Enterprise Modelling and Information Systems Architectures
Vol. 19, No. 5 (2024). DOI:10.18417/emisa.19.5

Special Issue on Enterprise Modeling and Knowledge Graphs

SENS: Semantic Synthetic Integrated Model for Sustainable Supply Chain Analysis and Benchmarking

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Abstract. *Supply Chain (SC) integrated modeling is required for visibility and proactive monitoring of members and processes across the SC network. Recent works have established SC models incorporating core relations and structures. However, such models are still rather isolated, thus preventing a holistic view of the SC. We identify a lack of End-to-End (E2E) SC data that enables integrated analysis of the SC. Existing logs or data from one company are not enough to validate the E2E SC models. We present SENS, a standardized integrated semantic model that provides an overall view of SCOR E2E SC structure and flows. This vocabulary is used to generate synthetic SC data compensating for the scarcity of the overall benchmarking data via SENS-GEN. 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 • Sustainability

Communicated by Robert Buchmann, Georg Grossmann, Andreas L. Opdahl. Received 2022-08-22. Accepted on 2023-04-24.

1 Introduction

Supply Chain Management (SCM) is essential to monitor, control, and enhance the performance of SCs. Increasing globalization and diversity of SCs lead to complex SC structures, limited visibility among SC partners, and challenging collaboration caused by dispersed data silos. SCs have evolved from being chains of businesses with one-to-one relationships to becoming networks of multiple interdependent businesses and flows that provide products and services to customers (Lambert and Cooper 2000). Hence, monitoring and analyzing the behavior of a SC are essential goals of SCM to ensure visibility, provide a holistic/comprehensive awareness of the network, and detect the changes, disruptions, and their consequences. SC visibility relates to the ability of the focal company, i. e., the SC leader, to access/share information related to the SC strategy and the operations of all SC partners (Caridi et al. 2014). Thus, SC visibility can improve strategic performance directly (Wei and Wang 2010). Samaranayake (2005) elaborates that the integration enables visibility of SC components and partners. Consequently, stakeholders can make more informative decisions towards enhancing SC performance and increasing resilience.

As part of SCM, modeling delivers visibility of SC partners and flows. Recent works have established SC models incorporating core relations and structures. However, such models are still rather isolated, thus preventing a holistic view of the SC. Existing models are limited in the way they represent operational SC relationships beyond

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Note: This work is based on Ramzy, Nour, et al. "SENS: Semantic Synthetic Benchmarking Model for integrated supply chain simulation and analysis." arXiv preprint arXiv:2205.06484 (2022).

one-to-one structures and flows. Additionally, the scarcity of empirical data from multiple SC partners and within a company's own SC hinders the analysis of the impact of supply network partners.

In this paper, we investigate how semantic SC models, relying on ontologies and Knowlegde-Graphs (KGs), ensure information exchange and allow partners in the internal and external SC to reach visibility and agile information integration. We implement semantic models that integrate, in a standardized way, SC processes, structure and flows, ensuring both an elaborate understanding of the holistic SCs and including granular operational details. We model various SC flows and explain the importance of understanding them and the interconnection between them. We demonstrate that these models enable the instantiating of a synthetic SC for benchmarking and analysis.

The results show that semantic models for the SC, such as SENS, result in high-level semantics-based descriptions of the domain capturing core artifacts of the E2E SC environment in a standardized way. The output models of our contributions integrate SC concepts, processes, structure, and flows thus creating operational E2E horizontal and vertical standardized SCs.

The remainder of the paper is structured as follows: in *Motivation and Contribution*, we highlight the purpose behind our work and our main contributions; in the *Literature Analysis* Section, we give an overview of the literature on existing SC models namely SCOR, E2E Supply Chain Network (SCN) and semantic models while examining the core SC aspects they tackle. Then, we present SENS, our SC model that incorporates SC core aspects in an integrated manner while addressing SC interoperability, standardization and structural coherence. We include various characteristics, e. g., geographical and environmental. Afterward, 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 the *Evaluation*, we evaluate SENS as an integrated SC model that enables the simulation of SC behavior in experimental contexts for comprehensive performance analysis. We present a use case that highlights various flows in the SC entailed by the complexity of the manufactured product. Finally, we conclude by presenting the limitations, implications, and outlook of our contribution.

2 Motivation and Problem Context

2.1 Supply Chain Challenges

Integrated modeling is required for visibility and proactive monitoring of members, flows and processes across the SC network (Winkelmann et al. 2009). Recent works have established SC models incorporating core relations and structures. However, such models are still rather isolated, thus preventing a holistic view of the SC. Existing SC models created by one organization are limited in the way they grasp the dynamics between SC partners beyond their one-to-one 'dyadic' relationships. They are not extensive enough to incorporate an E2E SC view while also including standard operational SC artifacts.

Additionally, given the competitive trait of SCs, it is essential to compare and benchmark SC behavior, consequently triggering learning outcomes and improvements (Simatupang and Sridharan 2004). We identify a lack of E2E SC data that enables integrated analysis of the SC. Existing logs or data from one company are not enough to validate the E2E SC models. Thus, we tackle the challenge of benchmarking the performance of an E2E SC.

2.2 Motivation and Contribution

Semantic modeling provides high-level descriptions of the domain to integrate SC pillars and increase inter-operability (Karagiannis and Buchmann 2016). Here, we identify the need and present initial comprehensive semantic E2E SC models that rely on existing standards to integrate partners, flows, operations and processes. Consequently, we propose SENS, a semantic model that incorporates structural and operational artifacts of a SC relying on semantic artifacts. In fact, SC models mimic reality and provide the means to simulate and benchmark the overall performance under multiple empirical scenarios. 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.

This work is based on a previous publication. In this paper, we extend the contributions and tackle some of the identified limitations. In the literature section, we elaborate on the model definition and explain the terminologies such as strategic, tactical, and operational SC. We present thorough concepts of existing SCs models. Moreover, we extend SENS model by adding environmental characteristics to describe a SC partner. We implement a multi-factor supplier choice based on the environmental characteristics and availability of the suppliers. We rely on this implementation to include a CO2 footprint querying for sustainability analysis and benchmarking. We model the information flow of a SC and reflect on the importance of understanding the interconnection between them. We rely on a concrete real-world use case to cover complex SC flows. Also, we extend the implementation details within the generator algorithm.

3 Literature Analysis

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

3.1 Supply Chain Models

SC modeling represents the real world and creates an empirical, coupled domain to study and monitor SCs. SC models incorporate static and dynamic, structural, and behavioral aspects of SCs.

3.1.1 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 (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., Key Performance Indicator (KPI), into a hierarchical structure *(C5)*. The SCOR model defines a metric as a standard for measurement of the performance of a supply chain or process. SCOR recognizes three levels of pre-defined metrics: Level-1 metrics are diagnostics for the overall health of the SC and Level-2 metrics serve as diagnostics for the level-1 metrics. The diagnostic relationship helps to identify the root cause or causes of a performance gap for a level-1 metric. Similarly, Level-3 metrics serve as diagnostics for level-2 metrics. These metrics compare the performance of SC on various levels, e. g., top strategies, tactical configurations, and operational processes (Irfan et al. 2008). In addition, SCOR describes best-in-class management practices *(C6)* and maps software products that enable best practices *(C7)*. In order to gain an overall perspective of SC operational performance and structural coherence, E2E SCN models are fundamental.

3.1.2 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 et al. 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

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[1] https://www.ascm.org/

end customers. The literature review by Bier and Lange (2018) highlights key SC artifacts 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.

		Supply Chain Concept
SCOR	*C1*	Span all customer interactions
	C2	Span all physical material transactions
	C3	Show all market interactions
	C4	Contain standard descriptions of the process
	C5	Represent the SCOR metrics
	C6	Describe best-in-class management practices
	C7	Map of software products for best practices
End-to-End	*C8*	Represent vertices
	C9	Represent edges
	C10	Consider various materials
	C11	Distinguish supply, demand
	C12	Represent SC vs SC
Semantic	*C13*	Include strategic, tactical, and operational views of the SC
	C14	Cover internal or external organizational extent
	C15	Incorporate an industry sector
	C16	Have a purpose
	C17	Support SC applications

Table 1: Supply chain core concepts covered by SCOR, End-to-End and Semantic models and the abbreviation codes, e.g., C1,C2.

3.1.3 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)*. According to Misni and Lee (2017), strategic decision planning is long-term and includes coordination of SC network, capacity planning, and designing systems with environmental consideration. Tactical configurations entail production planning and inventory management, while operational decisions are related to day-to-day processes. Besides, an SC ontology covers an organizational extent i. e., internal or external *(C14)*. The first integrates and manages the flows of an organization or a two-party relationship, while the latter focuses on the chain and network of businesses. The model incorporates an industry sector *(C15)*, has a purpose *(C16)* and supports SC applications *(C17)*. We summarize the identified artifacts in the studied models and the previously listed SC concepts *(C1-12)* summarized in Table 1.

3.2 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 concepts *(C1-17)*.

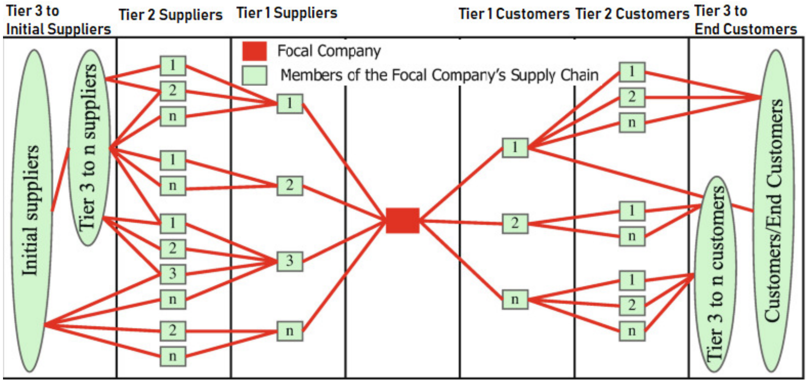


Figure 1: Supply chain network structure by (Lambert and Cooper 2000).

3.2.1 Gap Analysis for SC Models

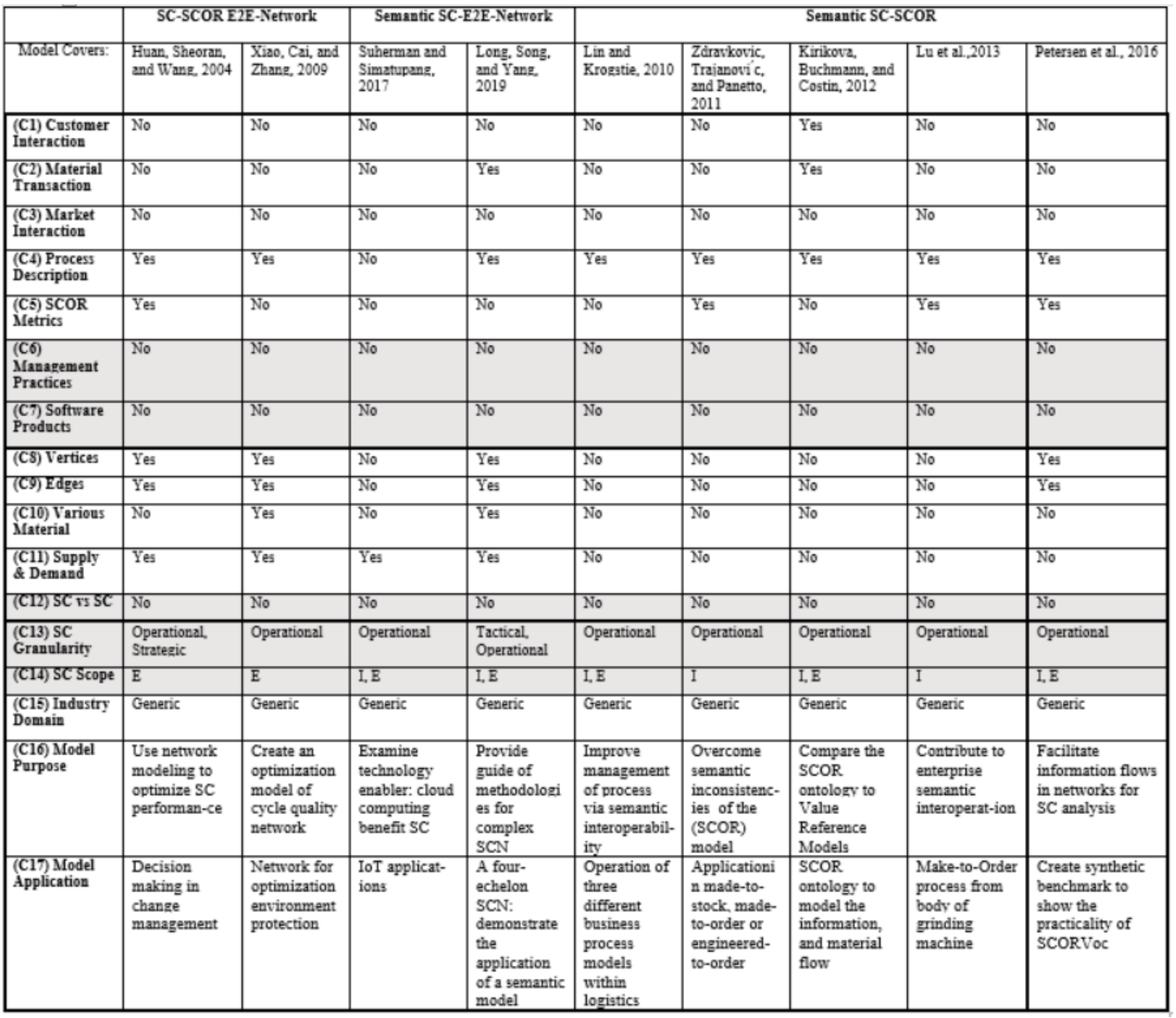
We note that existing SC SCOR models do not include management practices and software products *(C6, C7)* as they are considered sensitive information to keep a competitive advantage (Delipinar and Kocaoglu 2016). Moreover, Bier and Lange (2018) create a comparison framework of SC E2E network models and conclude that the academic literature does not contain studies that address the topology of SCN *(C8: vertices, C9: edges)* together with detailed insights on structural information *(C10, C11)* respectively to consider various materials and distinguish between supply and demand. Additionally, emergent SCN topology literature include SC nodes operations independently and not as part of one or many SC *(C12)* (Brintrup and Ledwoch 2018).

Ye et al. (2008) developed Onto-SCM to provide shared terminologies for representing SC concepts and relations. Also, Jachimczyk et al. (2021) formulated a comprehensive domain ontology to improve SC management efficiency by facilitating data integration. As identified by Grubic and Fan (2010), all the existing SC ontologies cover the strategic level of granularity; none of the models support tactical and operational levels as described by *(C13)*. Also, the authors explain the lack of inductive and collaborative modeling approaches *(C15)*. As well, the scope of SC defined by *(C14)*, is limited to the inter-business network.

3.2.2 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 2 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 the existing SC models discussed in the previous section. In the gap analysis process, we consider different models as follows:

1. We examine models that combine SCOR and E2E SCN and the corresponding SC concepts i. e., *(C1-7)*, *(C8-12)*. Namely, the model by Xiao et al. (2009) include SCOR metrics *(C5)* and various raw materials *(C10)* while modeling the SCN, subsuming vertices, edges, various materials, and supply and demand *(C8-11)*. Also, the work by Huan et al. (2004) models the SCOR process descriptions and metrics defined by *(C4, C5)* while including SC partners as vertices and corresponding relationships as edges as per *(C8, C9)*. However, existing models do not cover the following SCOR notions: customer interactions *(C1)*, material transactions *(C2)*, market interactions *(C3)*, management practices*(C6)*, and software products *(C7)*.
2. We study models incorporating E2E *(C8-12)* and semantic *(C13-17)* concepts. Long et al. (2019) present a semantic model that subsumes SCN structure and covers multiple flows, develops and uses certain strategies, undergoes



	SC-SCOR E2E-Network		Semantic SC-E2E-Network		Semantic SC-SCOR				
Model Covers:	Huan, Sheoran, and Wang, 2004	Xiao, Cai, and Zhang, 2009	Suherman and Simatupang, 2017	Long, Song, and Yang, 2019	Lin and Krogstie, 2010	Zdravkovic, Trajanović, and Panetto, 2011	Kirikova, Buchmann, and Costin, 2012	Lu et al.,2013	Petersen et al., 2016
(C1) Customer Interaction	No	No	No	No	No	No	Yes	No	No
(C2) Material Transaction	No	No	No	Yes	No	No	Yes	No	No
(C3) Market Interaction	No	No	No	No	No	No	No	No	No
(C4) Process Description	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
(C5) SCOR Metrics	Yes	No	No	No	No	Yes	No	Yes	Yes
(C6) Management Practices	No	No	No	No	No	No	No	No	No
(C7) Software Products	No	No	No	No	No	No	No	No	No
(C8) Vertices	Yes	Yes	No	Yes	No	No	No	No	Yes
(C9) Edges	Yes	Yes	No	Yes	No	No	No	No	Yes
(C10) Various Material	No	Yes	No	Yes	No	No	No	No	No
(C11) Supply & Demand	Yes	Yes	Yes	Yes	No	No	No	No	No
(C12) SC vs SC	No	No	No	No	No	No	No	No	No
(C13) SC Granularity	Operational, Strategic	Operational	Operational	Tactical, Operational	Operational	Operational	Operational	Operational	Operational
(C14) SC Scope	E	E	I, E	I, E	I, E	I	I, E	I	I, E
(C15) Industry Domain	Generic	Generic	Generic	Generic	Generic	Generic	Generic	Generic	Generic
(C16) Model Purpose	Use network modeling to optimize SC performance	Create an optimization model of cycle quality network	Examine technology enabler: cloud computing benefit SC	Provide 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 interoperation	Facilitate information flows in networks for SC analysis
(C17) Model Application	Decision making in change management	Network for optimization environment protection	IoT applications	A four-echelon SCN: demonstrate the application of a semantic model	Operation of three different business process models within logistics	Applicationi n made-to-stock, made-to-order or engineered-to-order	SCOR ontology to model the information, and material flow	Make-to-Order process from body of grinding machine	Create synthetic benchmark to show the practicality of SCORVoc

Table 2: Gap analysis of existing SC models and covered SC concepts. E: External, I: Internal.

processes, uses multiple types of resources, and produces and uses several items. This work offers a semantic model addressing all concepts of an E2E SCN model *(C8-11)* except *(C12)* to represent a SC vs SC. Also, the authors include the tactical and operational granularity levels *(C13)*. Also, Suherman and Simatupang (2017) cover SC semantic model concepts *(C13), (C15), (C16), and (C17)* to include the tactical and operational granularity levels, incorporate an industry sector and have a clearly defined purpose of their model and support SC applications. Both proposed works cover an internal and external SC scope *(C14)*. In fact, the work by X. Wang et al. (2010) create scorBPMN ontology which specifies semantics of supply chain process models at both meta-model level and mode level. Also, Leukel and Kirn (2008) propose definitions of core elements of logistics ontologies. Similarly, Ye et al. (2008) create an ontology-based architecture for implementing semantic integration of supply chain management.

3. We analyze semantic SCOR models *(C1-7)* and *(C13-17)*. Zdravković et al. (2011) describe the SCOR-Full ontology and its relations with rel-

evant domain ontologies. Also, Petersen et al. (2016) introduce the SCORVoc RDFS vocabulary to fully formalize the latest SCOR standard along with the key performance indicators (KPIs) defined by SCOR. Kirikova et al. (2012) propose a semantic alignment between SCOR and Value Reference Model (VRM) as two business process reference models. Lu et al. (2013) create a product-centric SC ontology framework for facilitating the interoperation between all product applications involved in an extended SC. Fayez et al. (2005) model an ontology for SC simulation modeling that enables the user to capture the necessary knowledge to build and generate simulation models. All models listed in Table 2 address SCOR SC artifacts *(C4)* and *(C5)* and contain descriptions of the processes and the metrics. However, we note that *(C1), (C2), (C3), (C6),* and *(C7)* are not satisfied; the models lack customer interactions, material transactions and market interactions as well as management practices. The models include the operational granularity of an SC, *(C13)*. None of the models are industry-specific. However, they provide a purpose and an application: *(C15), (C16),* and *(C17)*.

4 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. Also, SENS models supply and demand and a SPARQL-based demand fulfillment algorithm. We include a representation of the SC physical, financial, and information flow.

4.1 SENS Ontology Model

SENS subsumes E2E and structural aspects of a SC as well as operational details incorporated by the SCOR model.

4.1.1 SENS Structural Model

The core of SENS Ontology depicted in Figure 2 is nodes representing SC partners. We model each partner as an 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* (Brintrup 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 the flow of demand, materials and products between SC partners. This is also referred to as the material flow. Likewise, *SupplierTier*s 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*

4.1.2 SENS Operational Model

Also, we model a node's 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 Level-1 KPI *hasResponsiveness, hasReliability, hasCost, hasAgility, hasAssetManagementEfficiency* to evaluate the operational behavior of this node based on the SCOR metrics standard. We limit our choice to the SCOR KPI as they enable a standardized benchmarking of SC.

Each node is described by *hasLocation*. We resolve node locations using geo-coordinates represented with the properties *hasLongitude, hasLatitude*. Furthermore, each node is described by data properties that depict its environmental performance, e. g., *hasCO2Footprint*.

4.2 Supply Chain Demand Fulfillment

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

4.2.1 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.

4.2.2 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 (Xiao and Qi 2016).

4.2.3 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*.

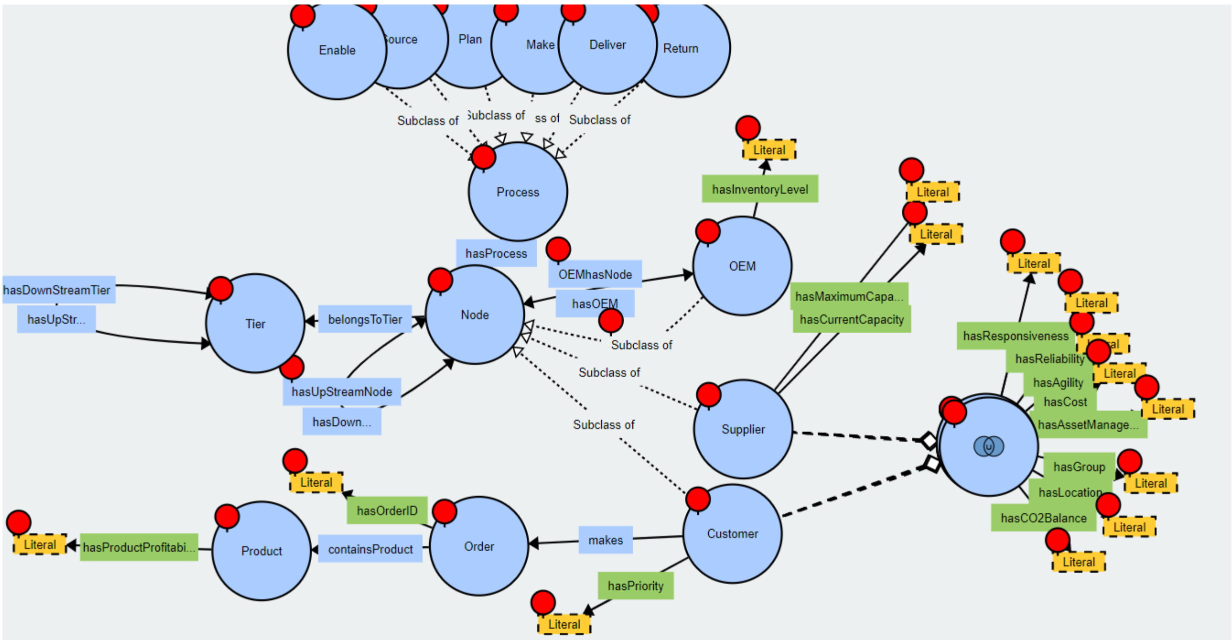


Figure 2: Depiction of the core concepts of the SENS ontology modeling End-to-End and SCOR supply chain concepts.

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 et al. 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.

In this sense, 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 [2] For all upcoming SPARQL queries we state ":" as a prefix defined as <http://http://www.semanticweb.org/ramzy/ontologies/2021/3/sens-ontology#>

1. Listing 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 $DT(O) - LT(O) = t$. The following follows the described triple structure to retrieve, for each order (depicted by the variable ?o), the

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[2] Removed for blind review

corresponding variables e. g., Delivery Time (?dt), Product (?p).

Listing 1: Get Orders by customer priority

```
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 $Q(I) >= Q(O)$, 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 2: Get all intermediate products and quantities to manufacturer P. We assume that P is known, not a variable, since we have already executed *Listing 1* to get the specific products for this order.

Listing 2: Get all intermediate products for Product P

```
SELECT * WHERE {
<< :P :needsProduct ?comp >>
:needsQuantity ?quant.
}
```

   b) Listing 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. We represent in the following query $LT(S)$ by the variable *?lt*. The variable ?quant is from the previous query and quantifies the number of intermediate products to get.

Listing 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.
?s :hasCO2Footprint ?ft.
FILTER  (?sat >= ?q + ?quant) &&
(?t - ?lt= ?t0).
}
ORDER BY (?ft)
```

4.2.4 Multi-factor Supplier Choice

External and internal supplier selection process is about choosing suppliers that fulfill the customers' orders while playing an essential role in fulfilling a company's strategic goals. Supplier selection is influenced by various tangible and intangible criteria, such as price, quality, delivery time, service level, and technical capability (C. Wang et al. 2020). Setak et al. (2012) provide multi-factor-based decision making for suppliers.

In fact, with the increased awareness of climate change and the corporate responsibility towards mitigation strategies, companies are driven to consider environmental factors in their operations and manufacturing processes. Consequently, suppliers' choice based on environmental factors becomes essential to attain sustainability goals. Hashmi et al. (2021) proposes a model where CO2 footprint is considered as one of the crucial dimensions for the evaluation and selection of the suppliers.

We consider a low-carbon supplier selection in our implementation in Listing 3. During the choice of supplier, we retrieve the corresponding carbon footprint modeled by the triple *?s hasCO2Footprint ?ft*. The part of the query where we *ORDER BY (?ft)* entails the choice of the available supplier with the lowest carbon footprint.

4.3 Supply Chain Information Flow

SCM distinguishes three main flows in the SC Pfohl and Gomm (2009). The physical flow involves the flow of goods and materials from one location to another. The information flow determines the movement of information from the supplier to the customer and from the customer back to the supplier. The information flow relies on data from the physical flow and the financial flow. Finally, the financial flows are the inflows and outflows of financial value from one economic agent to another. An economic agent refers to an entity that play a role in an economic process (ESCWA 2018). Financial flow can be either inside a company or with an exterior entity. In fact, responsiveness to customer demand, and overall customer satisfaction, cannot be achieved without proper management of the goods movement and associated information flow throughout the SC (Singh 1996).

As part of SENS, we introduce the *Entrepreneur model* as shown in Figure 3. Indeed, the Entrepreneur model is an ontology model that does not exist in the schema.org model base yet Brickley (2015), but it is not only relevant for OEM, Tier1 and Tier2 E2E SC but also for internal global SCs where several entrepreneurs in different countries within a company handle the physical and financial flow. We see the property *hasUpstreamNode* modelling the physical flow of goods between the SC partners *Node1* and *Node2*. For the financial and information flows, we define a class *Entrepreneur*. The Entrepreneur does receive the physical goods, yet it is necessary to model the information and financial flows. It is important to detail that *Node1 sellsToEntrepreneur Entrepreneur*, which in turn *sellsToNode Node*. The properties *sellsToEntrepreneur* and *sellsToNode* entail inverse properties *purchasesFromNode* and *purchasesFromEntrepreneur* respectively. The coupling of a sale and a purchase with a company subsumes a Transfer Price.

The Transfer Price sets the price for goods and services sold between controlled (or related) legal entities within a company. A legal entity refers to any organization that has legal rights and responsibilities including liabilities (Cornell 2022).

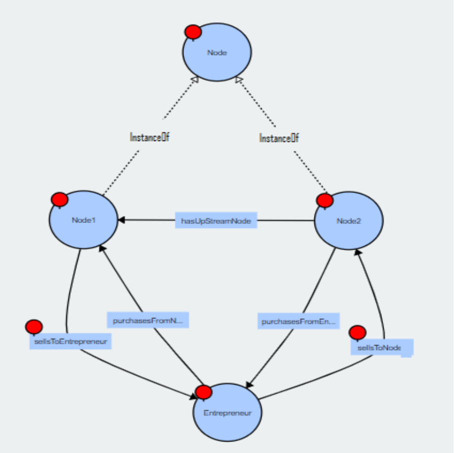

Figure 3: Ontology of the Entrepreneur model.

In fact, a Transfer Price includes two entities (an entity to sell and an entity to purchase). This trade-off is usually accompanied by an inter-company shipment, where goods will be moved. Hence, as multiple entities are under different countries' jurisdictions, the ownership of the goods, tax payment, and customs clearances are at stake. Therefore, it is relevant to understand who is involved, when, and where within the financial and information flows of the SC.

5 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.

5.1 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 3.

The KG describes the behavior of the SCN through the values assigned to the nodes' data properties e. g., *hasReliability, hasCO2Footprint*. 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 1 (cf. the technical report (SC Generator 2021) for the detailed code).

`create_OEM`: this function creates one instance of the class OEM and sets the values for the following properties: *hasDeliveryTime, hasTransportMode, hasInventory* and the corresponding characteristics of an inventory *hasProduct, hasCost, hasQuantity, hasTimeStamp*. The following function `create_SupplierTier(n)` generates SupplierTier1 to SupplierTiern, similarly for `create_CustomerTier(c)` CustomerTier1 to CustomerTierc. Then, with `create_SupplierNode(m.n)` where *m* is the parameter designating the Node_Supplier_Tier and *n* is Supplier_Tier. Then, `create_CustomerNode(l.c)` creates the customer nodes where *c* is Customer_Tier parameter and *l* is Node_Customer_Tier. After the execution of `create_relations`, nodes are connected via *hasUpStreamNode, hasDownStreamNode* while tiers are linked with *hasUpStreamTier, hasDownStreamTier*. We add specific properties' values with `add_SupplierGroup` and `add_CustomerPriority` to supplier and customers respectively. Afterward, for each SCOR metric, geographical and environmental property P, e. g., *hasCO2Footprint*, we assign to all `SupplierNode(m.n)` and `CustomerNode(l.c)` a random value. For suppliers, we generate the initial values for capacity, inventory and saturation for all nodes. Also, via `create_orders`, we assign orders to customer nodes and corresponding products, delivery times, and quantities.

Algorithm 1 SENS knowledge-graph generation algorithm

```
create_OEM
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)
        create_relations
        add_SupplierGroup
        for Property P of SupplierNode(m.n) do
            add_Properties
        end for
        generate_capacity
    end for
end for
for ($c = 1;\ c <= Customer\_Tier;\ c{+}{+}$) do
    create_CustomerTier(c)
    for ($l = 1;\ l <= Node\_Customer\_Tier[c];\ l{+}{+}$) do
        create_CustomerNode(l.c)
        create_relations
        add_CustomerPriority
        for Property P of CustomerNode(l.c) do
            add_properties
        end for
        generate_orders
    end for
end for
```

Parameter **Triple Representation**	**Explanation**	**Automotive Industry**	**Dairy Industry**
Supplier_Tier	**SC** depth, manufglsturing steps	3	1
Customer_Tier	**SC** distribution and sales interglstions (OEM to end customer)	3	2
Node_Supplier_Tier	**SC** width, the suppliers providing materials for manufglsturing	<2, 3, 5>	<3>
Node_Customer_Tier	**SC** customer availability	<2, 2, 4>	<2, 3>
Supplier_Group_Tier *Supplier hasGroup xsd:integer*	**Supplier** exchangeability to provide same products per tier	<1, 2, 4>	<1>
Node_Priority range *Node hasPriority xsd:integer*	**Customer** relationship management to prioritize customers	[1-3]	[1-3]
Node_capacity_Saturation *Node hasSaturation xsd:integer*	**Node** maximum capacity to manufglsture	[1-3] million unit	[0.5-1] million unit
Node_Delivery_Time *Node hasDeliveryTime xsd:integer*	**Node** time to deliver from node to node in following tier	[1-7] days	[1-3] days
Node_Initial_Inventory *Node hasInventory Inventory*	**Node** inventory at t=0	[10-50] thousand unit	[5-10] thousand unit
Node_Initial_capacity *Node hascapacity capacity*	**Node** capacity at t=0	1 thousand unit	1 thousand unit
Data Property range *Node (hasResponsiveness,ca hasReliability, hasCost, hasAgilty, hasAssetMangmentEfficeny) xsd:integer*	**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 *Node hasCO2Footprint xsd:integer*	**SC** environmental performance	[30-45] Tg	[30-45] Tg
Data Property range *Node hasLongitude xsd:integer Node hasLatitude xsd:integer*	**SC** globalization (geographically dispersed network of nodes)	Long/Lat: [0-180/ 0-90]	Long/Lat: [90-180/ 45-90]
Customer_Demand_Frequency *Customer makes Order*	**SC** constant demand frequency	2	10
Product type and quantity per order *Order hasProduct Product* *Order hasQuantity xsd:integer*	**SC** orders variability and size	1: 100 thousand unit	1: 5000

Table 3: SENS-GEN parametrization and exemplary parameters for automotive and dairy industry.

5.2 Generated Showcase Examples

We present two examples of SCNs from the automotive and dairy industries. Table 3, in the Appendix, shows the parametrization of the model and the variation of topology and properties based on the industry. In Figure 4, 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 5 consists of one supplier tier, i. e., the dairy farms 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 Footprint varies according to the policies of countries where nodes are located as well as OEM environmental strategies but ranges 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.

6 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 performance analysis of the generated automotive SCN example introduced and show behavioral changes under experimental conditions. Afterward, we show the implication of applying SENS and SENS-GEN for sustainability and environmental impact analysis. We present a use case that relies on the information and material flows model in SENS to tackle a real-life scenario of a SC problem.

6.1 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 4 attached in the Appendix, 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.

6.2 SENS Knowledge Graph Behavior Analysis

This section shows the benchmarking and integrated analysis in experimental contexts enabled by SENS.

Setup: We use the automotive SENS KG in Figure 4 generated via the parameters in Table 3. 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 4 evaluates how many orders the SC fulfills. 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 measures the extent to which a node employs its installed productive capacity after executing the demand fulfillment algorithm. *Average SCOR KPI* in Listing 6 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 4: Order Fulfillment

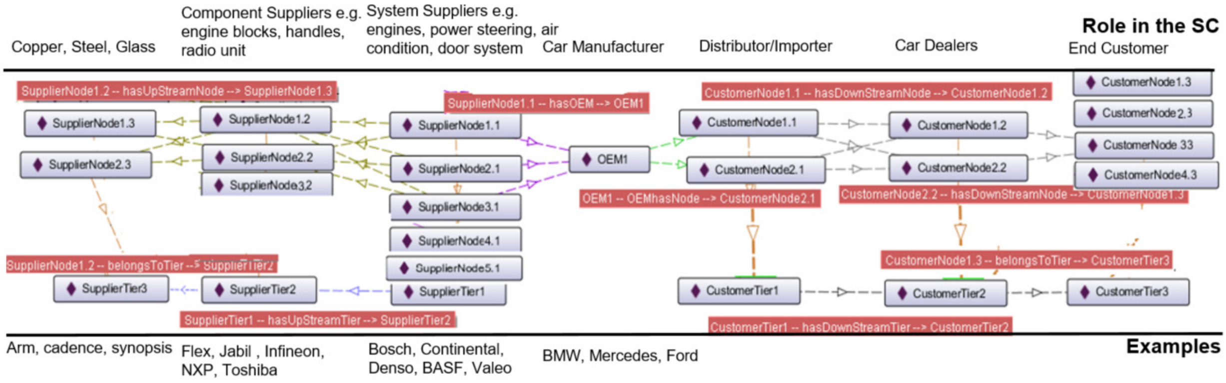

Figure 4: Automotive industry SENS KG example with three supplier tiers raw material, component, and system suppliers.

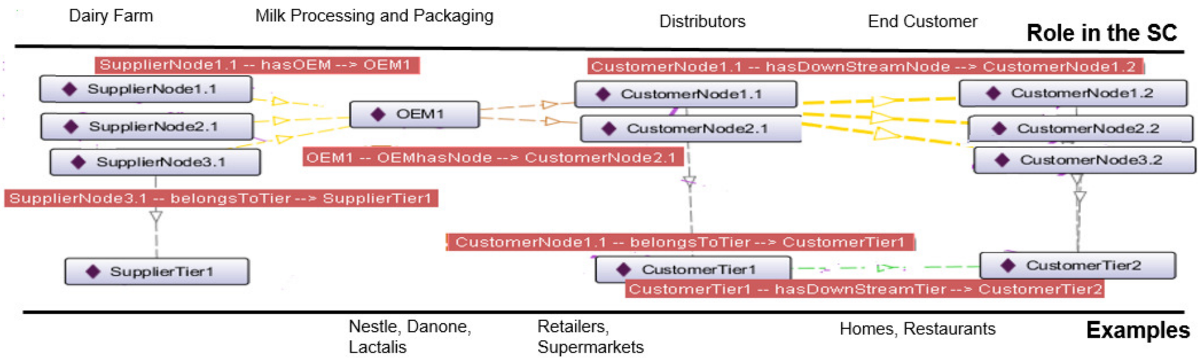

Figure 5: Dairy industry SENS KG example with one supplier tier, i. e., the dairy farms, and one end-customers tier.

```
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.
} GROUP BY ?order
```

Listing 5: Node Utilization

```
SELECT 100*?quant/?max AS ?Utilization
WHERE {
?supplier :hasSaturation ?max.
?supplier :hascapacity ?cap.
?cap :hasQuantity ?quant.
?cap :hasTimeStamp 178.
}
```

Listing 6: Average SCOR KPI

```
SELECT AVG(?res) AS ?Responsiveness
WHERE {
?supplier :hasResponsiveness ?res.
} GROUP BY ?supplier
```

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

The graph in Figure 6 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

<table>
<tr><th></th><th>SPARQL Query:
SELECT * WHERE</th><th>Example Output Triples</th></tr>
<tr><td>(C1) Customer Interaction</td><td>?customer makes ?order.
?customer hasDownStream ?c</td><td>Node3.2 makes OrderJZHu5
Node3.2 hasDownStream Node3.3</td></tr>
<tr><td>(C2) Material Transaction / (C10) Various Materials</td><td>«Product needsProduct ?p» needsQuantity ?q</td><td>«ProductA needsProduct Product1» needsQuantity 1</td></tr>
<tr><td>(C4) Process Description</td><td>?node hasProcess ?process.</td><td>Node3.2 hasProcess ProcessA. ProcessA rdf:type Make</td></tr>
<tr><td>(C5) SCOR Metrics</td><td>?node hasResponsiveness ?r.</td><td>Node3.2 hasResponsiveness ’24’</td></tr>
<tr><td>(C8)Vertices / (C9) Edges</td><td>?node a Node ?node ?prop ?node2.</td><td>Node3.2 rdf:type Node Node3.2 hasDownStreamNode Node3.3</td></tr>
<tr><td>(C3) Market Interaction / (C11) Supply and Demand</td><td colspan="2">Algorithm described in Section 4 detailed by SC Generator (2021)</td></tr>
<tr><td>(C12) SC vs SC</td><td colspan="2">Supplier exchangeability is modeled by <i>Supplier hasGroup xsd:integer</i>. Nodes share and compete over suppliers and customers.</td></tr>
<tr><td>(C13) SC Granularity</td><td colspan="2">Operational: SENS-SC spans SCOR operational processes e.g. <i>Source, Plan</i> and the supply plans address operational planning. Tactical, Strategic: Describing the performance via data properties e.g. <i>hasCO2Footprint</i> enable analysis on different aggregation levels.</td></tr>
<tr><td>(C14) SC Scope</td><td colspan="2">SENS-SC models Internal node processes and External interactions by modeling the flow of supply and demand.</td></tr>
<tr><td>(C15) Industry Domain</td><td colspan="2">Model parametrization to tailor the KG to any industry.</td></tr>
<tr><td>(C16) Model Purpose</td><td colspan="2">Provide a topology of SCN with detailed and standardized operational SCOR processes and relying on semantics for interoperability.</td></tr>
<tr><td>(C17) Model Application</td><td colspan="2">SC behavior analysis in empirical scenarios as shown in the following section.</td></tr>
</table>

Table 4: SENS as an integrated semantic model covering SC core aspects.

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.

6.3 SENS Knowledge Graph Environmental Analysis

The increasing concern about global climate change and carbon emissions as a causal factor has led many companies and organizations that are pursuing “carbon footprint” projects to estimate their own contributions to global climate change, the total CO2 footprint a company is responsible for, and what actions are being taken to reduce that footprint. This includes not only the impact that occurs directly at a company’s manufacturing operations but also the indirect impacts that result from all of the supporting activities that occur because of the business, including supply chain partners. We show that SENS and SENS-GEN enable environmental analysis. We identify the following queries to determine the CO2 footprint of the operational activities.

- Get CO2 footprint per customer: companies are driven to consider their including their customers’ participation in such emissions via transportation or via products. The following query evaluates the CO2 footprint of each customer making orders.

Listing 7: Get CO2Footprint by Customer

```
SELECT ?customer ?priority
(SUM(xsd:integer(?co2)) as ?custprint)
WHERE{
```

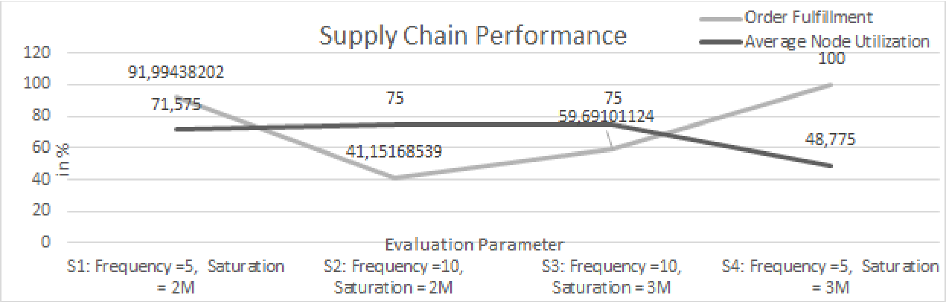

Figure 6: SENS knowledge graph performance evaluation with parameter variation.

```
?customer :makes ?order.
?customer :hasPriority ?priority.
?order :hasSupplyPlan ?plan.
<<?plan :needsNode ?supplier>>
 ?y ?z.
?supplier :hasCO2Footprint ?f.
}
GROUP BY ?customer ?priority
```

- To get product CO2 footprint: the demand for transparency about product emissions is increasing. The following query calculates the sum of the CO2 footprint of the different products included in the customers' orders.

Listing 8: Get CO2Footprint by Product

```
SELECT ?product
(SUM(xsd:integer(?CO2print))
AS ?productprint)
WHERE{
?order :hasSupplyPlan ?plan.
?order :hasProduct ?product.
<< ?plan :needsNode ?supplier >> ?y ?z
?supplier :hasCO2Footprint ?CO2print.
}
GROUP BY (?product)
```

- CO2 footprint per product per customer: this query is to analyze the CO2 footprint of customers and products. The result in Figure 7 shows the contribution of each product per customer to the company's CO2 footprint.

Listing 9: Get CO2Footprint by Customer/Product

```
SELECT ?customer ?product
(SUM(xsd:integer(?print))
as ?sumprint)
WHERE{
?customer :makes ?order.
?order :hasProduct ?product.
?customer :hasPriority ?prioirty.
?order :hasSupplyPlan ?plan.
<< ?plan :needsNode ?supplier >>
?y ?z.
?supplier :hasCO2Footprint ?print.
}
GROUP BY ?customer ?product
```

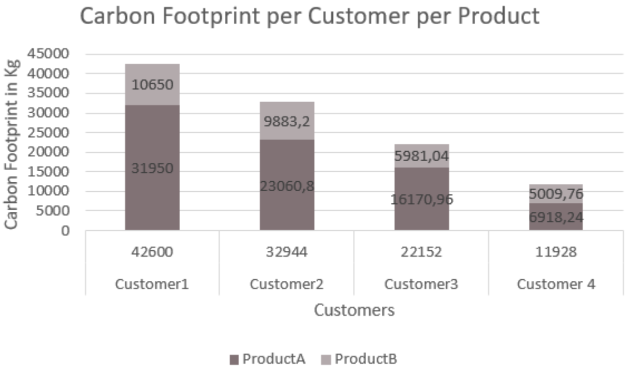

Figure 7: SENS knowledge graph sustainability analysis.

6.4 Use Case

We rely on the Entrepreneur model to illustrate the information and financial flows in the semiconductor SC from a German semiconductor manufacturer. We showcase the necessity of differentiating the three flows in order to avoid problems such as possible taxation. Such challenges arise within the semiconductor SC and SCs containing semiconductors due to the high complexity of the manufactured products and the need to comply to all custom, tax and reporting duties while fulfilling the customer demand.

In this use case, we model the flows between the final steps of the Front-End (FE) facility located in Southeast Asia (SEA) and the first step of a Back-End (BE) facility located e. g., in Malaysia, but both are affiliated to the same Entrepreneur located in Europe (EU). Thus, the use case is useful to consider the different nature of flows that an inter-company shipment can involve, as it goes beyond the simple shipment of goods.

As shown in Figure 8, the Entrepreneur never “sees” the goods as they are shipped directly from the FE (*Node1*) to the BE (*Node2*) location. However, since the European Entrepreneur is the attached entrepreneur for both entities, it gathers the information and financial flows from both sides, namely in terms of goods ownership and money trade-off. From left to right in the figure, the Front-End (FE) facility sells the semi-finished good to the Entrepreneur. The two triples (shown in the figure) *Front-End sellsToEntrepreneur Entrepreneur* and *Entrepreneur purchasesFromNode1 Front-End* represent this transaction and sell. This transaction leads to the first Transfer Price. The Entrepreneur purchases the goods and earns the ownership of the goods. However, since the Entrepreneur does not perform BE manufacturing operations, the goods purchased need to be sent to a BE location. This leads to a second Transfer Price where the Entrepreneur loses the ownership of the goods, and the BE facility earns it while entities respectively sell and purchase the goods. We model this by *Entrepreneur sellsToNode2 Back-End* and *Back-End purchasesFromEntrepreneur Entrepeneur*.

Furthermore, when referring to a Transfer Price, entities involved are most likely located in a different country where each country has its on-tax income policy, with its own rate on the income tax.

With the Entrepreneur model, we are able to distinguish the physical, information, and financial flows in order to obey legitimated rules, pay fair taxes, and reduce the admin effort by keeping the maximum flexibility for resilient operations.

7 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. Modeling various SC flows and the corresponding integration ensures operational excellence and enables the understanding of complex scenarios.

7.1 Limitations and Future Research

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. Future research options include an interactive interface where the user can tailor the values for each node individually to fine-tune the parameter space; a more detailed analysis of an internal semiconductor supply chain and modeling the commit process.

7.2 Implications

We demonstrate the impact of SENS being a semantic standard SC model.

7.2.1 SENS as a Semantic Supply Chain Model:

Semantic modeling provides a human and machine-understandable representation of the domain. Therefore, we see implications of SENS, an ontology-based model, on the re-producibility

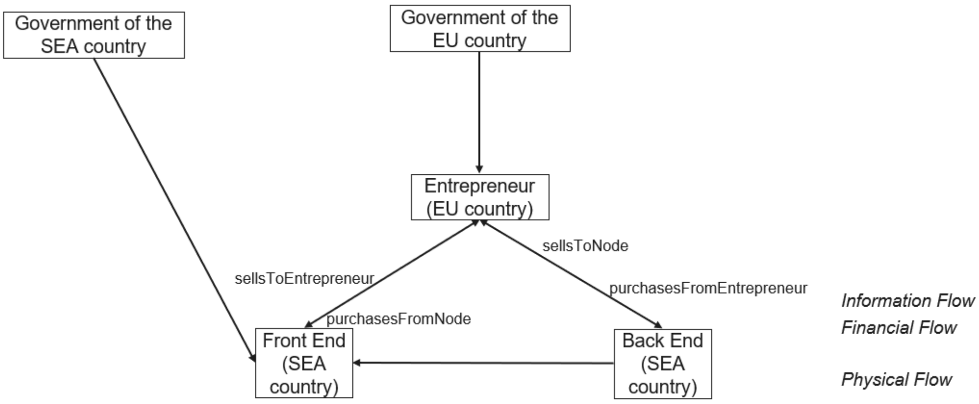

Figure 8: Instance of the Entrepreneur model.

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).

Furthermore, SENS resembles digital twins, that facilitate information exchange and integration, hence, 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 structural and operational information integration in the overall SC enabled by our work increases visibility. This, in turn, may lead to dramatically reducing demand distortion, i. e., the bullwhip effect Blomkvist and Ullemar Loenbom 2020 and strategic positioning an organization in the supply network. The SENS model provides explicit, uniform semantic descriptions of terms and concepts, which enables a correct understanding of the different flows and decision logic within the complicated real-world processes to model. SENS includes environmental factors in suppliers' choice implementation which allows companies to attain their sustainability goals. SENS applies in concrete real-world use cases to cater to the specific characteristics entailed by the complexity of the manufactured product.

7.2.2 SENS Operationalized

Furthermore, semantic models mix the schema level and the instance level of a domain and this is crucial for SC reporting. In fact, the conceptual model describes a domain's key business objects and their relationships on a schematic level. This indicates the schema as an abstract overview of the information structure from a business perspective (Otto and Hüner 2009). The data model consists of an application architecture containing the entirety of a company's applications that create, store, and update instances coming from various data formats (structured and unstructured) (Kokemüller and Weisbecker 2009). Reporting is the creation of reports to access and analyze different SC aspects. Reporting enables SC partners to make informative decisions regarding business-entities modeling and data structures. It allows understanding the conceptual model, retrieving data from the physical layer and connecting/mapping the conceptual model to the underlying data. The grasping of the conceptual and data models as well as the relations between them is necessary to standardize and consolidate SC reporting and create efficient and methodological decision-making process.

Relying on SENS we can query mixing the schema level and the instance level to enable understanding, retrieval and analysis of SC artifacts. Ramzy et al. (2022) give a concrete example on the use of semantic model for SC Master Data reporting as part of SC analytics. Authors design a knowledge-graph-based approach to create a SC Master Data semantic operational model, deploy it, and define and obtain the consensus of involved stakeholders. The proposed methodology relies on iterations to incorporate stakeholders' inputs allowing evolutionary development of the model. This facilitates the ingestion and adoption of the new model increments among the stakeholders as well as the deployment in the organization.

7.2.3 SENS as a Reference Model:

SC modeling is essential as it provides domain representation that allows to understand the complexity and test the behavior in empirical environments. Reference models enable benchmarking of operational processes and behaviors measurements. The SCOR model is a well-established standardized operational SC model that offers a mutual understanding of concepts and processes. SENS subsumes all aspects that define a SCOR model as discussed. Hence, SENS can be used to observe, standardize, and benchmark SCs. Also, we refer to the Digital Reference Moder et al. (2020) that builds up on SENS to create a verified standardized vocabulary for semiconductor SCs. DR is publicly available on https://w3id.org/ecsel-dr.

8 Conclusion

Integrated modeling is required for visibility and proactive monitoring of members and processes across the SC network. Existing SC models created by one organization are limited in the way they grasp the dynamics between SC partners. There exist several SC models e. g., SCOR, E2E, that incorporate SC artifacts e. g., operations, production scheduling, flow of materials. We identified that existing models comprise SC core concepts but in an isolated manner, thus hindering integrated SC performance analysis. Semantic models for the SC, such as SENS, result in high-level semantics-based descriptions of the domain capturing core artifacts of the E2E SC environment in a standardized way. The output models of our contribution integrate SC concepts, processes, structure, and flows, ensuring an elaborate understanding of the holistic SCs, beyond direct one-to-one relationships and including operational granular details. Hence, semantic models help create operational E2E standardized SCs.

Moreover, SC stakeholders do not disclose SC data, as it is considered sensitive. Thus, the lack of real-world data constraints empirical behavioral analysis and performance benchmarking required for particular circumstances, e. g., resilience simulation under disruption. SENS-GEN, leveraging semantic models (SENS), offers effective means to create empirically controlled and designed SC scenarios.

SC stakeholders can rely on SENS and SENS-GEN to assess and control complex SC scenarios, determine operational strategies and SC structure, increase resilience, and ultimately enable digitalization. Thus, SENS and SENS-GEN contribute to creating a sustainable SC where all partners are aligned on environmental goals. Better simulation and analysis help increase the integrated analysis capabilities to standardize and benchmark SCs.

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