SENS: SEMANTIC SYNTHETIC BENCHMARKING MODEL FOR INTEGRATED SUPPLY CHAIN SIMULATION AND ANALYSIS

Research Paper

Nour Ramzy, Infineon Technologies AG, Neubiberg, Germany, nour.ramzy@infineon.com
Sören Auer, TIB Leibniz Information Centre for Science and Technology, Hannover, Germany, auer@tib.eu
Hans Ehm, Infineon Technologies AG, Neubiberg, Germany, hans.ehm@infineon.com
Javad Chamanara, L3S Research Center, Leibniz University of Hannover, Hannover, Germany, chamanara@l3s.de

Abstract

Supply Chain (SC) modeling is essential to understand and influence SC behavior, especially for increasingly globalized and complex SCs. Existing models address various SC notions, e.g., processes, tiers and production, in an isolated manner limiting enriched analysis granted by integrated information systems. Moreover, the scarcity of real-world data prevents the benchmarking of the overall SC performance in different circumstances, especially wrt. resilience during disruption. We present SENS, an ontology-based Knowledge-Graph (KG) equipped with SPARQL implementations of KPIs to incorporate an end-to-end perspective of the SC including standardized SCOR processes and metrics. Further, we propose SENS-GEN, a highly configurable data generator that leverages SENS to create synthetic semantic SC data under multiple scenario configurations for comprehensive analysis and benchmarking applications. The evaluation shows that the significantly improved simulation and analysis capabilities, enabled by SENS, facilitate grasping, controlling and ultimately enhancing SC behavior and increasing resilience in disruptive scenarios.

Keywords: Ontology, Supply Chain Modeling, Synthetic Data, Benchmarking

1 Introduction

Our increasingly global economy results in a high interconnection between Supply Chains (SCs) (Soundararajan et al., 2021). Consequently, SCs are evolving from being a chain of businesses with one-to-one relationships to becoming a network of multiple businesses that provide products and services to customers (Lambert and Cooper, 2000). Thus, analyzing the behavior of SC is essential as it does not only affect one organization but a highly complex, dispersed and connected network. Namely, SC modeling and benchmarking enable proactive monitoring of processes across the network (Winkelmann et al., 2009). For instance, the End-to-End (E2E) Supply Chain Network (SCN) model provides an overall perspective of the SC partners as well as the flow of products, services, and materials which conveys SC structural coherence and resilience. The SCOR model provides standard definitions of operational processes and Key Performance Indicator (KPI) to enable SC standardization and benchmarking. Existing SC models tackle core aspects but still in an isolated manner, hence, limiting integrated SC behavioral analysis. Furthermore, the scarcity of integrated empirical data from SC members limits the study of the overall
behavior. Firms do not disclose their connections to keep a competitive advantage or simply because there are not enough associated incentives or rewards (Brintrup, Y. Wang, and Tiwari, 2015). Also, logs or data from one company are not enough to validate the end-to-end SC models.

In this paper, we investigate how semantic models aid the benchmarking of SCs for better simulation and integrated analysis. Our main contribution is SENS, a semantic model that leverages ontologies, KGs and the SPARQL query language to provide an overall perspective of an E2E SCN, standardized SCOR processes and performance indicators. SENS comprises of SC partners and the relations between them, representing the flow of materials and goods. Moreover, based on the production and inventory capacity model included, we provide a SPARQL-based demand fulfillment algorithm that mimics how a SC operates to achieve its ultimate goal of meeting end-customers’ order requests. Additionally, we propose SENS-GEN, a highly configurable synthetic data generator that, using input parameters and SENS model, produces an exemplary instance of an SCN. SENS-GEN enables the generation of SC data for various industries, e.g., automotive and dairy, determined by the topology and properties of the instantiated output KG. As a result, companies can rely on SENS and SENS-GEN to generate data for various simulated SCs in order to apply analysis methods and make informed decisions faster and more reliably. Ultimately, we deem that better simulation and analysis, as put forward by SENS, will contribute to standardizing and benchmarking SCs, thus mastering more complex SC scenarios, increasing the resilience of supply networks and ultimately facilitating digitalization.

The remainder of the paper is structured as follows: in Section 2, we give an overview of the literature on existing SC models namely SCOR, E2E SCN and semantic models while examining the core SC aspects they tackle. In Section 3, we present SENS, our SC model that incorporates SC core aspects in an integrated manner. We propose SENS-GEN, a configurable data generator that leverages the SENS ontology to create a particular synthetic realization of an SCN i.e., SENS KG in Section 4. In Section 5, we evaluate SENS as an integrated SC model that enables the simulation of SC behavior in experimental contexts for comprehensive performance analysis. Finally, we conclude by presenting the limitations, implications and outlook of our contribution.

2 Background and Motivation

Modeling aids the understanding and monitoring of structural and operational aspects within SCs. In this section, we review the SC concepts incorporated by SCOR, E2E SCN and semantic models as they address essential aspects such as standardization, coherence, interoperability and information integration.

2.1 Supply Chain Models

**SCOR (SCOR) Model.** To evaluate SC performance and continuously improve, SC standardization offers a mutual understanding of concepts and processes, consequently enabling benchmarking and comparison of performance. The classic SCOR model, introduced by APICS[1] in 1997, provides a common terminology to define SC standardized activities and performances (SCC, 2010). The SCOR model covers all customer interactions (order entry through paid invoice); we refer to this as (C1). Additionally, it spans all physical material transactions (C2) and all market interactions (from the understanding of aggregate demand to the fulfillment of each order) (C3). Also, the SCOR model contains standard descriptions of the SC processes e.g., Source, Plan, Make, Deliver, Enable and Return, (C4). Furthermore, the SCOR model organizes SC performance metrics, i.e., KPI, into a hierarchical structure (C5) to determine and compare the performance of SC on various levels e.g., top strategies, tactical configurations and operational processes (Irfan, Xiaofei, and Chun, 2008). In addition, SCOR describes best-in-class management practices (C6) and maps software products that enable best practices

[1] https://www.ascm.org/
In order to gain an overall perspective of SC operational performance and structural coherence, E2E SCN models are fundamental.

**End-to-End Network Models.** An SCN is a network representation of the physical nodes of a SC and how they relate to one another (Golan, Jernegan, and Linkov, 2020). The E2E model provides an overall perspective of the SC nodes topology that starts at the procurement of raw materials and ends at the delivery of finished goods to the end customers. The literature review by (Bier and Lange, 2018) highlights key SC aspects in an E2E SCN model. The authors identify that an SCN consists of a representation of vertices i.e., nodes acting as SC partners, (C8). SC partners are connected with edges (C9) modeling product, demand flow and contractual relations as shown in Figure 1. Nodes are organized in tiers, nodes in the same tier supply goods and services for the following tiers.

An SCN model considers various materials used to manufacture the end product (C10). The authors describe that the focal company, i.e., Original Equipment Manufacturer (OEM), distinguishes between supply and demand flows, i.e., (C11). Partners in the SCN can be facilities, companies, or warehouses. Nevertheless, the competition in the future will be SC vs. SC where each node participates in one or more SCs (C12) while sharing and competing with other nodes over suppliers and customers (Rice and Hoppe, 2001). Due to the diversity, dispersion and complexity within an SCN, interoperability is challenging. However, relying on semantic models enables information exchange and allows partners to reach full and agile information integration.

Figure 1. Supply chain network structure by (Lambert and Cooper, 2000).

**Semantic Models.** Semantic models have been developed as an attempt to represent the complexity of the SC domain, e.g., (Ye et al., 2008) developed Onto-SCM to provide shared terminologies for SC concepts and relations. The literature review by (Grubic and Fan, 2010) lists existing SC ontologies to model the SC’s key concepts. The authors identify that a semantic model includes the strategic, tactical and operational views of the SC (C13). Besides, an SC ontology covers an organizational extent i.e., internal or external (C14). The model incorporates an industry sector (C15), has a purpose (C16) and supports SC applications (C17).

### 2.2 Gap Analysis

We examine the literature reviews by (Delipinar and Kocaoglu, 2016), (Bier and Lange, 2018) and (Grubic and Fan, 2010) for existing SCOR, E2E, semantic models respectively. We identify the gap between the artifacts in the studied models and the previously listed SC aspects (C1-17).
Gap Analysis for SC Models. We note that existing SC SCOR models do not include management practices and software products (C6, C7) as they are considered sensitive information to keep a competitive advantage (Delipinar and Kocaoglu, 2016). Moreover, (Bier and Lange, 2018) create a comparison framework of SC E2E network models and conclude that the academic literature does not contain studies that address the topology of SCN (C8, C9) together with detailed insights on structural information (C10, C11). Additionally, emergent SCN topology literature include SC nodes operations independently and not as part of one or many SC (C12) (Brintrup and Ledwoch, 2018).

Furthermore, all the existing SC ontologies cover the strategic level of granularity, yet none supports tactical and operational levels (C13) (Grubic and Fan, 2010). For (C14), existing models are limited to the inter-business network scope.

Gap Analysis for Hybrid SC Models. In an attempt to fulfill the shortcomings of existing models, we study hybrid models that combine SCOR, E2E, semantic SC models pair-wise. Table 1 lists the literature for SC hybrid models and identifies gaps with respect to the concepts (C1-17). We highlight, in gray, the SC concepts that are not covered by existing SC models discussed in the previous section. In the gap analysis process, we consider different models as follows:

| Model Covers | SC-SCOR E2E Network | Semantic SC E2E Network | Semantic SC SCOR |
|--------------|----------------------|-------------------------|-----------------|
| (C1) Customer Interaction | No | No | No | No | Yes |
| (C2) Material Transaction | No | No | No | Yes | No |
| (C3) Market Interaction | No | No | Yes | Yes | Yes |
| (C4) Process Description | Yes | Yes | No | Yes | Yes |
| (C5) SCOR Metrics | Yes | Yes | No | Yes | Yes |
| (C6) Management Practices | No | No | No | No | No |
| (C7) Software Products | No | No | No | No | No |
| (C8) Vertices | Yes | Yes | Yes | Yes | Yes |
| (C9) Edges | Yes | Yes | Yes | Yes | Yes |
| (C10) Various Material | Yes | Yes | No | No | No |
| (C11) Supply & Demand | Yes | Yes | Yes | Yes | Yes |
| (C12) SC E2SC | No | No | No | No | No |
| (C13) SC Granularity | Operational, Strategic | Operational | Operational, Tactical, Operational | Operational, Operational | Operatio
| (C14) SC Scope | E | E | I.E | I.E | I.E |
| (C15) Model Purpose | Use network modeling to optimize SC performance | Create an optimization model of cycle quality network | Examine technology enabling cloud computing benefits SC | Provide a guide of methodologies for complex SCN | Improve management of process via semantic interoperability | Overcome semantic inconsistencies of the (SCOR) model | Compare the SCOR ontology to Value Reference Models | Contribute to enterprise semantic interoperability and enterprise information flows in networks for SC analysis |
| (C16) Model Application | Decision making in change management | Network for optimization of environment protection | IoT applications | A framework of semantic SCN, demonstration the application of a semantic model of three different business process models within logistics | Operations of three different business process models within logistics | Applications made-to-stock, made-to-order or engineered-to-order | Make-to-Order process from body of grinding machine |

Table 1. Gap analysis of existing SC models and covered SC concepts. E: External, I: Internal.
1. We examine models that combine SCOR and E2E SCN and the corresponding SC concepts i.e., (C1-7), (C8-12). We observe that (C4), (C8), (C9) and (C11) are incorporated by existing approaches in the literature. Namely, the model by (R. Xiao, Cai, and Zhang, 2009) includes SCOR metrics (C5) and various raw materials (C10). However, existing models do not cover the following SCOR notions: customer interactions, material transactions, market interactions, management practices and software products.

2. We study models incorporating E2E (C8-12) and semantic (C13-17) concepts. Only the work of (Long, Song, and Yang, 2019) offers a semantic model addressing all aspects of an E2E SCN model (C8-11), except (C12). Also, the authors include the tactical and operational granularity levels (C13). Both proposed works cover an internal and external SC scope (C14).

3. We consider semantic SCOR models (C1-7) and (C13-19). We mention only the attempts at semantic modeling of SCOR-based SCs revised in latest works. All models listed in Table 1 address SCOR SC aspects (C4), (C5), however, we note that (C1), (C2), (C3), (C6) and (C7) are not satisfied. While none of the models is industry-specific (C15), they include only the operational granularity of a SC (C13) though, they provide a purpose and an application, respectively (C16) and (C17).

2.3 Motivation and Contribution

Integrated modeling of the SC enables enriched behavioral analysis and benchmarking, as it incorporates various SC concepts, e.g., materials, metrics and processes, while giving a holistic perspective of the SC structure, flows and partners. Existing SCOR, E2E and semantic models alongside corresponding hybrid models are limited as they convey essential SC aspects in an isolated manner. Also, the scarcity of empirical data from multiple SC partners hinders the analysis of the overall impact of supply network partners on each other. Available data and logs from one company are not enough for E2E benchmarks. Therefore, we propose SENS-GEN, a highly configurable data generator that relies on the SENS integrated semantic model to generate a synthetic SC instance for standardization and benchmarking of an E2E SCN.

3 SENS: Integrated Semantic Supply Chain Model

We present SENS, an integrated semantic SC model that incorporates an end-to-end perspective of the SC including standardized SCOR processes and metrics SCs.

3.1 SENS Ontology Model

The core of SENS Ontology depicted in Figure 2 is nodes representing SC partners. We model each partner as instance of the class Node, i.e., Supplier, Customer or OEM. SC nodes are organized in tiers, so we model this information using RDF triples of the form Node belongsToTier Tier. Accordingly, we distinguish between SupplierTier and CustomerTier.

The supply side is organized so that the raw material suppliers belong to the highest supplier tier, which is the most upstream tier, i.e., SupplierTierN (Brinrup and Ledwoch, 2018). Supplier nodes in low tiers are connected to suppliers in upstream tiers using the property hasUpStreamNode while on the customer side, end customers belong to the most downstream tier, i.e., CustomerTierN. Similarly, customer nodes in the low customer tier are connected to customers at downstream tiers with the property hasDownStreamNode. The links between nodes model contractual relations, organizing the flow of demand, materials and products between SC partners. Likewise, SupplierTiers are connected with hasUpStreamTier while CustomerTier with hasDownStreamTier.

The Original Equipment Manufacturer (OEM) is the focal node responsible for assembling the product or getting it ready for distribution by delivering it to a warehouse or a wholesaler, followed by various
distribution centers to the end-customer. The OEM is directly linked to the suppliers in SupplierTier1 via the property hasOEM and CustomerTier1 via OEMhasNode. Also, we model node operations with RDF triple statements of the form Node hasProcess Process and the class Process has as subclasses the SCOR processes: Source, Plan, Make, Deliver, Enable and Return. Consequently, for each node, we model the SCOR KPI hasResponsiveness, hasReliability, hasAgility, hasAssetManagementEfficiency to evaluate the operational behavior of this node based on the SCOR metrics standard. Furthermore, each node is described by data properties that either depict its performance e.g., hasCO2Balance or its characteristics e.g., hasLocation. We resolve node locations using geo-coordinates represented with the properties hasLongitude, hasLatitude.

### 3.2 Supply Chain Demand Fulfillment

The goal of an SCN is to fulfill end-customers’ demand relying on production and inventory capacities. SENS models supply and demand and a SPARQL-based demand fulfillment algorithm to simulate SC production planning and scheduling.

**Supply Chain Demand.** We model the demand as orders of products via triples of the following form: Node makes Order, Order hasProduct Product, Order hasDeliveryTime xsd:dateTime and Order hasQuantity xsd:integer. Moreover, customer orders are fulfilled depending on their priority modeled by Node hasPriority xsd:integer. Customer relationship management determines a customer’s priority based on various factors, e.g., customer revenue, contract type.

**Supply Chain Capacity and Production.** SC nodes produce and stock products in order to fulfill the demand. We rely on RDF-star, a framework to model in a compact way statements about statements (Arndt and Broekstra, 2021). RFD-star is widely implemented by tools such as GraphDB and Virtuoso; reification (Patel-Schneider and Hayes, 2014) is a viable alternative. The following list of triples models capacity and production of nodes in the SCN:

- **Node manufactures Product**: defines what products are manufactured by this node e.g., OEM manufactures Car. «Product needsProduct Product» needsQuantity xsd:integer models the intermediate products needed to manufacture the final product. For instance, «Car needsProduct Wheel» needsQuantity ‘4’ and «Wheel needsProduct Rubber» needsQuantity 10m.
• **Node hasTransportMode xsd:string**: SC nodes rely on one or more shipment modes e.g., air cargo, maritime to transport products.

• **Node hasGroup xsd:integer**: in order to reduce purchasing prices and benefit from the supreme performance, suppliers capable of supplying the same products, i.e., belong to the same group, are exchangeable (Hofstetter and Grimm, 2019).

• **Node hasCapacity Capacity**: defines the availability of labour and resources to make a product by a node. The capacity is detailed by Capacity hasProduct Product, Capacity hasCost xsd:integer, Capacity hasQuantity xsd:integer and Capacity hasTimeStamp xsd:dateTime.

• **Node hasSaturation xsd:integer**: is the bottleneck defining the maximum capacity to manufacture at any time.

• **Node hasInventory Inventory**: models the node keeping stock of products describing the inventory using triples of the following form: Inventory hasProduct Product; hasCost xsd:integer; hasQuantity xsd:integer; hasTimeStamp xsd:dateTime.

• **Node hasDeliveryTime xsd:integer**: indicates the time for a node to deliver to the customer after finishing production (T. Xiao and Qi, 2016).

**Demand Fulfillment.** SCs follow a customer order-based strategy to determine its production scheduling (Borgström and Hertz, 2011). We present a SPARQL-based demand fulfillment algorithm relying on backward scheduling, i.e., starting from the delivery time of an order and planning backward for its fulfillment. The input is incoming orders containing a standard product with constant repetitive demand. The output of this algorithm is a supply plan specific for each order modeled by Order hasSupplyPlan SupplyPlan. This plan is a scheduled capacity allocation for products among production facilities as well as the needed parts among suppliers as shown by the following triple representation: «SupplyPlan needsNode Node» getsProduct Product; hasTimeStamp xsd:dateTime; hasQuantity xsd:integer; hasUnitPrice xsd:double.

We determine the following base assumptions about the model:

• Nodes have a standard delivery time. When the node capacity is lower than the saturation limit, i.e., the node is operating far from the bottleneck, orders are fulfilled and delivered in constant time (Cannella et al., 2018).

• The supplier selection process is based on respective capacities while suppliers’ choice can potentially consider other factors, e.g., price, quality of service or CO2 balance (Setak, Sharifi, and Alimohammadian, 2012).

• The demand fulfillment is a recursive cascading problem, e.g., nodes in TierN receive orders from nodes in TierN+1. Then, the fulfillment either relies on the available inventory or production capacities. On the supply side, nodes in TierN decompose the product to the intermediate products supplied by nodes in TierN-1, whereas on the customer side, the same finished ordered products flow between nodes.

• SC planners determine the frequency of execution of the demand fulfillment algorithm.

We consider the relationships between three tiers of the SC (SupplierTier1, OEM and CustomerTier1). The incoming demand to the OEM is the orders by customers in CustomerTier1 and is the aggregation of the incoming demand flow starting from the end-customer. The following steps, executed at time \( t \), outline the demand fulfillment algorithm. For conciseness, we show exemplary queries while we provide the detailed code and SPARQL queries in our accompanying technical report and GitHub repository (SC Generator, 2021).

1. **Listing 3.1** At \( t \): Get orders by customer priority from CustomerTier1 where \( O \) rdf:type Order, \( O \) hasProduct \( P \), \( O \) hasDeliveryTime \( DT(O) \). The OEM has delivery time modeled by OEM hasDeliveryTime \( LT(O) \) where \( DT(O) - LT(O) = t \).
Listing 3.1. Get Orders by customer priority

```sql
SELECT * WHERE {?o hasDeliveryTime ?dt. ?o hasQuantity ?q. ?o hasProduct ?p. ?cus makes ?o. ?cus hasPriority ?prio. ?oem hasDeliveryTime ?lt. FILTER (?dt−lt=t)} ORDER BY DESC ?prio
```

2. If OEM inventory at \(t\) hasQuantity \(Q(I)\) suffices to fulfill the order quantity i.e., \(O\) hasQuantity \(Q(O)\) and \(Q(I) \geq Q(O)\), then the order is fulfilled, a supply plan generated and the OEM inventory updated: \(Q(I) = Q(I) - Q(O)\). Otherwise, we proceed with production in step 3.

3. Place a production order for the remaining \(Q(I) - Q(O)\), if the OEM capacity at \(t\) is smaller than its saturation.

   a) Listing 3.2: Get all intermediate products and quantities to manufacturer P.

   ```sql
   Listing 3.2. Get all intermediate products for Product P
   SELECT * WHERE { << P needsProduct ?comp >> needsQuantity ?quant. }
   ```

   b) Listing 3.3: Choose a supplier in SupplierTier1 with capacity for intermediate products smaller than the bottleneck at \(t_0\) with \(t_0 = t - LT(S)\), where Supplier hasDeliveryTime \(LT(S)\). This means that the supplier has the capacity to produce the intermediate products at \(t_0\) to reach the OEM at \(t\) to manufacture and fulfill the order at its delivery time \(DT(O)\). If suppliers are chosen for all intermediate products, then the order is fulfilled and a supply plan generated. Otherwise, the order is not fulfilled.

   ```sql
   Listing 3.3. Get Supplier capacity for intermediate product at time \(t_0\)
   SELECT * WHERE {?s hasOEM OEM1. ?s hasCapacity ?cap. ?cap hasProduct ?p. ?cap hasQuantity ?q. ?cap hasTimeStamp ?t0. ?s hasSaturation ?sat. ?s hasDeliveryTime ?lt. FILTER (?sat >= ?q + tofulfill) && (t - ?lt = ?t0). }
   ```

4 SENS-GEN: Synthetic Supply Chain Knowledge Graph Generator

This section presents SENS-GEN, a highly configurable data generator that relies on the SENS model to create a specific synthetic instance of an SCN, incorporating SC concepts in an integrated manner.

4.1 SENS-GEN Parametrization

SENS-GEN receives input parameters to instantiate SENS ontology, i.e., SENS KG, that determines the topology and the performance of the SCN. Namely, the topology depends on the industry sector as it signifies the complexity of the products (the steps needed to manufacture), the variability and the number of customers and suppliers. In fact, the topology is defined by the Supplier_Tier, Node_Supplier_Tier, Customer_Tier, Node_Customer_Tier parameters in Table 2.

The KG describes the behavior of the SCN through the values assigned to the nodes’ data properties e.g., hasReliability, hasCO2Balance. Namely, the capacity and inventory of the nodes allow the simulation of the demand fulfillment and evaluate the performance of this particular SC realization. The parameters assigned per node can be randomly generated from the range of values given, e.g., [1-5], or manually defined per node as an input. For conciseness, we show only the supplier side generation in Algorithm I (cf. the technical report (SC Generator, 2021) for the detailed code).

---

**Table 2**

| Parameter          | Description                                                                 |
|--------------------|----------------------------------------------------------------------------|
| Supplier_Tier      | Industry sector                                                             |
| Node_Supplier_Tier | Number of steps needed to manufacture                                      |
| Customer_Tier      | Number of customers                                                          |
| Node_Customer_Tier | Number of suppliers                                                          |

**Algorithm I**

1. Input parameters to instantiate SENS KG.
2. Build SENS KG based on the input parameters.
3. Simulate demand fulfillment and evaluate performance.
4. Output the synthetic SCN.

---

*Thirtieth European Conference on Information Systems (ECIS 2022), Timisoara, Romania*
Algorithm 1 SENS knowledge-graph generation algorithm

```plaintext
for (n = 1; n <= Supplier_Tier; n++) do
    Create SupplierTier(n)
    for (m = 1; m <= Node_Supplier_Tier[n]; m++) do
        Create SupplierNode(m.n)
        Add SupplierNode(m.n), :hasGroup, Random(1, Supplier_Group_Tier[n])
        for Property P of SupplierNode(m.n) do
            Add SupplierNode(m.n), p, Random(min_val, max_val)
        Generate saturation capacity, initial capacity and inventory
```

4.2 Generated Showcase Examples

We present two examples of SCNs from the automotive and dairy industries. Table 2 shows the parametrization of the model and the variation of topology and properties based on the industry. In Figure 3, we provide an example of a SCN in the automotive industry. We choose three supplier tiers, i.e., raw material, component and system suppliers. The dairy SCN example in Figure 4 consists of one supplier tier, i.e., the dairy farms that are directly linked to the OEM. At the OEM, products are processed and packaged to be sent to retailers CustomerTier1 then end-customers CustomerTier2 e.g., homes, restaurants.

There exist multiple KPIs to assess SC behavior, yet we focus on the SCOR KPIs as they enable a standardized performance evaluation and benchmarking. We set for the SCOR KPI, a range of [0-100]% as explained by (Petersen et al., 2016). The CO2 balance varies according to policies of countries where nodes are located as well as OEM environmental strategies but range between 30-45 Teragram (Tg) (Thoma et al., 2013). Since the dairy products are easily perishable, dairy SCs are not dispersed. The range for longitude, latitude and inventory is smaller and the delivery time is shorter than in the automotive industry. However, in the dairy industry, customer orders are more frequent but include smaller product quantities.

![Figure 3. Automotive industry SENS KG example with three supplier tiers raw material, component and system suppliers.](image)

5 Evaluation

5.1 SENS Evaluation

We perform a two-fold evaluation. First, we prove that SENS is a semantic SC model that integrates core aspects of SC and deals with shortcomings caused by isolated models. Then, we provide an empirical
Table 2. SENS-GEN parametrization and exemplary parameters for automotive and dairy industry.

| Parameter                  | Triple Representation | Explanation                                                                 | Automotive Industry | Dairy Industry |
|----------------------------|-----------------------|-----------------------------------------------------------------------------|---------------------|-----------------|
| Supplier_Tier              | SC depth, manufacturing steps | 3                                                                           | 1                   |
| Customer_Tier              | SC distribution and sales interactions (OEM to end customer)                | 3                                                                           | 2                   |
| Node_Supplier_Tier         | SC width, the suppliers providing materials for manufacturing              | <2, 3, 5>                                                       | <3>                |
| Node_Customer_Tier         | SC customer availability                                                | <2, 2, 4>                                                      | <2, 3>             |
| Supplier_Group_Tier        | Supplier exchangeability to provide same products per tier                 | <1, 1, 4>                                                      | <1>                |
| Node_Priority              | Customer relationship management to prioritize customers                  | [1-3]                                                          | [1-3]              |
| Node_Capacity_Saturation   | Node maximum capacity to manufacture                                      | [1-3] million unit                                               | [0.5-1] million unit|
| Node_Delivery_Time         | Node time to deliver from node to node in following tier                  | [1-7] days                                                      | [1-3] days         |
| Node_Initial_Inventory     | Node inventory at t=0                                                    | [10-50] thousand unit                                             | [5-10] thousand unit|
| Node_Initial_Capacity      | Node capacity at t=0                                                     | 1 thousand unit                                                  | 1 thousand unit    |
| Data Property range        | SCOR KPIs. Petersen et al. [2016] explain how to calculate level 1 SCOR KPI from lower level metrics for SCOR processes | [0-100] %                                                      | [0-100] %          |
| Data Property range        | SC environmental performance                                             | [30-45] Tg                                                       | [30-45] Tg         |
| Data Property range        | SC globalization (geographically dispersed network of nodes)              | Long/Lat: [0-180/ 0-90]                                           | Long/Lat: [90-180/ 45-90] |
| Customer_Demand_Frequency  | SC constant demand frequency                                             | 2                                                               | 10                 |
| Product type and quantity per order | SC orders variability and size                                      | 1: 100 thousand unit                                             | 1: 5000            |

performance analysis of the generated automotive SCN example introduced in Section 4 and show behavioral changes under experimental conditions.

SENS Model Validation. We validate that SENS is an integrated model by analyzing SENS coverage of SC concepts (C1-17) incorporated by SCOR, E2E and semantic SC models, listed in our literature assessment. In Table 3 we show the executed SPARQL queries and sample results from the automotive SENS KG. We note that the proposed SENS ontology and KG enable us to model and retrieve SC aspects (C1-17) except (C6, C7). However, existing research in the domain implies that management practices and software products are hard to assess and thus not commonly represented in SC models. We can conclude that SENS integrates SC aspects covered by SCOR, E2E and semantic SC model.

SENS Knowledge Graph Behavior Analysis. This section shows the benchmarking and integrated analysis in experimental contexts, enabled by SENS.
Figure 4. Dairy industry SENS KG example with one supplier tier, i.e., the dairy farms and one end-customers tier.

| SPARQL Query: | Example Output Triples |
|---------------|------------------------|
| (C1) Customer Interaction | Node3.2 makes OrderZHuo5 Node3.2 hasDownStream Node3.3 |
| (C2) Material Transaction / (C10) Various Materials | «Product needsProduct ?p» needsQuantity ?q |
| (C4) Process Description | Node3.2 hasProcess ProcessA. ProcessA rdf:type Make |
| (C5) SCOR Metrics | Node3.2 hasResponsiveness ‘24’ |
| (C8) Vertices / (C9) Edges | Node3.2 rdf:type Node Node3.2 hasDownStreamNode Node3.3 |
| (C3) Market Interaction / (C11) Supply and Demand | Algorithm described in Section [3][detailed by SC Generator (2021)] |
| (C12) SC vs SC | Supplier exchangeability is modeled by Supplier hasGroup xsd:integer. Nodes share and compete over suppliers and customers. |
| (C13) SC Granularity | Operational: SENS-SC spans SCOR operational processes e.g. Source, Plan and the supply plans address operational planning. Tactical, Strategic: Describing the performance via data properties e.g. hasCO2Balance enable analysis on different aggregation levels. |
| (C14) SC Scope | SENS-SC models Internal node processes and External interactions by modeling the flow of supply and demand. |
| (C15) Industry Domain | Model parametrization in chapter 4 to tailor the KG to any industry. |
| (C16) Model Purpose | Provide a topology of SCN with detailed and standardized operational SCOR processes and relying on semantics for interoperability. |
| (C17) Model Application | SC behavior analysis in empirical scenarios as shown in the following section. |

Table 3. SENS as an integrated semantic model covering SC core aspects.

Setup: We use the automotive SENS KG in Figure 3 generated via the parameters in Table 2. We run the demand fulfillment algorithm for 178 t (days), i.e., half a year.

Metrics: The following metrics are a sample of the SPARQL-based performance indicators to benchmark the performance of a semantic E2E SCOR SC. Order Fulfillment in Listing 5.1 evaluates how many orders the SC fulfills and generates corresponding supply plans. This metric quantifies the SC ability to achieve its goal of satisfying end customers’ demand. Also, operating close to the saturation capacity entails longer delivery times and straining production labor and machinery. Thus, Node Utilization in Listing 5.2 measures the extent to which a node employs its installed productive capacity after executing
the demand fulfillment algorithm. **Average SCOR KPI** in [Listing 5.3] is an example to calculate the average responsiveness of the SC nodes. This metric allows the estimation of the speed at which a SC provides products to the customer.

**Listing 5.1. Order Fulfillment**

```sql
SELECT ?order (SUM(IF(REGEX(str(?x), "True"), 1, 0)) AS ?fulfill) (SUM(IF(REGEX(str(?x), "False"), 1, 0)) AS ?notfulfill) WHERE { ?order isFulfilled ?x. }
```

**Listing 5.2. Node Utilization**

```sql
SELECT 100*?quant/?max WHERE { ?supplier hasSaturation ?max. ?supplier hasCapacity ?cap. ?cap hasQuantity ?quant. ?cap hasTimeStamp 178.}
```

**Listing 5.3. Average SCOR KPI**

```sql
SELECT AVG(?res) AS ?Responsiveness WHERE { ?supplier hasResponsiveness ?res. }
```

**Parameter variation:** We measure the performance of the SC under various experimental scenarios by changing the input parameters Customer_Demand_Frequency, Node_Capacity_Saturation.

![Figure 5. SENS knowledge graph performance evaluation with parameter variation.](image)

The graph in [Figure 5] shows that the order fulfillment metric drops when the demand frequency doubles (on the x-axis S1-S2), which is a potential scenario during, e.g., the holidays season. Recovering with increasing saturation capacity can help the SC perform better as we can see in the graph the surge in order fulfillment from S2 to S3 where Node_Capacity_Saturation increased from 2M to 3M. Moreover, we note that the node utilization is reduced when the Node_Capacity_Saturation increases. This result is logical as the nodes are not operating close to their production saturation. This is a required setup as it guarantees operational stability and constant delivery time. The average responsiveness is 85% and does not change with parameter variations.

### 5.2 Discussion

Including the SCOR model into SENS provides a standardized representation of SC processes and KPI. The E2E perspective brings an overall view of the SC partners and their relations and flow of supply and demand. Integrating these models using semantic artifacts facilitates the benchmarking of the overall SC behavior.

**Limitations and Next Steps.** We assume the nodes’ characteristics to be constant throughout the simulation. As a result, the SENS parametrization is rigid to some extent, while real-life scenarios might impose some fuzziness. Thus, we propose as a next step to include a degradation function representing...
deterioration in behavior. For instance, the model should include delay functions for transit lead times or a variation of the SCOR KPIs in different operational conditions, e.g., to reduce responsiveness under high utilization. In addition, we generate parameter values randomly or via user input. As a next step, we will implement an interactive interface where the user can tailor the values for each node individually to fine-tune the parameter space.

Also, we can extend SENS to optimize for additional node performance characteristics such as carbon footprint, service level and price. This will enable extending the implemented supplier choice to include multi-factor-based decision making as explained by (Setak, Sharifi, and Alimohammadian, 2012). The evaluation of SENS and the presented examples cover the basic flows at this stage. Thus, we will further assess SENS and SENS-GEN in light of concrete real-world use cases. The goal will be to validate that SENS can cater to the specific characteristics entailed by the complexity of the manufactured product.

Implications. SENS is a semantic model, resembling a digital twin, that facilitates information exchange and integration, thus allowing an optimized control in complex SC scenarios (Barykin et al., 2021). For instance, (Ivanov and Dolgui, 2021) elaborate that SC digital twins enable integration to discover the link between SC disruption and performance deterioration. The strategic and tactical information integration in the overall SC enabled by SENS increases visibility. This, in turn, may lead to dramatically reducing demand distortion, i.e., the bullwhip effect (Blomkvist and Ullemar Loenbom, 2020).

Furthermore, semantic modeling provides a human and machine-understandable representation of the domain. Therefore, we see implications of SENS, an ontology-based model, on the reproducibility and re-useability of SC models. Other SC modeling research areas, e.g., Supply Chain Formation (SCF) and simulation can rely on SENS to ease the extraction of SC configurations for SCF (Ameri and Kulvatunyou, 2019) or to standardize the creation of simulation models as proposed by (Ramzy et al., 2020).

6 Conclusion

SC modeling is of monumental importance for globalized and complex SCN. There exist several SC models, e.g., SCOR, E2E, that incorporate SC artifacts, e.g., operations, production scheduling and flow of materials. We identified that existing models comprise SC core concepts but in an isolated manner, thus hindering integrated SC performance analysis. Moreover, the lack of real-world collective SC data constrains empirical behavioral analysis and performance benchmarking required for particular circumstances, e.g., resilience simulation under disruption.

With SENS, we proposed a semantic SC model that integrates SC concepts. SENS leverages a well-defined ontology, SPARQL queries to include SCOR model artifacts, e.g., processes and performance indicators, as well as an end-to-end perspective to model SC partners and the flow of goods and materials. Moreover, SENS includes production and inventory capacity models and a SPARQL-based demand fulfillment algorithm. Consequently, SENS ensures SC standardization, topological and operational coherence and integration. Additionally, we propose SENS-GEN, a highly configurable data generator that leverages the SENS model to produce exemplary data based on input parameters and create a specific synthetic instance of a SCN. Namely, SENS-GEN generates synthetic data to simulate SC behavior in controlled and designed scenarios. SC stakeholders can rely on SENS and SENS-GEN to assess, benchmark and control complex SC scenarios, to determine operational strategies and SC structure, increase the resilience and ultimately enable digitalization.

Acknowledgment

This work has received funding from the project CoyPu - Cognitive Economy Intelligence Platform for the Resilience of Economic Ecosystems (grant 01MK21007A) within the program Federal Ministry for...
Economic Affairs and Climate Action (BMWK) Innovation Competition on Artificial Intelligence.

References

Ameri, F. and B. Kulvatunyou (2019). “Modeling a supply chain reference ontology based on a top-level ontology.” In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Vol. 59179. American Society of Mechanical Engineers, V001T02A052.

Arndt, D. and J. Broekstra (Dec. 2021). RDF-star and SPARQL-star. W3C Community. https://w3c.github.io/rdf-star/cg-spec/editors_draft. W3C.

Barykin, S. Y., A. A. Bochkarev, E. Dobronravin, and S. M. Sergeev (2021). “The place and role of digital twin in supply chain management.” Academy of Strategic Management Journal 20, 1–19.

Bier, T. and A. Lange (2018). “A Formation Model for Supply Networks: a Fundament for Investigations of complex Supply Networks.” ECIS 2018 (139).

Blomkvist, Y. and L. Ullemar Loenbom (2020). Improving supply chain visibility within logistics by implementing a Digital Twin: A case study at Scania Logistics.

Borgström, B. and S. Hertz (2011). “Supply Chain Strategies: Changes in Customer Order-Based Production.” Journal of Business Logistics 32 (4), 361–373.

Brintrup, A. and A. Ledwoch (2018). “Supply network science: Emergence of a new perspective on a classical field.” Chaos: An Interdisciplinary Journal of Nonlinear Science 28 (3), 033120.

Brintrup, A., Y. Wang, and A. Tiwari (2015). “Supply networks as complex systems: a network-science-based characterization.” IEEE Systems Journal 11 (4), 2170–2181.

Cannella, S., R. Dominguez, B. Ponte, and J. M. Framinan (2018). “Capacity restrictions and supply chain performance: Modelling and analysing load-dependent lead times.” International Journal of Production Economics 204, 264–277.

Delipinar, G. E. and B. Kocaoglu (2016). “Using SCOR model to gain competitive advantage: A Literature review.” Procedia-Social and Behavioral Sciences 229, 398–406.

Golan, M. S., L. H. Jernegan, and I. Linkov (2020). “Trends and applications of resilience analytics in supply chain modeling: systematic literature review in the context of the COVID-19 pandemic.” Environment Systems and Decisions 202, 222–243.

Grubic, T. and I.-S. Fan (2010). “Supply chain ontology: Review, analysis and synthesis.” Computers in Industry 61 (8), 776–786.

Hofstetter, J. S. and J. H. Grimm (2019). “Multi-tier sustainable supply chain management.” In: Handbook on the Sustainable Supply Chain. Edward Elgar Publishing.

Huan, S. H., S. K. Sheoran, and G. Wang (2004). “A review and analysis of supply chain operations reference (SCOR) model.” Supply chain management: An international Journal 9 (1), 23–29.

Irfan, D., X. Xiaofei, and D. S. Chun (2008). “A SCOR Reference Model of the Supply Chain Management System in an Enterprise.” International Arab Journal of Information Technology (IAJIT) 5 (3).

Ivanov, D. and A. Dolgui (2021). “A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0.” Production Planning & Control 32 (9), 775–788.

Kirikova, M., R. Buchmann, and R. A. Costin (2012). “Joint Use of SCOR and VRM.” In: International Conference on Business Informatics Research. Springer, pp. 111–125.

Lambert, D. M. and M. C. Cooper (2000). “Issues in supply chain management.” Industrial marketing management 29 (1), 65–83.

Lin, Y. and J. Krogsie (2010). “Semantic annotation of process models for facilitating process knowledge management.” International Journal of Information System Modeling and Design (IJISMD) 1 (3), 45–67.

Long, Q., K. Song, and S. Yang (2019). “Semantic modeling for the knowledge framework of computational experiments and decision making for supply chain networks.” IEEE Access 7, 46363–46375.
Lu, Y., H. Panetto, Y. Ni, and X. Gu (2013). “Ontology alignment for networked enterprise information system interoperability in supply chain environment.” *International Journal of Computer Integrated Manufacturing* 26 (1-2), 140–151.

Patel-Schneider, P. and P. Hayes (Feb. 2014). *RDF 1.1 Semantics*. W3C Recommendation. https://www.w3.org/TR/2014/rdf11-mt-20140225/. W3C.

Petersen, N., I. Grangel-González, G. Coskun, S. Auer, M. Frommhold, S. Tramp, M. Lefrançois, and A. Zimmermann (2016). “SCORVoc: vocabulary-based information integration and exchange in supply networks.” In: *2016 IEEE Tenth International Conference on Semantic Computing (ICSC)*. IEEE, pp. 132–139.

Ramzy, N., C. J. Martens, S. Singh, T. Ponsignon, and H. Ehm (2020). “First steps towards bridging simulation and ontology to ease the model creation on the example of semiconductor industry.” In: *2020 Winter Simulation Conference (WSC)*. IEEE, pp. 1789–1800.

Rice, J. and R. Hoppe (2001). “Supply Chain versus Supply Chain: The Hype & The Reality.” *Supply Chain Management Review* 5 (5), 46–54.

SC Generator (2021). *Semantic Supply Chain Generator*. DOI: 10.5281/zenodo.5675085

SCC (2010). *Supply Chain Operations Reference (SCOR) Model: Overview – Version 10.0*. Report. Cypress, TX: Supply Chain Council.

Setak, M., S. Sharifi, and A. Alimohammadian (2012). “Supplier selection and order allocation models in supply chain management: a review.” *World applied sciences journal* 18 (1), 55–72.

Soundararajan, V., S. Sahasranamam, Z. Khan, and T. Jain (2021). “Multinational enterprises and the governance of sustainability practices in emerging market supply chains: An agile governance perspective.” *Journal of World Business* 56 (2), 101149.

Suherman, A. G. and T. M. Simatupang (2017). “The network business model of cloud computing for end-to-end supply chain visibility.” *International Journal of Value Chain Management* 8 (1), 22–39.

Thoma, G., J. Popp, D. Nutter, D. Shonnard, R. Ulrich, M. Matlock, D. S. Kim, Z. Neiderman, N. Kemper, C. East, et al. (2013). “Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008.” *International Dairy Journal* 31, S3–S14.

Winkelmann, A., S. Fleischer, S. Herwig, and J. Becker (2009). “A conceptual modeling approach for supply chain event management (SCEM).” *ECIS 2009 Proceedings* 2.

Xiao, R., Z. Cai, and X. Zhang (2009). “An optimization approach to cycle quality network chain based on improved SCOR model.” *Progress in Natural Science* 19 (7), 881–890.

Xiao, T. and X. Qi (2016). “A two-stage supply chain with demand sensitive to price, delivery time, and reliability of delivery.” *Annals of Operations Research* 241 (1), 475–496.

Ye, Y., D. Yang, Z. Jiang, and L. Tong (2008). “Ontology-based semantic models for supply chain management.” *The International Journal of Advanced Manufacturing Technology* 37 (11-12), 1250–1260.

Zdravković, M., H. Panetto, M. Trajanović, and A. Aubry (2011). “An approach for formalising the supply chain operations.” *Enterprise Information Systems* 5 (4), 401–421.