GREEN HYDROGEN, INDUSTRIAL SYMBIOSIS, AND BLOCKCHAIN: ENHANCING SUSTAINABILITY AND RESILIENCE IN SUPPLY CHAINS

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ABSTRACT

The purpose of this article is to present two types of optimization models for simultaneously increasing sustainability and resilience in industrial supply chains. Sustainability increases when the chain as a whole reduces its carbon footprint. Resilience increases when increasing the supply chain's ability to recover from disruptive events. In principle, the objectives are antagonistic. Some sustainability approaches advocate that efficiency should increase, reducing supply alternatives and, consequently, the chain's resilience. This article proposes to combine two supply strategies, green hydrogen and industrial symbiosis, and a management strategy, blockchain, which can simultaneously increase sustainability and resilience. Adding sources such as green hydrogen and reusing material and energy waste generated by members of the same or another supply chain reduce the carbon footprint (by replacing fossil fuels and virgin raw materials). It also reinforces the supply chain, adding redundant edges. The article discusses the requirements of two models to optimize the implementation, one based on mixed integer linear programming and the other based on agent-based simulation. A cloud information system based on blockchain technology ensures data reliability.

INTRODUCTION

Supply chain (SC) management (SCM) achieves strategic objectives differently than individual companies do (Wiengarten et al., 2019). While companies achieve their own competitive priorities, such as cost reduction, quality assurance, increased dependability, or flexibility (Esmizadeh and Parast, 2021), SCM achieves objectives by combining capacities among multiple members (Saragih et al., 2020). SCM usually deals with conflicting individual objectives that require handling to reach an optimal global result (Mckone-Sweet and Lee, 2009). For example, if the SCM aims to reduce the cost of a system assembled by company A, using a subsystem supplied by B, and transported by C, it is unlikely that the economic quantity order is the same for all companies. A trade-off solution should optimize the overall cost, not the individual costs.

Multilateral commitments in SC require meta-strategies (or network strategies). Such strategies determine broad objectives for the SC achieved by combining individual, not necessarily optimal, achievements (Wiengarten et al., 2019).

A first approach to a network strategy points to two scenarios, the efficient SC and the agile SC (Gligor et al., 2015). Efficient SC requires low uncertainty on the demand and supply sides (Wiengarten et al., 2019). Its main result is an accurate supply of low-cost, high-quality, functional products that meet the low-price market's needs. Agile SCs match with high uncertainty on both the demand and supply sides. Its main result is the on-time delivery of innovative products that meet differentiated markets' needs (Shabbir et al., 2019).

Another approach to network strategy adds two scenarios to the initial ones; the resilient SC and the responsive SC. Resilient SCs match with low uncertainty in the demand and high uncertainty on the supply side. Such type of SC ensures deliveries of functional products, even under an increased supply disruption risk. Some resilience mechanisms are a high inventory of critical items and mainly redundancy for critical suppliers (Dubey et al., 2017). Such redundancy requires multiple competing suppliers, preferably located in distant geographic regions, to avoid simultaneously being susceptible to the same natural disasters or political uncertainties. Such a strategy jeopardizes the cost but ensures high dependability even at the risk of disruption on the supply side (Purvis et al.,

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2016). Blockchain is promising for managing supply uncertainty (Zhang et al., 2019). The exchange of information allows assessing in real-time inventories and demands and quickly reallocating physical inventory and resources, minimizing the disruption probability.

Responsive SCs match with high uncertainty in the demand and low uncertainty in the supply. Its main result is to ensure deliveries of innovative products, even under high uncertainty on demand (Roh et al., 2014), such as fashion and technology items. Some responsive mechanisms are high inventories of critical items and mainly reconfigurable manufacturing systems (RMS) that allow fast-track deliveries (Nayeri et al., 2023). Such a strategy jeopardizes the cost and fails to ensure quality (due to the low learning time) but provides high flexibility in uncertain markets (Purvis et al., 2016).

Other approaches introduce sustainability as a strategic element of the SCM, the Green Supply Chain Management (GSCM) (Hermann et al., 2021). Authors use the acronym LARG (lean, agile, resilient, and green) for multiple strategic attributes of the SC (Azevedo et al., 2016). One strategy for greening the SC is using green hydrogen (GH) as an energy carrier. The industrial sector and mainly transport account for a large generation of greenhouse gas (GHG), due to fossil fuels. Replacing it with renewable energy sources, such as wind, solar, biomass, or GH, can significantly reduce the so-called ecological footprint and achieve the strategic greening objectives of the SC (Butturi and Gamberini, 2022). The topic is part of strategies that seek to reduce greenhouse gas (GHG) emissions by developing carbon-neutral technologies (Garlet et al. 2022; Lo Faro et al., 2022). Another strategy is the so-called industrial symbiosis (IS), in which SC companies exchange materials, energy, and information to allow the waste of one activity to turn into input for another (Sellitto and Murakami, 2018). For example, exploring an eco-design perspective (Borchardt et al., 2009), if cement, rubber, and rice manufacturers are nearby, under a low logistical cost, rubber shavings and rice husks become fuel for cement manufacturing (Sellitto et al., 2013). SC greening is usually an enabler, a meta-strategy underlying the others, as many markets consider greening the SC a necessary condition for new businesses (Umarov et al., 2019).

A survey in the Scopus databases, under the keywords "green hydrogen" and "blockchain"; "industrial symbiosis" and "blockchain"; and "green hydrogen" and "industrial symbiosis" resulted in zero, twelve, and two studies, respectively, in the last five years. Given the scarcity of recent research connecting the themes, the research gap this study aims to bridge is the relationship between green hydrogen production, industrial symbiosis activities, and blockchain technology. In particular, this study aims to investigate the topics in the context of sustainable and resilient SC.

The purpose of this article is to discuss types of optimization models to support the development of resilient and green SC. This study is limited to implementing GH production and symbiotic exchanges managed by blockchain information systems. The remainder of this article embraces concerns on GH, IS, blockchain, types of valuable models, and final remarks.

GREEN HYDROGEN AND INDUSTRIAL SYMBIOSIS IN THE SC STRATEGY

The energy transition from fossil fuels, such as those used in industrial SCs, to zero carbon emission fuels is one of the main challenges governments, research institutes, and industrial entities should overcome in the coming years (Bonacina et al. 2022). In energy-intensive SCs, the main challenges include reheating furnaces, thermal processes in general, and especially the transport infrastructure, both for supplying raw materials and distributing finished products.

One of the most attractive alternatives for reducing the GHG generated in SC is employing GH to replace fossil fuels. The primary technique for producing GH is electrolysis (other techniques involve biogas and biomass), which consists of the breakdown of water molecules by electric currents from renewable sources. As the process emits a low amount of CO_2 (10 kg CO_2 / kg of hydrogen circa), it becomes attractive for energy-intensive SCs who face difficulties in going green, such as industrial ones. Renewable sources include solar, wind, water, biomass, or ocean (Gawlik and Mokrzycki, 2021; Gondal et al., 2018).

Given the recent spread of renewable sources, hydrogen has become a promising solution to problems of intermittency and uncertainty in demand (Jang et al. 2022) and storage of electrical energy for consumption, mainly industrial (Ishaq et al. 2021). A green hydrogen-based economy is a transition requirement in energy systems and essential support for sustainability goals in SC (Raman et al., 2022). One problem is the low energetic effectiveness of the water electrolysis process that produces hydrogen. Future research should address this issue (Noussan et al., 2020). In short, despite incentives and public policies, significant obstacles persist, such as developing technology, restricted infrastructure, and low overall efficiency of the production and distribution process.

Another problem is the delay in building industrial infrastructure for large-scale economic production. Europe concentrates most initiatives, even if regulatory agencies still consolidate no standards. Doubts persist regarding the mode of production, guarantees of origin, percentage of renewable energy used, carbon accounting method, emission limits, raw materials, and technologies included in the production and distribution scheme (Abad and Dodds, 2020). The European Union launched a strategic plan for structuring GH production chains. In the short term, the goal is to decarbonize SC, develop new applications, and increase local production. The objective is to create an international distribution infrastructure in the medium term. The long-term goal is to reach technological maturity and consolidate large-scale production.

The GH SC includes sources of supply, production, and distribution (Li et al., 2018). The production relies on renewable energy sources that supply electrolyzers, compressors, and storage tanks before transport to the point of consumption (Nikolaidis and Poullikkas, 2017). As there is no consolidated production chain model, this is an open field for research (Frankowska et al., 2023). For example, the distribution route and supply and demand locations determine the use of transportation, which can affect global CS emissions (Abad and Dodds, 2020). One possible solution involves using blockchain to optimize inventories and distribution routes. The blockchain digitally and securely records GH production, transport, and consumption, allowing verification of hydrogen's origin and quality and providing transparency in commercial transactions.

Both sustainability and resilience may interconnect in SC strategy. Some sustainability approaches even advocate for higher resource efficiency, which would require fewer preventative redundancies in a first, fast approach. As SCs are more susceptible to disruption under lower backup inventories (Fahimnia and Jabbarzadeh, 2016), improving sustainability may eventually imply decreasing resilience.

IS is a strategy that should mitigate environmental impact while increasing resilience (Moosavi et al., 2022). IS initiatives usually take place in intertwined networks. In such networks, companies exchange information, energy, and materials, resulting in mutually beneficial transactions regarding low-cost raw materials that partially replace virgin materials, rewarded destinations for material and energy waste, and different raw materials for newly developed products (Lombardi et al., 2016). As IS increases the network's density, it also boosts SC resilience in a closed reinforcing loop (Turken and Geda, 2020).

Likewise to what happens regarding GH, blockchain-based systems can also ensure the resilience of industrial symbiotic networks by providing information transparency and transaction security.

BLOCKCHAIN IN THE SC STRATEGY

Resilience in an SC is maintaining and recovering the overall performance or at least in critical priorities after unexpected disruptions. Belhadi et al. (2021) distinguish between proactive and reactive decisions to increase resilience. The former depends more on infrastructures and redundancy, while the latter on real-time, secure information systems. One technology that can be useful in a reactive decision is blockchain.

The blockchain is a decentralized technology used in information systems (Nakamoto, 2008), a distributed ledger technology (DLT) that allows for secure information recording. This feature is due to cryptographic evidence of the validity of records added to the data. The blockchain embraces a chain of sequential blocks, where each new block receives a cryptographic hash generated from its content and the block's hash that precedes it. Therefore, alterations in an antecedent block require alteration of all subsequent blocks (Alladi et al., 2019), invalidating the adulterated records. Other network participants verify and accept new records when updating the state of such documents (Fell et al., 2019). All members have a copy of all records added to the ledger, which allows transactions between unreliable peers without an intermediary controller (Li et al., 2018). Applications include the financial market, the Internet of Things (IoT), healthcare (Musleh et al., 2019), digital identity, and real estate bookkeeping (Khattak et al., 2020), among others.

Systems based on DLTs appear in several applications due to their resiliency characteristics. Centralized systems are susceptible to network congestion, scalability limitation, systemic breakdown failures, and the need for a centralized trusted entity (Augello et al., 2022). A failure or attack on a node does not shut down the entire system, allowing the other members to operate normally (Dehalwar et al., 2022). Excessive connections to a single server can also lead to high latency and congestion. A distributed system based on DLTs can mitigate such shortages (Nour et al., 2022).

Globalization increases SC's complexity and dependence on information systems to provide agility, responsiveness, collaboration, redundancy, and transaction flexibility (Taqui et al., 2022). Blockchain-based distributed systems allow immediate visibility to SC members, which enables the SCM to evaluate the impact of transactions quickly and suggest direct interventions, which increases SC resilience (Meng et al., 2022).

Systems based on DLTs can also favor sustainable practices in SC (Varriale et al., 2020). From the need for guarantees of origin for GH generation systems, a traceability system based on DLT has the potential to store information regarding the total volume of hydrogen produced, facilitating fraud prevention and ensuring transparency in CO_2 emissions along the entire SC for every involved member. The same applies to energy and material exchanges focused on IS practices. The granularity of information allows the analysis of weaknesses and the development of strategies to avoid disruptions and take advantage of opportunities to reuse material and energy waste (Xu et al., 2021).

MODELS FOR MANAGING GREEN HYDROGEN AND INDUSTRIAL SYMBIOSIS IN THE SC

Implementing strategies aimed at greening SC and increasing resilience may require optimizing models. Such models can target only greening, only resiliency, or both. Among the alternatives present in the literature (Fahimnia and Jabbarzadeh, 2016; Hosseini et al., 2019), this study chose to discuss the feasibility of two: mixed-integer linear programming (MILP) and agent-based simulation (ABS). The former tackles problems subject to deterministic variables that move in time. The latter tackles probabilistic variables with known distribution. Issues subject to time-constant deterministic variables are of less interest in uncertain SC. Issues subject to erratic variables require other techniques, such as chaotic methods, which is outside the scope of this study.

As systems based on DLTs entail immutability and resilience characteristics, the models' developers can take advantage of applying security and reliability elements based on blockchain technology.

MILP model

Regarding MILP, the primary objective function aims at minimizing the overall cost of the execution of the strategy. Considering both implementations at the same time (GH and IS) requires a graph including consumers, producers, and tank farms of GH; consumers, deposits, and generators of industrial waste (materials and energy); the transport routes between GH producers, tank farms, and consumers; and transport routes between generators, deposits and consumers of industrial waste. The model requires the production capacity of each generator and the point demand (current requirement minus current inventory) needed by each consumer (linear part of the model). In seasonality, binary variables assign for the periods of the year (binary part of the model). Economic order quantities, the batch size that optimizes the cost of transportation, are needed as each transfer of material or energy must be compatible with an integer multiple of the EOQ, which is the integer part of the model. When the EOQ logic does not apply, the lot size is unitary. Finally, the costs of holding excessive inventory in the consumption units are also necessary, as transferring an integer number of economic lots implies holding the excess until the consumption. Such a feature imposes a time horizon, such as six months, to economically match the production and consumption of GH and IS transfers.

In short, the decision variables are the number of EOQ routed in each network edge along a given time horizon (for instance, six months) in a given periodicity (for example, once a week). The objective function must minimize a non-linear expression, including the cost of holding the excessive inventory at each consumption point and the cost of transportation at each edge. The constraints are the generators' production capacity and the consumers' requirements. Eventually, if the overall network is unbalanced, which is the most likely scenario, some producers may remain idle. On the consumption side, resilience allows no shortage.

The essential role of blockchain is to provide, at affordable costs, reliable and updated information on all the variables managed by the model: consumption, production, inventories, holding costs, and transportation costs of all the nodes and edges of the system. The dynamics of the execution may vary according to the SC dynamics. One example is running the model with updated monthly information and scheduling six-month deliveries. Eventually, some corrections should apply if the performance differs from the projection. If the model aims at only one target (GH or IS), removing the inactive edges and nodes from the problem is enough to enable it.

Agent-based model

Regarding ABS, an agent-based model simulates, according to decision rules based on distributed artificial intelligence, the decision-making behavior of components that act according to predefined behavior patterns. Such components are the agents of the system. Agents are autonomous components with specific behaviors determined by decision rules that relate to each other and the simulated environment. Even if the behavior of a single agent does not faithfully follow the reality of this agent, the sum of individual behaviors, over time, approaches the system's behavior. Therefore, each agent must pursue its goals, acting according to its own rules developed from the reaction of other agents. Decision rules, thus, constitute a learning process based on artificial intelligence requirements and supported by big data analytics techniques. Therefore, applying an agent-oriented approach to solving a problem means decomposing it into multiple autonomous components with particular, interrelated objectives that react to new situations according to a defined, well-known behavior pattern (Macal and North, 2010).

Agents play four roles in the system: production units that supply materials and energy (GH and energy waste); warehouses that receive, organize, and optimize materials distribution; transportation; and consumers. Eventually, a fifth entity may appear, a centralized regulator such as the SCM agent. Production units embrace GH producers, material waste producers, and energy waste producers. It is not unusual for a particular agent to perform multiple roles. For instance, an agent can supply material and energy waste to different consumers using different transportation methods. Warehouse units can receive and accumulate inventories until the due date, which allows for exploring optimal lot sizes. Such agents can gather materials as well as energy waste. Transportation agents can operate one or multiple modes, such as trucks, trains, or vessels, while a single agent can work with material and energy loads. Finally, consumer agents are the final destination of material and energy and the sole agent inserting new money into the system. The other agents only exchange money through intermediate payments.

Agents behave according to rules deductible from previous reactions to well-known situations. Case-based reasoning and fuzzy logic are helpful techniques to identify a consistent set of rules that govern the strategy targeted by the agent. Big data techniques are also beneficial. Key variables should follow well-known distributions fitted from previous performance data gathered and processed by a cloud computing system.

Key inputs influence agents' decisions. The most relevant are the current inventories and those of other agents, demands, own current availability and those of other agents, price estimation of production, warehousing and transportation, deadlines, consumers' specifications, target prices supported by final consumers, and seasonality. Point events, such as disruption threads and augmented risk in the SC, also influence the agent reaction. The expected agent's outputs are the production schedule, warehousing and transportation requirements, prices, delivery dates, and payment timelines.

Key variables for production units are nominal production capacity (tons/day), demand (tons/day), productivity (tons/day), cost ($/unit), dependability (likelihood of full compliance to an order's requirement), and quality (likelihood of part's full conformity with specifications). Key variables for warehousing agents are the rate of receiving and dispatching (tons/day), holding cost and prices ($/unit), capacity (tons), and efficiency in deliveries (%). Key variables for transport agents are capacity (tons), demand (tons/day), transportation cost and prices ($/unit), capacity (tons), lead times (days), and efficiency in deliveries (%). Key variables for consumer agents are demand (tons/day), processing cost and prices ($/unit), local capacity to support excessive inventories (tons), lead times of reception (days), quality of received material (%) and efficiency in deliveries (%).

Likewise, as in the case of the MILP model, the essential role of blockchain is to ensure integrity, prevent the model execution against fraud, and ensure the reliability of the gathered data. As the model should run regularly and periodically, the information system must continuously gather and process a large amount of data, which turns blockchain into an essential technological element to ensure the reliability of the model's outputs.

FINAL REMARKS

This article discussed optimization models to support the development of resilient and green SC based on GH production and symbiotic exchange implementations managed by blockchain information systems. This study is one of the first attempts to bridge the research gap among GH production, IS activities, and blockchain technology aimed to provide reliability to data required to manage the relationships involving both issues. In particular, this study targeted the use of GH and IS to provide, supported by blockchain technology, at the same time, sustainability and resilience to industrial SC.

The final delivery of the study was a set of grounding considerations on how two types of model, MILP and ABS, could be developed to manage the implementation of GH and IS initiatives to enhance sustainability and resilience in industrial SC. GH should replace fossil fuels, while IS should route waste from members to new use as raw material or secondary fuel in other members of the SC. Both should make the SC thicker, increasing redundancy and therefore improving resilience. Replacing fossil fuels and avoiding disposal reduces the SC's carbon footprint and consequently enhances sustainability.

The study opens room for further research. The next step is to identify at least one confirmed case of an SC or eco-park in which at least one of the models (MILP or ABS) is feasible to apply. A real-data application should refine the notion and provide advances in front of the state-of-the-art of sustainable and resilient SC strategies.

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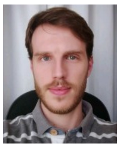

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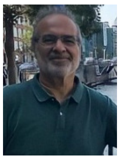

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