Entropic measurement in supply chain network: past applications, current trends, and future research

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Abstract: Increased product variety, flexibility in production, decentralized production and distribution sites are some of the answers that companies found to differentiated, fast changing, and urgent customer's demand. While having positive effect on revenue and market share, those actions had a profound impact on the conformation of the supply chain (SC). Moreover, challenges such as environmental impact and disruptive events shifted the goal of production and distribution systems from mere efficiency (economical sustainability) to encompass first environmental and social sustainability, and then resiliency. Those factors increased the complexity of managing supply chain networks (SCNs), with deep implications for costs, for choosing the facility location, for understanding the global effect of varying the range of produced goods, for forecasting the effect of change in customer demands, or distribution policies. In recent years, many authors have proposed concepts related to information entropy to deal with these issues: the main reason is that more complex SCs require more information to be described and managed, while also affecting material and financial flows. This paper is an overview of the different ways in which entropy has been brought into correspondence with SCs: mainly to address their sources of complexity, but also with other interesting aspects such as recoverability. The overview describes the main results for each area of application, and then it suggests future developments.

Keywords: Entropy, Supply Chain Network, Complexity, Resiliency

I. INTRODUCTION

Supply chain (SC) complexity increases when firms try to satisfy customers with strategies such as proposing a more differentiated range of products, characterized by shorter lifecycles [1], [2], a more reliable system against disruptions, with redundancies in facilities (production and distribution centres, DCs), or by designing SCs that react quicker to changes in demand with many and less centralized DCs. Practitioners and researchers usually consider complexity as an impediment to SC operations and an obstacle to flows of materials and information [3]. This means that firms have to find the right compromise in terms of complexity [4], in an era when SCs grew to become more global and to involve more elements, that interact in a more differentiated way and that over time are subject to a wider range of needs and constraints than in the past, with less certain timing and effects [5]–[7].

In such a complex environment, with a lot of intricated variables to control, it is hard to pool operational, tactical, and strategical choices in the proper way towards long term goals [8], also because participants may be member of other SCs that have different goals [9]. Increased complexity makes it harder to align information and SC incentives, and these are needed to make partners act towards the best solution for the whole SC [10]. Despite the growing interest in complexity management, it is not widely implemented in the industry also due to the lack of tools to quantify complexity itself [11]. Entropy is one of the tools that has been brought into correspondence with SC complexity [7]. This paper aims to examine how entropy has been used to quantify different aspects of SC.

Entropy was first used in SC studies to measure its complexity: this measurement process started by noticing that more complex systems have more possibilities in SC flows (of information, financial, and of materials) and more uncertain (less predictable) operations, in analogy to what Frizelle and Woodcock [12] did for manufacturing purposes. Shannon's entropy formulation [13] from 1948 considers both the number of possibilities and their probabilities in a process (as described in section II): these features led many authors to use entropy concepts to describe SC complexity, again as already done in neighbouring fields [14].

SCs complexity must be managed considering both the environment's effect on SCs and the effect that SCs have on the environment. An example of environment's effect on SC is a disruption, that is an unexpected and high-impact event, that may even lead to an equilibrium situation that is different from the one preceding the disruption. Disruptions have increased in intensity and frequency from the 2010s, particularly due to climate events, the spread of pandemics, and political tensions [15]. In fact, in the last twenty years studies on SC moved from efficient to robust and resilient: a robust SC can manage fluctuating variations in factors such as demand and lead times [16], while a resilient SC has the capability to withstand, adapt, and recover from disruptions [17], [18]. SCs must consider these changes and even be prepared to unprecedented events: this adds another layer of complexity in managing the system.

Besides being susceptible to external conditions, SCs impact themselves on the external environment: the interest in this theme is certified by vast research on closed-loop SCs [19] and disassembly lines [20] to collect disposed products, to remanufacture or recover components and materials. SCs must follow always stricter governmental legislations on end-of-life of products, such as WEEE directive [21]. Literature addressed industrial processes also to reduce the CO_2 emissions to avoid catastrophic global warming [22], considering the relevant amount of energy consumed worldwide by industries [23]. Industrial plants play a key role in managing SCs' complexity: there is the need to find the strategy of supplying and delivering materials, to choose the right level of inventories, of product variety and of process standardization, guarantying flexibility in production. This must be accomplished in the era of workforce shortage [24], not overlooking the impact that decisions have in preserving both the workers' productivity and their long-term health. The complexity of this task is presented for example by Najjar and Nassin [25], addressing a SC's social sustainability in terms of labour and working standards of low-tier suppliers.

The originality of this paper lies in being the first overview that investigates the use of entropy in the context of SC. The paper continues as follows: section II describes the concept of entropy, section III presents the literature review, while section IV is for conclusions and future research.

II. ENTROPY

While there is the wish of linear and easy-to-manage SCs, today's conditions make it very uncommon to have such simple systems. SCs are complex also because their elements can be so intertwined that we cannot understand SCs by analysing their components one at the time [26]: it is required to consider the connections between every component. For example, supply network design (SND) usually considers both investment and operational costs. The first encompass building DCs, the latter distribution costs. Investment and operational costs are coupled because routes and inventory levels interweave with the decision of how many DCs to open, and with their locations. Making decisions on investments without considering all the operational costs generally lead to a suboptimal SC design.

Difficulty in considering connections grow when there are more customers, DCs and suppliers, when there are more products requiring different storage technologies (e.g.: high value goods, perishable, frozen food), but also when external conditions change or have high uncertainty.

From early 2000s to present days, many authors proposed entropic measures to deal with SCs' intrinsic and growing complexity: first entropy was considered suitable to measure the complexity of a system because it is representative of the number of possibilities that are available and of the amount of information those possibilities are conveying [4].

In this overview, we will refer mainly to Shannon's formulation of entropy [13], generated from the field of information theory: Shannon's main goal was to understand under which conditions a receiver could identify the data sent by the source based on the signal received. The formulation is as follows:

$$H = -K \sum_{i=1}^{n} p_i \, log \, p_i = K \sum_{i=1}^{n} p_i \; log \frac{1}{p_i} \quad (1)$$

In (1), H is the entropy, p_i is the a priori probability of occurrence of an event i out of the n possible states (with: $p_i \geq 0$ and $\sum_{i=1}^{n} p_i = 1$), while $log \frac{1}{p_i}$ is related to the amount of information conveyed by that event (less likely events bring more information). K is a constant value, usually set equal to 1 in information theory. K recalls the Boltzmann constant when entropy is used in statistical mechanics: the formula is analogous for measuring entropy of a physical system with n possible microscopic states. The base of the logarithm is usually set equal to 2, so the resulting unit of measurement of entropy is *bits*. Choosing another base of the logarithm will lead to values of entropy that differ only by a multiplicative constant and will be expressed with another unit of measure (*Hart* if the base is equal to 10, *nats* if the base is *e*). An intuitive meaning of (1) is described as follows: an event that is certain to happen has H=0: this happens when the conditions of a system are clarified [26].

A process that can develop in 2 different states of equal probability has H=1 bit (e.g.: toss of a fair coin). A process that can develop in 4 different states of equal probability has H=2 bits. In a process with 4 possibilities, not all of which have the same probability of occurring, the entropy is less than 2 bits: this is because a uniform probability distribution (highest degree of uncertainty) of events conveys less information than any other distribution. The range of entropy function is $0 \leq H \leq \log n$.

III. Literature Review

A. Selection Criteria

This overview starts from a systematic search of papers in the Scopus database, focussing on the ones written in English that contain the word "entrop*" and at least one between "supply chain" or "supply network" in title, abstract or keywords. The search is updated to 30th April 2023; the publication year was not restricted, as well as the document type. The search led to 577 papers. Among those, 171 were considered interesting based on their title and abstract. Subsequently, these 171 papers were read with the aim of proposing a first categorization according to how they use entropic measurements in SC. The identified main categories are related to the use of entropic indexes in (1) complexity assessment; (2) supply chain resilience; (3) complexity reduction for enhancing visibility; (4) supplier-customer systems; and finally (5) to understand the propagation of complexity from product variety to assembly systems and SCs. In the next subsection we describe the main entropic formulations, while in the subsequent one we describe the proposed categories by reporting some of the papers considered to be the most relevant for the scope of this preliminary study. These are the ones that opened the topic of entropy in SC, the most cited, and/or the ones that brought (or could bring) innovative perspectives on the use of entropic measures topics related to SC.

B. Entropic formulations

We introduce entropy-derived formulations that are common among the applications found in the literature overview, to have the background to describe these applications in the next subsection. The structural complexity index $H_{(s)}^{I}$ of a system with M resources, N number of states of each resource, and probability p_{ij} that the resource i is in state j can be computed as in (2). An intuitive meaning of (2) is that a more complex system needs more variables to be described, thus, it is correlated to higher entropy. (2) is an extensions of (1) made from Frizelle and Woodcook in 1995 [12] and adapted by Isik in 2010 [5], to quantify the structural complexity of a system.

$$H_{(s)}^{I} = -\sum_{i=1}^{M} \sum_{j=1}^{N} p_{ij} \, log \, p_{ij} \tag{2}$$

$$H_{(o)}^{I} = -(1 - P) \sum_{i=1}^{M} \sum_{j=1}^{N} p_{ij} \, log \, p_{ij} \tag{3}$$

$$H^{I} = -\sum_{i=1}^{n} [log \, p_i] \, p_i d_i \tag{4}$$

$$H_I = -\sum_{j=1}^{N} \frac{t_{.j}}{t_{..}} \log \frac{t_{.j}}{t_{..}} \tag{5}$$

$$H_O = -\sum_{i=1}^{N} \frac{t_{i.}}{t_{..}} \log \frac{t_{i.}}{t_{..}} \tag{6}$$

$$H_{O,I} = -\sum_{I=1}^{N} \sum_{j=1}^{N} \frac{t_{ij}}{t_{..}} \log \frac{t_{ij}}{t_{..}} \tag{7}$$

$$AMI = H_O + H_I - H_{O,I} \tag{8}$$

$$R_{O,I} = H_{O,I} - AMI \tag{9}$$

$$TST = \sum_{I=1}^{N} \sum_{j=1}^{N} t_{ij} = t_{..} \tag{10}$$

To assess operational complexity, (2) gets modified to consider the probability $(1 - P)$ of the system of being out of control as in (3), where $H_{(o)}^{I}$ stands for operational complexity index, and P is the probability of the system of being in control (or scheduled) state. (4) is a modification by Isik [5] where d_i is the deviation of the outcomes from the expected value for the state. Input and output flows can be quantified by the exchange of goods and values. From those flows, transition probabilities can be computed by assuming that the probability of a product to move from node i to node j is proportional to the flow from node i to node j, the previous expressions can be extended and modified as in equations (5)-(7), where t_{ij} is the flow from node i to node j and the operator “.” is short for summatory along the index, such as $(t_{.j} = \sum_{i=1}^{N} t_{ij})$. H_I is called input entropy, H_O output entropy, $H_{O,I}$ is the combined entropy (or joint entropy). Following the previous equations, (8)-(10) can be defined, where AMI stands for Average Mutual Information, related to the order of the system arcs, $R_{O,I}$ is the degree of disorder of system arcs, while TST is the total size of the throughput.

C. Uses of entropic measurements

Complexity assessment

Wang, Efstathiou and Yang [27] in 2005 proposed entropic-related measures to investigate the complexity, uncertainty, and unpredictability in a dynamic decision-making process. Starting from the consideration that complexity was not only linked by the numerosity of elements of a system and by their distribution of probability to happen [28], Isik [5] in 2010 proposed a complexity measure that considered also the differences between forecasted and real orders. They did so claiming that those differences must be part of the indicators of the complexity of the SC, since they represented the mis-alignment between the flows of information and materials: they proposed (4) and then particularized it for both static and dynamic entropy, leading to formulations that allowed to give more meaning to resulting indexes because, through d_i, they weigh more the states that differ the most from the expected outcome. Basing on (2), Martínez-Olvera [3] in 2008 compared information-handling systems in supply chain information sharing approaches, validating through scenarios where higher levels of entropy are found to be linked to more uncertain processing times, longer queue and average waiting times. Battini, Persona and Allesina [29] in 2007 took an approach typical of ecological network analysis to calculate performance indexes starting from (5)-(10), then extended in 2010 [30]. They added other nodes to investigate information (total import into the system, total export from the system, and dissipation) to calculate ascendancy, capacity, and overhead, that described respectively the level of organization, the maximum organizational potential of the system, and the difference between the previous two. They suggested that a more organized SC is more efficient, as in ecological systems. Cheng, Chen and Chen [26] started from the approach constructed in [30] and defined “degree of order” and “diversity” of SCs and proved the relation they have with the product of indexes ((8), (10)), and ((9), (10)), that is AMI e $R_{O,I}$ when multiplied by TST. Finally, they proposed and demonstrated through examples that system structural complexity ($\mathrm{C_{st}}$) can be measured as: $\mathrm{C_{st}} = R_{O,I} \cdot TST + H_{\mathrm{Type}} \cdot \mathrm{n}$, where another entropic index, i.e. H_{Type}, described the diversity of the average system member types, and n the number of types. Types of structural combination depend on the ratio between entering and exiting arcs in each node. Following graph theory considerations, in 2021 Lin et al. [11] investigated which SC complexity measure can be defined as consistent, meaning in which the complexity of a network is always higher than the complexity of its subnetwork. The indexes respecting this requirement do so only for unweight graphs, meaning for adjacency matrix where the cell a_{ij} is equal to 1 only if there is a connection between those nodes, in contrast to a weight graph where a_{ij} can take any value. They concluded by proposing a consistent measure for weight graphs.

Supply chain resilience

SC disruptions increased in frequency in 2010s due to different factors. For example, climate change impact SCs through the increased occurrence of climate-driven disruptions that seem to compound one on each other [31], leading to extreme events that are ‘expected to become more frequent, longer lasting, and more intense in the coming decades’ [32]. To curb climate change, governments imposed some regulations on fuels and emissions, impacting again SC in terms of investments, operating costs, and facility locations.

Disruptions continued in a period already marked by COVID-19 pandemic, that represents the first super-disruption in history. The result is a complex interlacement of causes and effects that is hard to investigate and manage [15]: for example, resilience and sustainability have to be addressed at the same time [33], to avoid that surviving disruptions comes at cost of sustainability [34]. Durowoju, Chan and Wang [35] in 2012 investigated the perturbation coming from the disruption of a flow of critical information between firms in a manufacturing SC: they used entropy theory to assess risk, and simulation to evaluate disruption’s impact on diverse SC entities. Ekinci et al. [36] in 2022 used the indexes in (9), (10) to analyse resilience of global SCs, claiming that a more complex system has higher probability of facing a disruption. By comparing first and second COVID-19 waves, they assessed that systems learnt how to deal with disruptions because perceived complexity decreased even if system complexity increased.

Degree of disorder $R_{O,I}$ was calculated for perceived complexity, while $(R_{O,I} \cdot TST)$ measured system complexity.
Ivanov [37] in 2019 suggested an entropy-based measure to estimate SC recoverability: in fact, he identified in variety of paths the recovery strategy for a flexible reaction towards a disruption.

Complexity reduction to enhance visibility

Compared to the past, SCs are more intertwined and global, so more susceptible to events happening in other parts of the world, for example when delays and inefficiency are propagated through the SC: this propagation of effect is called ripple effect [38]. Levner and Ptuskin [39] in their work from 2018 assumed that an increase in the decision maker's knowledge of risks in a node is equivalent to a decrease of the entropy level in that node: thus, reducing the entropy of the system allows a simpler management, reducing the risk of disasters. They used an example defined by ecological risks, but the approach can be generalized to other risks: measuring complexity through entropy is considered critical in identifying and reducing the ripple effect. A similar need to reduce risks to have higher sustainability levels lead Apeji and Sunmola [40] in 2020 to link an entropic approach to visibility in a SC.

Supplier-Customer systems

Even for markets that have little variations in final consumer demand, it is common to see considerable swings in warehouse's stock levels and orders. This effect propagates from downstream to upstream the SC is known as bullwhip effect (BE): it grows with information asymmetry between SC players. Huaccho Huatuco [41] claimed that BE represents a cascading propagation of complexity: these authors focused on entropic indexes as measure for defining categories of complexity ranges due to variability in time of the deliveries (early, on time, late) between various players of SC. The same process can be applied to measure uncertainty in delivery quantity. This method allows to use entropic indexes to compare different industries, and to identify which entities act as complexity sources or sinks, depending on how they transfer, amplify, or reduce complexity. A sink, that is an entity that reduces the complexity that flows through the whole system, could be an element that has unreliable suppliers, but uses its inventory to satisfy a customer demand that is unstable and subject to late changes. As a result, they noticed that a complexity transfer mechanism like BE can happen downstream the supply chain (from suppliers to customers). Some considerations on roles of generating, transferring, importing and exporting operational complexity were already introduced with entropic measures by [42] in 2002. In a different way, Saikouk, Zouaghi and Spalanzani [43] in 2011 assumed that BE is a consequence of SC's entropy and thus it represents the concretization of the dissipation of information: more complex systems behave in a more turbulent way leading to higher rates of dissipation of information. While being an interesting approach, there is no use of mathematical formulation to measure this dissipation of information. Azzi et al. [44] in 2010 used the entropic indexes from formulas like (5)-(9), ascendancy, capacity, and overhead to measure the reduction in information required by firms as they increase their use of third-party logistics to simplify SC management.

From product variety to assembly systems and SCs

Many practitioners and researchers use the number of variants of a product as an indicator of the complexity of a process, but this not enough to understand how product-induced complexity propagates through manufacturing, organization and other SC players [45]. Hu *et al.* [46] in 2008 described mixed-model assembly systems and multi-echelon assembly supply chains: complexity deriving from product's variety transferred to assembly system, since an operator chooses the right part or the right processing to customize products following consumers' choices. The choice complexity was described by a Shannon-like formulation (1) with p_{ij} representing the probability choice i to take the outcome j. The complexity of the assembly supply chain was then assessed by joining entropic-based indexes representing complexity in the station level. Modrak and Soltysova [45] in 2023 assessed product variety complexity starting with the transformation of all the possible product variants into a design structure matrix linking the functional requirements and the design parameters. Then, a new structural design complexity was defined based on the analogy with Boltzmann-Gibbs entropy, thus through a thermodynamical analogy: a more disordered system requires more information to be described and has a higher entropy. They used a modified entropy formulation for structural design complexity already suggested by Guenov in 2002 [47], considering the number of couplings per design parameter. This new measure incorporates more principles of system complexity, such as the number and the complexity of interactions between the elements.

IV. Conclusions and Future Research

We analysed the applications of entropy measurements in SC and proposed a first categorization of them. As future deepening, an analysis highlighting connections across themes could help in defining a more detailed categorization, understanding also which fields are receiving more attention recently. The search could then include neighbouring areas to give a more complete view of the topic, even with a snowball search.

Nonetheless, this first overview gives already enough insights to propose future research developments: a short-term research theme comes from noticing that entropy measures related to flows (of materials, of information, and financial flows) still lack an absolute index: indexes found in literature are useful for comparing different SCs alternatives (for example to evaluate alternative graphs of a SC), but the single index does not provide much information on its own on a single graph. Most authors applied entropic concepts to one or few sources of SC complexity at the time. This has two reasons: first, the topic is considerably vast and far from maturity; second, the authors described the factors they considered more relevant. Still, overlooking some factors of complexity must be justified, and this needs measurements. For example, it is correct to focus only on SC graph complexity when all other elements of the SC add little complexity. By contrast, using the same graph-related indexes on a SC characterized by huge product variety and demand variability looks a faulty procedure. Cheng, Chen and Chen [26] and Modrak and Soltysova [45] used entropy's additive property to consider more aspects of SC complexity: this path looks promising. Nonetheless, it must be clearly defined when the necessary conditions between different sources of complexity holds in the SC context: for random variables X, Y the relation: $H(X,Y) = H(X) + H(Y)$ is true only when X and Y are independent [48]. Limitations on this could lead to the use of different entropies (such as Tsallis entropy and Rényi entropy) that rely on assumptions that affect additive properties and have potential applications to graph theory [48]. It would be useful to understand better entropic indexes applicability and have a framework that guides practitioners towards the most relevant ones in different contexts. After clarifying indexes and connections among sources of complexity, researchers could finally aim at managing SC complexity in a holistic way. This global complexity measure could benefit from the integration of entropic measures with other methods. Entropic measurements could benefit from ideas already developed for layout design, since there are many entropic indexes on that field [49]. Moreover, study on entropic complexity measures could head towards emerging SC research fields on which this overview did not find any contribution, such as viable SC: it refers to the capability to withstand long crisis [50], in opposition to resilience that refers to punctual events.

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