary for a high value of Y" and that X increases to the right and Y increases upward (Dul, 2020).

TABLE 3 Virtues of good necessity theories and theoretical contributions from necessity theorizing, inspired by Wacker (2008) and Whetton (2009)

Virtue	Key feature	Implications for necessity theories
Concepts	The theory has precisely defined concepts.	Necessity theories include focal concepts that are formally defined (semantically and/or ontologically). Complementary concepts in additive theories could be focal concepts in necessity theories.
Domain	The theory is supposed to hold for a certain universe of instances.	Necessity theories apply to specific focal units and are limited in their applicability across populations, times, and/or places in the theoretical domain. Necessity theorizing can help to specify domains for any theory.
Relationships		
Fecundity	The theory offers new and wider research areas to explore.	Pure necessity theories solely consist of necessity relationships. Embedded necessity theories are part of (existing) theories. Any theory can be expanded and/or improved by integrating important necessity relationships. Necessity relationships are parsimonious and can add new value to understanding phenomena by predicting the absence of the outcome when a single causal concept is absent.
Internal consistency	The theory is logically consistent.	Necessity theories are coherently built and tested using necessity logic.
Statistical parsimony	The theory is tested using a specific statistical technique.	Necessity theories require tailored statistical techniques for theoretical interpretation (e.g., effect size, *p*-value, and bottleneck table). Descriptive statistics in NCA include "ceiling line" and "necessity effect size." Inferential statistics in NCA include significance testing of effect size using approximate permutation testing (randomness of the observed effect size).
Substantive versus statistical significance	The theory and the statistics go hand in hand.	Necessity theories must be theoretically justified prior to testing. It is impossible to interpret NCA results without theorizing. At least three criteria must be met to claim a necessity relationship from data: (1) theoretical justification, (2) reasonably large effect size (substantive significance), and (3) reasonably small *p*-value (statistical significance). Testing necessity theories requires sound research empirical practice such as proper selection/sampling of cases, good measurement, and replications.
Predictions		
Falsifiability	The theory can be falsified.	Necessity theories can predict the absence of outcomes with precision. Necessity relationships can be falsified by rejecting their theoretical justification by finding observations in a priori predicted empty spaces or finding that effects are due to random chance of unrelated variables.

Abbreviation: NCA, Necessary Condition Analysis.

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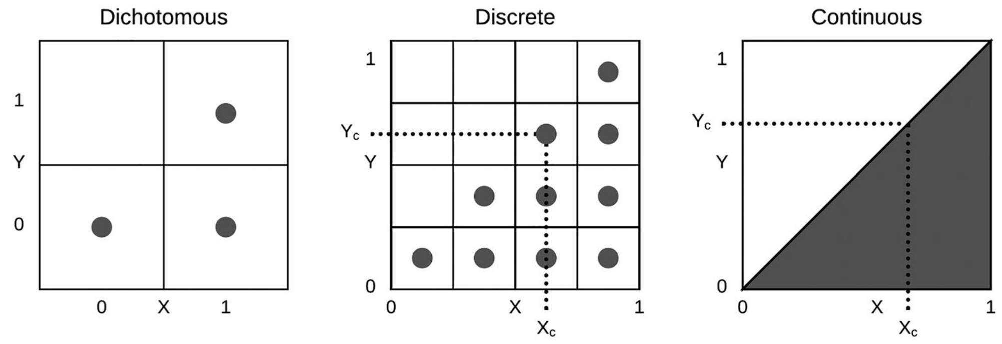

FIGURE 1 Dichotomous, discrete, and continuous necessary conditions, adapted from Dul (2016)

(Dul, 2016; Vis & Dul, 2018). Most scholars have an intuitive idea of a dichotomous necessary condition but usually have little idea of what a continuous necessary condition looks like (Goertz, 2017). A dichotomous necessary condition is when X and Y have only two levels, as in McLachlin (1997), where the "provision of training is a necessary condition for JIT flow" (p. 275). Figure 1 shows that level 1 of X is necessary but not sufficient for level 1 of Y. For discrete or continuous necessary conditions, the outcome has more than two levels: "a certain level of X is necessary for a certain level of Y" (Dul, 2020). For example, "relationships that have high levels of innovation [...] must necessarily have contracts with at least medium levels of contractual detail" (Van der Valk et al., 2016, p. 266). In Figure 1, the discrete necessary condition has four levels of X and Y. In the continuous necessary condition, the dark area represents all cases where X is continuously necessary but not sufficient for Y. In the discrete and continuous necessary conditions, level $X \geq Xc$ is necessary but not sufficient for level Yc (Dul, 2016). In the examples in Figure 1, we presume that the maximum values of Y increase linearly and at the same rate as X and therefore produce triangular potential data zones. However, discrete and continuous necessary conditions can also produce pentagonal (and other nonlinear) data zones where the maximum value of Y for a given X does not increase linearly with X at the same rate.

Theory testing using NCA

NCA provides a data analysis method for testing necessary condition hypotheses. With theory testing, we mean to test if theoretical propositions hold in reality by using empirical data from that reality. Following Popper, falsification is the core of theory development. Testing necessary condition hypotheses is a falsification process to discover whether or not necessity is a plausible part of the explanation of the relationship between X and Y. Testing necessity relationships without statistics can be achieved by means of falsification with thought-experiments (consider cases with the outcome present and check whether the condition can be absent; if so the condition is not necessary) or visual inspections of scatter plots (check for empty spaces in the upper-left corner; if not, the condition is not necessary). Because NCA is an emerging approach that is not yet extensively used within the SCM discipline, this section briefly introduces how necessary condition hypotheses can be empirically tested with NCA. Appendix A provides extended technical details.

NCA can be used with observational (small *N* case or large *N* survey studies) and experimental research designs, which are both widely used in SCM (Bachrach & Bendoly, 2011; Flynn et al., 2018). If the cause cannot be manipulated, observational studies can be applied to observe whether the necessary condition is present in cases with the effect, or if the effect is absent in cases without the necessary condition (Dul, 2016). If the cause can be manipulated, a "necessity experimental research design" can be used (Dul, 2016). Appendix A shows an example of such a design.

NCA software is available as an R package (Dul & Buijs, 2019). When testing necessary condition hypotheses with NCA, the following results are generated (for details, see Dul, 2020): (1) scatter plots with ceiling lines. The ceiling is the border line between the empty space without cases in the upper-left corner of the XY scatter plot and the space with cases (no high X without high Y). The ceiling line represents the level of Y that can be reached with a certain level of X, or in other words, the level of X that is necessary for reaching a certain level of Y. Two default techniques for drawing ceiling lines are available: Ceiling Envelopement Free Disposal Hull (CE-FDH) for discrete data (a small number of levels, e.g., up to five) or when the ceiling is nonlinear, and Ceiling Regression Free Disposal Hull (CR-FDH) for discrete and continuous data with a large number of levels or when a linear ceiling is assumed.

(2) NCA parameters include the necessity effect size, which is the extent to which a condition constrains the outcome, and the statistical test of the effect size. The effect size (*d*) can range from 0 to 1. The statistical test reduces the risk of false positive conclusions by evaluating the evidence of the observed effect being due to random chance of unrelated variables (*p*-value). (3) Bottleneck tables that facilitate interpretation by providing a tabular representation of the ceiling line of one or several necessary conditions, in terms of the required level for the condition to enable a desired level of the outcome. NCA can be used as a single bivariate analysis with one necessary condition and one outcome or a multiple bivariate analysis with combinations of necessary conditions and one outcome (Dul, 2016). Dul et al. (2020) offer at least three criteria that must be met before a researcher can conclude that the data represent necessity: (1) theoretical justification using necessity logic, (2) reasonably large effect size (e.g., ≥0.1), and (3) reasonably small *p*-value (e.g., ≤0.05). All three criteria are necessary (i.e., failing to meet any of them may falsify the hypothesis), and theory lies at the very heart of the NCA approach (criteria 1 reflecting logic). NCA cannot be reduced to a statistical technique for detecting empty spaces in datasets (criteria 2 and 3 reflecting data analysis).

Limitations of necessity theories and NCA

Necessity theories (pure or embedded) predict the absence of the outcome when a single causal concept (the necessary condition) is absent, but it does not predict the presence of the outcome when the causal concept is present. Necessity relationships are asymmetric, meaning that the necessary condition must be in place to have the outcome, but whether the outcome occurs also depends on other (unknown) concepts.

Like all data analysis techniques, NCA also has limitations. The general limitations of statistical inference and generalizing from a sample to a population are the same for NCA as any other data analysis technique. For example, NCA tests necessary condition hypotheses by falsifying theoretically justified empty spaces, either by finding observations in a priori predicted empty spaces or by finding that the empty space is due to random chance of unrelated variables. This can eliminate necessity as a part of the explanation for the relationship between X and Y. Because the process of falsification rests on eliminating alternative explanations (Aguinis & Cronin, 2022), identifying expected empty spaces in datasets may provide support for the hypothesis, but a series of replications are needed before any theoretical proposition can be considered robust and generalizable. Such replication logic also applies to NCA and it implies that a necessity causal relationship cannot be proven from a single study. Thus, the requirements for causal inference with NCA are the same as for other types of cause–effect relations (e.g., X precedes Y). NCA can yield erroneous conclusions if the research design is incorrect, and NCA is not immune to validity threats such as sampling and measurement error (Dul, 2016). For example, the cases that define the ceiling must be representative and have valid scores. Similarly, exceptions or outliers may influence the ceiling line and must be evaluated (see Dul, 2020, 2021 for details about outliers). Therefore, the best strategy to mitigate erroneous conclusions about necessary conditions is to carefully establish solid theoretical support, follow general guidelines for rigorous empirical research (e.g., sampling and measurement), and correctly analyze and interpret the data using NCA.

NCA and other methods

We have presented NCA as an emerging approach capable of testing necessity. However, it is also imperative to describe how NCA can be combined with other methods. Owing to the novelty of NCA and its differences from conventional methods, it is likely that logical and technical misinterpretations will accompany the diffusion of NCA within SCM.

Methods that fit with additive theories and thus cannot test necessary condition hypotheses are variants of the general linear model, including basic variants such as ordinary least squares (OLS) regression and more advanced variants such as difference-in-difference regression (Goertz & Mahoney, 2012). The estimated regression coefficients from such models provide information on how the variables differentially covary with the outcome (Aguinis et al., 2020). In other words, a variable with a large and significant regression coefficient contributes considerably to the variance in the outcome. The evidence from such models thus supports the claim that a variable can help produce or predict the outcome in combination with other variables. However, the variable is neither necessary nor sufficient for the outcome. NCA can be combined with any method that follows an additive logic. This provides complementary views on causal relationships and more precision in theory development and practical advice. Specifically, insights from supported necessity theories tell practitioners that if any necessary condition is not satisfied first, the outcome will not improve by changing the value of any other concept (Dul, 2016).

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QCA (Ragin, 2000, 2008) is an analytical approach that can test necessary conditions. In response to the 2020 Emerging Discourse Incubator, Ketchen et al. (2021) explained how QCA can be used to enhance configural research within SCM. Both NCA and QCA share the causal logic of necessity and sufficiency. NCA uses linear algebra and focuses on (the levels of) individual concepts (and their combinations) that are necessary but not automatically sufficient. QCA uses Boolean algebra and can therefore only test dichotomous necessary conditions. It focuses on combinations of concepts (configurations) that are sufficient but not necessary (equifinality). The necessity analysis only results in a dichotomous "in kind" statement of necessity (absence/presence of X is necessary for absence/presence of Y) in both crisp-set and fuzzy-set QCA but does not consider discrete or continuous necessary conditions ("in degree") (Vis & Dul, 2018). NCA can be combined with QCA to add new insights and improve data analysis. Because the logic of necessity implies that all necessary conditions should be part of all sufficient configurations, NCA can be combined with QCA to identify "in degree" necessary conditions that typically remain undetected by QCA.

CONCLUSIONS AND RECOMMENDATIONS FOR SCM RESEARCHERS

Necessity theories are unique theories that can advance SCM research by identifying the concepts that must be put and kept in place to make an outcome possible. Necessity logic stimulates SCM scholars to theorize more precisely about the causal role of antecedent concepts that are "must haves" for the outcome in virtually all cases. This theorizing involves embarking on novel thought experiments about the nature of concepts, causal mechanisms, and theoretical domains. Because it is pointless to work on improving anything else but the bottleneck, necessity theories provide invaluable knowledge to SCM researchers and practitioners. In turn, NCA offers a valid way of testing necessity relationships. It can shape novel necessity theories that extend the limits and possibilities of the SCM discipline by seeing new phenomena, explanations, and patterns in data. Therefore, using the logic and methodology of NCA to build and test necessity theories is consistent with the intent of the 2020 Emerging Discourse Incubator to stimulate novel theory development, including the call for supply-chain-specific theories (Flynn et al., 2020).

To advance the development of necessity theories within the SCM discipline, we showed that necessary conditions are widespread in SCM, as demonstrated by our literature review of five leading SCM journals (JSCM, JOM, IJOPM, POM, and MSOM). Most of these statements have not been tested and adequately theorized, mainly because the conventional methods that fit additive theory (e.g., regression and SEM) are not suitable for providing evidence of necessary conditions. NCA is an emerging approach and data analysis tool capable of identifying the necessary conditions to make an outcome possible. It also identifies which condition, from a set of multiple necessary conditions, will become the bottleneck as the desired outcome increases.

We conclude by providing four core recommendations to SCM scholars when building and testing necessity theories. First, scholars should explicitly use necessity logic when building necessity theories that show how a concept is necessary for an outcome. They should acknowledge that propositions based on necessity logic and additive logic are fundamentally different. Second, they should ensure that necessity theories are correctly tested. NCA is the most suitable approach and data analysis tool. Third, scholars should search for explicitly and/or implicitly formulated but untested necessity statements in literature and practice, put them to theoretical consideration, and test them with NCA. Fourth, they should revisit necessary conditions hypotheses in existing datasets. They should not forget that only datasets with two variables are needed to test a necessary condition hypothesis with NCA.

To complement these recommendations, we provide a checklist for NCA studies, which can be used by researchers when conducting NCA studies and by reviewers and editors when evaluating manuscripts. It summarizes best practices (the dos) as well as pitfalls and misinterpretations (the don'ts) for NCA studies across four research stages (formulate the necessary condition hypothesis, collect data, analyze data, and write up the study). These best practices facilitate uniform application and comparability of NCA studies in SCM (Bergh et al., 2022). Note that this checklist consists of recommendations that are specific to NCA. Any NCA study must also adhere to the general guidelines for empirical research (e.g., justifying the selected research strategy and collecting sound data through proper sampling and measurement). Appendix A provides extended technical details of NCA. We hope this article will stimulate SCM scholars to appreciate the theoretical and empirical implications of necessity theories and inspire better research designs and methodologies that allow for a fuller understanding of the most pressing SCM questions.

Checklist of dos and don'ts for NCA studies

Research stage	Dos	Don'ts
Formulate the necessary condition hypothesis	☐ Use necessity logic to formulate the hypothesis. ☐ Explicitly theorize why X constrains Y, X enables Y, and/or why X cannot be compensated by other concepts.	☐ Confuse necessity logic with additive logic. ☐ Dismiss necessity because it is a non-dominant logic.
Collect data (research design, sampling, and measurement)	☐ If experimental research designs: Manipulate by removing or reducing the necessary condition in cases with the outcome present.	☐ Assume that specific requirements and approaches apply for research design (other than experiment), sampling, and measurement methods. NCA does not impose any new requirements for data collection. ☐ Assume that X and Y data must be normally distributed; NCA makes no assumptions about data distributions other than that X and Y are doubly bounded (i.e., not infinite). ☐ Assume that data on control variables must be available. Necessary conditions operate in isolation from the rest of the causal structure.
Analyze data	☐ Justify the choice of ceiling line(s). ☐ Specify the effect size threshold and *p*-value threshold for evaluating the hypothesis. ☐ Conclude that a hypothesis is not supported if one or more of the three minimum criteria for necessity are not met: Theoretical support, reasonably large effect size, and reasonably small *p*-value.	☐ Use regression-based methods to test necessary condition hypotheses. ☐ Misinterpret NCA's statistical test based on misunderstandings of null hypothesis testing and *p*-values. ☐ Conclude about necessity solely based on empty spaces in data or solely based on the *p*-value. ☐ A-theoretically conclude about necessity (e.g., "necessity data mining"). ☐ Be concerned about heteroscedasticity. It is irrelevant and often inherent to necessity logic.
Write up the study	☐ Justify the use of necessity logic and NCA. ☐ Formulate the necessary condition hypothesis as "X is necessary for Y" or similar. ☐ Describe how NCA is used at a level of detail that allows for replication. ☐ Report the XY plots with NCA parameters (effect size, *p*-value, etc.) for each hypothesis separately. ☐ Present and interpret the bottleneck table if multiple necessary conditions are supported. ☐ Explain the contributions of the NCA study (theoretical, practical, and/or methodological) and limitations and possibilities for future research.	☐ Formulate the conclusions about necessary conditions in conventional terms, or vice versa. ☐ Include the not-supported necessary conditions in the bottleneck table.

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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APPENDIX: TECHNICAL DETAILS OF NCA

This appendix provides extended technical details of NCA that can support SCM scholars in their NCA studies. For additional information about NCA, see also Dul (2020, 2021).

Necessity experimental research design

When causes can be manipulated, experiments can be used to test necessary condition hypotheses. However, the research design differs from conventional experiments. To exemplify, Van der Valk et al. (2016) used an observational study to test the hypothesis that contractual detail is necessary for innovation performance in buyer–supplier relationships. A necessity experiment to test this hypothesis would consist of (a) randomly selecting cases (relationships) *with* the cause (contractual detail) and *with* the outcome (high innovation performance) from a target population (e.g., all buyer–supplier relationships in an industry sector), (b) randomly assigning these cases to the experimental group (relationships that get a treatment) or the control group (relationships that do not get a treatment), and (c) *removing* the necessary condition only in the experimental group (e.g., deleting details in contracts) and observing whether the outcome *disappears* in the experimental group (reduction of innovation performance) but not in the control group (innovation performance constant).

Data

NCA can be used with any type of data (e.g., cross-sectional, panel, primary, and archival) and any type of scores (e.g., averages, sums, factors, and set memberships). However, general guidelines in empirical research need to be followed (e.g., ensuring good data through proper sampling and measurement). In NCA, the explanatory and response variables are assumed to be doubly bounded on an interval [a, b], which allows the effect size to be calculated. The boundedness assumption is reasonable because data commonly represent bounded phenomena (e.g., a person's height and people's responses ranging from "complete disagree" to "completely agree") or percentages, proportions, or fractions. NCA does not make an assumption about the distribution of the data.

Sample size

NCA does not impose any specific rules for sample size, but the estimation of the effect size improves with sample size as more cases that would appear above the ceiling line are included. The general guideline for sample size is "the more, the better, for confidence." However, if the hypothesis is "the presence of X is necessary for the presence of Y" and both X and Y are dichotomous, it can be tested with just one case. The hypothesis can be falsified by applying purposive sampling to select only cases with the outcome present and observing a single case where the condition is not present.

Scatter plots and ceiling lines

NCA generates scatter plots with ceiling lines (Dul, 2016) that separate the region with and without data (Goertz et al., 2013). The entire area with and without data is called the scope (S), and the empty space is called the ceiling zone (C). To draw ceiling lines, two default types of techniques are available: (1) Ceiling Envelopement (CE) and (2) Ceiling Regression (CR) (Dul, 2016). For CE estimation, Ceiling Envelopement Free Disposal Hull (CE-FDH) presumes a non-decreasing ceiling and thus provides a non-decreasing step function through the upper-left observations. The entire region of data is thereby enveloped under the ceiling line. For CR estimation, Ceiling Regression Free Disposal Hull (CR-FDH) smooths the piecewise linear function by means of ordinary least squares (OLS) regression through the CE-FDH upper-left observations (Dul, 2016).

Effect size

The effect size (d) of the necessary condition represents "the size of ceiling zone compared to the size of the scope" (Dul, 2016). That is, $d = C/S$. A larger ceiling zone means that the necessary condition has a larger constraint on the outcome. The effect size d can range from 0 to 1. Dul (2016, p. 30) suggests the following benchmarks: "$0 < d < 0.1$ as a small effect, $0.1 \leq d < 0.3$ as a medium effect, $0.3 \leq d < 0.5$ as a large effect, and $d \geq 0.5$ as a very large effect." Moreover, $d = 0.1$ could be used as a minimum level for considering the effect size as meaningful in theory and practice (Dul, 2016).

Statistical test

NCA also performs a statistical test to evaluate the evidence of the observed effect being due to random chance of unrelated variables. This is a null hypothesis test, not a test of an alternative hypothesis (Dul et al., 2020). The approximate permutation test is usually repeated 10,000 times and produces a p-value that helps researchers avoid Type I errors.

Bottleneck tables

The interpretation of NCA results is enhanced through bottleneck tables. A bottleneck table is a tabular representation of the ceiling line of one or several necessary conditions. It shows "which level of the necessary condition(s) that is (are) needed for a certain level of the outcome, according to the ceiling line" (Hauff et al., 2020). The conditions and the outcome can be represented as actual values, percentages, or percentiles (Dul & Buijs, 2019).

Multiple necessary conditions

NCA can be used as a single bivariate analysis with one necessary condition and one outcome or a multiple bivariate analysis with combinations of necessary conditions and one outcome (Dul, 2016). NCA is bivariate because this is consistent with the interpretation that a single X is necessary but not sufficient for Y, independent of other causes of Y. In multiple NCA, the multidimensional ceiling surface is projected on the two-dimensional XY planes, and the ceiling line in each plane is analyzed bivariately. NCA's bottleneck technique is particularly useful for analyzing situations with multiple necessary conditions. NCA combines the ceiling lines of the individual necessary conditions by taking the minimum ceiling value for a set of multiple necessary conditions. The bottleneck table shows the interplay between multiple necessary conditions at different levels of the outcome (Dul, 2016).

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Model parsimony and omitted variables

Necessary condition models can predict the absence of the outcome with even one or a few variables and can therefore be parsimonious (Dul, 2016). A key feature of necessary conditions is that if a single necessary condition is absent or below a certain level, the outcome will not be affected by the level of other variables (Hauff et al., 2020). In NCA, the correct estimation of the parameters of a necessary condition is not affected by omitting other necessary conditions or other variables. There is no risk of omitted variable bias (as in estimating regression coefficients), and control variables to mitigate this bias are not needed (Dul, 2016; Goertz, 2017). This can help decrease the complexity of the data collection and the model. Still, an observed necessity relationship between X and Y can be spurious if another variable Z is necessary for Y and sufficient for X (Mahoney, 2007).

Necessity and correlation

We all know that correlation does not imply causation and we should all know that empty space does not imply (necessity) causation. Still, it is important to note that necessary conditions can also correlate with the outcome. A sufficiency and a necessity causal relation both usually produce a correlation (dependency) between X and Y. However, if we observe correlation in a sample, we do not know if this comes from a sufficiency or necessity causal relationship, although many researchers immediately assume the former. Necessary conditions also often help the outcome, that is, contributes to sufficiency. For example, in the extreme case of the AMO model, the three necessary conditions are also jointly sufficient and can thus predict the presence of the outcome (Van Rhee & Dul, 2018). However, a single or several necessary conditions usually only partially contribute to the outcome.