# How product representation influences the understanding of supply chain process models

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**Abstract.** Process models are increasingly being used to analyse business processes within supply chains. Although products are an essential part of supply chain semantics, product representation in supply chain process models is insufficient. This research proposes a novel product representation, namely, "labelled flows," which directly assigns product names to flows instead of implicitly representing products through other visual constructs. Using a laboratory experiment, we find that using labelled flow improves domain understanding with respect to product comprehension and product modelling performance. Our contribution to modelling research is a novel product representation within supply chain process models, which enhances domain understanding.

**Keywords**: process model; modelling grammar; supply chain; supply chain management; laboratory experiment

This is an Accepted Manuscript of the following journal article:

Leukel, J., & Sugumaran, V. (2018). How product representation influences the understanding of supply chain process models. *Enterprise Information Systems*, 12(10), 1285-1307. https://doi.org/10.1080/17517575.2018.1533589

## 1. Introduction

Process models are frequently used to document the common understanding of activities, events, and control flow logic that constitute a business process (Alotaibi and Liu 2017). They are typically diagrammatic representations complemented with some textual description. Analysts require such models for the analysis of organizational procedures and interfaces (process analyst), and requirements for information systems (IT analyst) (Müller et al. 2016). A particular type of process model is the supply chain process model. The need for representation of supply chain phenomena in process models stems from the changes in the business environment. With managerial decisions moving from an organizational scale to the supply chain (Dyer and Singh 1998; Mentzer, Min, and Zacharia 2000), supply chain analysis has become a prevalent task of process and IT analysts.

The role of supply chain process models is to help analysts understand the domain semantics, facilitate communication between designers and users, and thus complement quantitative modelling approaches that seek for effective design solutions (Klibi, Martel, and Guitouni 2010). Although the origins of supply chain process modelling lie in business process modelling, the former focuses on the product flow, whereas the latter is concerned with the control flow. Product flow is different from control flow; it involves physical goods and services being transferred from one activity to another activity. This difference in representational focus is the reason why specific modelling grammars for supply chain processes have been proposed in the literature (Röder and Tibken 2006; Verdouw et al. 2010; Zhang et al. 2009), which are also referred to as supply chain grammar (Pentland 1994).

Despite the importance of product for the structure, behaviour, and sustainability of supply chains (Pashaei and Olhager 2015; Petersen, Handfield, and Ragatz 2005; Töni and Tjoa 2017), product representation in supply chain process models is insufficient for three reasons. First, the common thread of current approaches is *implicit* representation by using a non-product modelling construct. For instance, product names can be included into the labels of supply chain activities, e.g., an activity labelled “deliver wheel” would signify the delivery of wheels (Persson and Araldi 2009), or supply chain actors, e.g., “wheel supplier” would denote a supplier of wheels (APICS 2018). However, implicit representations undermine domain understanding from diagrams compared to explicit representations (Parsons 2011; Shanks et al. 2008). Second, some grammars restrict the scope of an entire diagram to one product or product family (Blecken 2010; Wang, Chan, and Pauleen 2010), which severely limits the expressiveness of diagrams. Third, empirical evidence for the usefulness of product representations proposed in prior research is lacking. Specifically, evaluation methods used in prior research are limited to scenario (Long 2014; Röder and Tibken 2006; Soffer and Wand 2007; Zdravković et al. 2011), informed argument (Millet, Schmitt, and Botta-Genoulaz 2011; Verdouw et al. 2010), and case study (Persson and Araldi 2009) such that the diagram user’s perspective is missing.

Against this backdrop, the objectives of our research are to: a) develop a new product representation through explicit labelling of flows, and b) empirically validate the usefulness of this representation using a laboratory experiment. We seek to fill the gap in the literature by proposing a novel representation, namely, "labelled flows." This representation is explicit by directly assigning product names to flows. Thus, product information is integrated into a product-related construct instead of using a non-product construct. Labelled flows minimize the distance between corresponding textual information (i.e., product name) and visual information (i.e., flow transferring the product). We derive this representation from the cognitive theory of multimedia learning and its spatial contiguity principle (Mayer 2001; Mayer and Moreno 2003), and predict that the proposed representation will be useful for analysts. We measure usefulness through performance in solving product comprehension and product modelling tasks. To scope our research, we turn to the Supply Chain Operations Reference (SCOR) model and its modelling grammar for the so called SCOR thread diagram (APICS 2018). Since its first publication in 1997, SCOR has received wide appreciation in practice and is often regarded as the industry-standard for supply chain process modelling (Addo-Tenkorang, Helo, and Kantola 2017; Bolstorff and Rosenbaum 2012). We develop the new product representation and provide a formal specification as well as transformation rules for existing diagrams. In our empirical evaluation using a controlled laboratory experiment, we find considerable improvement in solving product comprehension tasks as well as product modelling tasks, which are essential tasks of supply chain analysis.

Our research makes four contributions: The first contribution is a novel product representation within supply chain process models, which represents products explicitly through labelled flows instead of implicitly through other non-product constructs. This representation is theoretically underpinned by insights from the cognitive theory of multimedia learning. The second contribution is the formal specification of the modelling grammar for SCOR thread diagrams complemented by transformation rules for existing thread diagrams. The third contribution is empirical evidence for the usefulness of the proposed representation obtained from a controlled laboratory experiment, for which we provide all the materials and instructions to allow replication in future studies. The fourth contribution is the further understanding of the boundaries of cognitive theory of multimedia learning within modelling research. Our research provides empirical support for the theory's spatial contiguity principle.

The remainder of this article is structured as follows. We first discuss prior research related to product representation in supply chain process models. We then present our proposed representation. Next, we report on the experimental evaluation. Then, we discuss the findings from our study before concluding the article.

## 2. Prior Research

### *2.1 Product Representation in Supply Chain Process Models*

Supply chain process model is a particular type of process model that includes activities realizing the flow of products from upstream suppliers to the downstream customers. Therefore, products are an essential part of the domain semantics to be represented in the model. Analysts require an understanding of how the supply chain transforms elementary products (goods and services) across the various supply chain tiers into final products delivered to customers.

Supply chain process models can be created using diverse modelling grammars, which also differ with respect to product representation. On one hand, quantitative models seek effective supply chain designs and have been proposed for product-related tasks such as supply chain coordination (He, Guo, and Wang 2018; Sepehri 2012) and supply chain reliability analysis (Lam and Ip 2012). Such modelling approaches have one thing in common. They represent products mathematically, i.e., through variables, but no specific visualization for users is provided. On the other hand, diagrammatic models enable users to comprehend the product semantics, which is given through labels, i.e., textual annotations to graphical constructs. Thus, although the model is a diagrammatic representation, users can only reveal the true meaning of any visual construct if they identify and understand the labels assigned to the construct (Mendling, Reijers, and Recker 2010). Next, we discuss approaches for product representation and begin with non-SCOR representations, before turning to SCOR-based representations.

Petri nets have been proposed for supply chain process modelling. Blackhurst, Wu, and O'Grady (2005) use Petri nets, in which places represent products, transitions represent activities, and tokens represent product instances that move via transitions from one node to other nodes. Their argument for using Petri nets is the mathematical foundation, which complements the graphical representation. Petri nets are also the basis of the grammar used by Zhang et al. (2009). In their model, places represent organizational entities such as production sites, warehouses and customers, whereas products are denoted by coloured tokens; hence, colours encode different types of products. Note that colour is a metaphor for any code assigned to a token, which might also come in the form of a meaningful label such as product name. Both Blackhurst, Wu, and O'Grady (2005) and Zhang et al. (2009) posit that the resulting models would be easy to understand because of the graphical nature; however, the usefulness of the models has not yet been validated.

Several adaptations of the Business Process Model and Notation (BPMN) for supply chain process modelling have been put forward. BPMN is the most used grammar for business process modelling (OMG 2011). The approach proposed by Bae and Seo (2007) relies upon one BPMN diagram per final product, whereas diagram elements provide no specific product information. This limitation also holds true for the BPMN adaptations proposed by Blecken (2010) and Chandra and Grabis (2016). In summary, the BPMN models used in prior work describe activities for a large set of products that all share the same activities. Thus, products can only be represented through the scope definition of the model (e.g., by a textual annotation on the diagram). In addition, evaluations of the usefulness of BPMN-based models with respect to product representation have not yet been carried out.

### *2.2 SCOR-based Representations*

SCOR is the most popular supply chain grammar and provides a particular diagram type that focuses on product flows, namely the SCOR thread diagram. For the purpose of our discussion, we first briefly introduce the grammar for thread diagrams through its four main constructs as shown in Table 1. We focus on the core subset for representing primary product flows (but no secondary product flows and information flows).

**Table 1.** Grammar constructs for SCOR thread diagrams.

| Construct | Symbol | Definition |
|---|---|---|
| Process | Arrow-shaped rectangle with 2-character code | Represents an activity. Two-dimensional classification into so called *process categories*, depending on (1) process type [S, M, D] and (2) product specificity [1, 2, 3]. |
| Actor | Label | Represents an organizational entity that executes one or more processes. |
| Flow | Arrow | Represents the transfer of a product from one process to another process. |
| Tier | Vertical swim lane with label | Represents the involvement of actors in the entire supply chain by arranging them from left (supply) to right (demand). |

A thread diagram is horizontally segmented into tiers that contain actors who execute processes, which are linked through flows. Processes are categorized along two dimensions and a 2-character code is used to signify the resulting process category: The first character corresponds to the process type, which can be either a source (S), make (M), or deliver process (D). The second character corresponds to product specificity, which represents the degree of customization. It could be a (1) indicating stocked product, (2) for make-to-order product being manufactured for a specific customer, or (3) for engineer-to-order product being designed and manufactured based on a specific customer requirement. For instance, S2 stands for a source process of make-to-order products. The grammar further defines that each diagram represents processes for one product family, which can be an arbitrary aggregation of products that are provided to the final customers. Therefore, all flows to these customers represent the transfer of products from that product family, while all other flows are more or less related to that product family (Wang, Chan, and Pauleen 2010).

Despite SCOR's apparent significance, it provides no specific guidance on how to represent products in thread diagrams. Contrary to the definition of flow, its modelling construct does not allow to specify the product that is the subject of the flow. To mitigate this representational deficit, different practices have been proposed by academia and used in the industry. A rather intuitive way to represent products is by including product-related terms in the labels of actors (APICS 2018). For instance, the thread diagram in Figure 1 (left hand side) contains three product-laden *actor labels* to signify the products tire, rim, and wheel. To be able to represent complex product structures more effectively, prior research yields several concrete grammar modifications, which we discuss next.

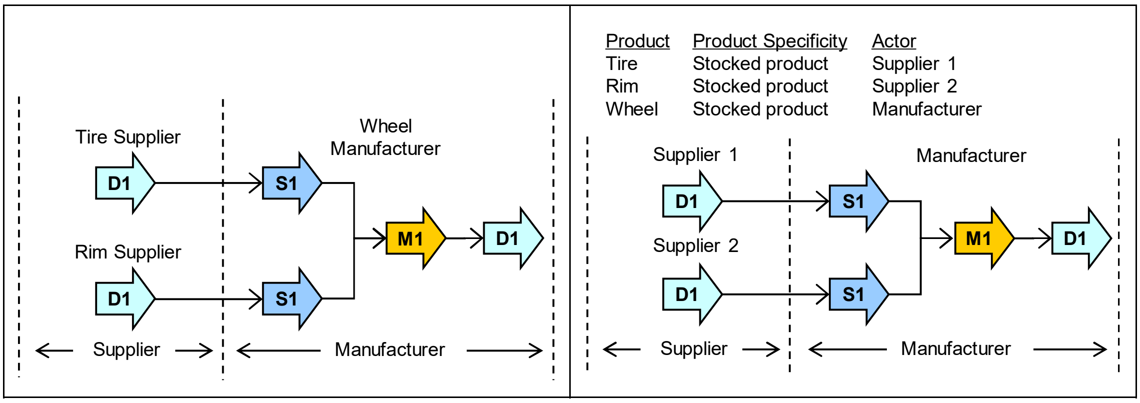


**Figure 1.** Diagram with product-laden actor labels (left) and diagram with attached product topology model (right).

The approach by Zdravković et al. (2011) amends the SCOR grammar with constructs for product topology and linking topology elements to actors. Product topology defines the structure of products that are delivered to final customers through hierarchical relationships between products. This approach requires us to first define the product topology and the actors for each product. Then, the thread diagram could be inferred to some extent. As a result, product semantics is contained in a supplementing three-column table for product topology (as shown in Figure 1, right hand side). Product is represented through textual information that is stored separately from the diagrammatic representation. For retrieving domain semantics from the diagram, the user must identify the relationship between two forms of elements (table and symbols). The effectiveness of this retrieval might be undermined in case of complex diagrams and large number of products.

The grammar used by Persson and Araldi (2009) allows optional product labels for processes. For instance, in the example shown in Figure 1 (left hand side), the source processes could have the labels “Tire” and “Rim,” respectively. However, this grammar modification changes the semantics of the process construct by binding each labelled process to exactly one product. The revised grammar is in conflict with the original grammar, which defines processes not through common products but common organizational procedures, which may be valid for multiple products. As a consequence, processes in existing diagrams must be carefully reviewed if they are still valid with respect to the modified semantics of the process construct.

In summary, the current approaches differ in terms of the grammar construct used for product representation, and have various consequences for grammar use. Moreover, the effects of each representation on diagram understanding are unknown. The above discussion indicates that the approaches to implicit representation by Zdravković et al. (2011) and Persson and Araldi (2009) have far reaching consequences for diagram interpretation by adding a second, table-based representation and modifying the semantics of the process construct, respectively. Contrary to that, the implicit representation using product-laden actor labels relies on a particular labelling style. We commence our study by proposing an alternative but theoretically-derived representation.

## 3. Proposed Product Representation

This section presents the proposed SCOR-based product representation by: a) describing the underlying rationale, b) providing a formal specification, and c) demonstrating its use.

### *3.1 Rationale*

For revising the SCOR grammar, we draw on the *cognitive theory of multimedia learning*, which provides explanations of how representations are used by individuals for problem-solving (Mayer 2001). This theory first assumes that individuals have two separate channels of limited capacity for processing verbal (textual) and visual information (Paivio 1991). Second, each channel has limited processing capacity available (Chandler and Sweller 1991). Third, learning from a multimedia representation requires significant cognitive processing in both channels. These processes include recognizing the various parts of the representation, formulating a mental representation, and integrating the mental representation with prior knowledge.

SCOR thread diagrams can be regarded as multimedia representations from which users want to learn domain semantics. Textual information includes at least three types of labels, i.e., 2-digit labels placed within the symbol for processes, labels spanning across tiers, and labels placed next to a set of processes to denote the actors that execute this set of processes. Visual information includes rectangles (processes), swim lanes (tiers), and arrows (flows). Processing the diagrams requires the user to pay attention to the various elements in the presented diagram, organize them into a consistent mental representation, and integrate the diagram with their prior knowledge of both the supply chain described in the diagram and the modelling grammar used for creating the diagram.

A fundamental insight from multimedia learning is that representations should activate both channels for processing visual and textual information to exploit the limited capacity of each channel. However, product representation mostly relies on textual information, e.g., denominating the product; hence, the potential of improved visual representations such as product icons is severely limited (Moody 2009). Therefore, the interplay of visual and textual information becomes our primary design consideration. This gap can be filled by the spatial contiguity principle for multimedia learning (Mayer and Moreno 2003). This principle demands placing corresponding textual and visual information rather near than far from each other. In case of thread diagram, flow is the visual information (visual construct) and product is the textual information (no visual construct but text only).

If we assess spatial contiguity for diagrams using product-laden actor labels (one type of implicit representation), then the product-related textual information is spatially associated with the actor construct, thus its distance to the corresponding flow construct is rather large. We now adopt the spatial contiguity principle to minimize the distance between corresponding textual information (the product name) and visual information (the flow transferring the product) in the diagram. We call this representation "labelled flow," which directly assigns product names to flows. This representation is explicit by assigning product names to a product-related construct. We propose that product information should be placed on the flow arrow and thus integrated into the flow construct to achieve greater spatial contiguity.

### *3.2 Specification*

We first specify the revised grammar. Then we define transformation rules that allow modellers to transform existing thread diagrams into the new representation.

#### *3.2.1 Revised Grammar*

The literature provides a formal specification of the original SCOR grammar for thread diagrams (Leukel and Sugumaran 2013). This specification uses a formalism that relies on mathematical graphs by defining processes as nodes, flows as arcs, and functions that map related diagram elements onto each other. The original specification includes eight elements as follows: Four sets represent the grammar constructs, namely, process, flow, actor, and tier (denoted as $P$, $F$, $A$, and $T$), three functions map processes onto process categories, actors, and tiers (denoted as $PC$, $PA$, and $PT$), and one function defines the order of tiers (denoted as $N$). For the purpose of our grammar revision, we additionally define the set of product names (denoted as $Prod$) and the mapping of flows onto product names (denoted as $FProd$). Therefore, the eight-tuple of the original specification becomes a ten-tuple. We provide the revised specification in Definition 1.

**Definition 1 (Thread diagram)**: A SCOR thread diagram is a directed graph defined by the ten-tuple $TD = (P, F, A, T, PC, PA, PT, N, Prod, FProd)$ such that:

- $P$ is a finite set of processes $p \in P$,
- $F$ is a finite set of directed flows $f \in F$ with $F \subseteq P \times P$,
- $A$ is a finite set of actors $a \in A$,
- $T$ is a finite set of tiers $t \in T$,
- $PC$ is a function that maps each process onto a process category with $PC: P \rightarrow \{S1, S2, S3, M1, M2, M3, D1, D2, D3\}$,
- $PA$ is a function that maps each process onto an actor with $PA: P \rightarrow A$,
- $PT$ is a function that maps each process onto a tier with $PT: P \rightarrow T$,
- $N$ is a function that maps each tier onto a positive integer, with 1 standing for the left most tier and $|T|$ for the right most tier, with $N(T) := \{1, .., |T|\}$.
- $Prod$ is a finite set of product names $prod \in Prod$,
- $FProd$ is a mapping of flows onto product names with $FProd: F \rightarrow Prod$.

For each process $p \in P$, we use $\circ p$ to denote the set of ingoing flows with $\circ p = (f \mid (m, p) \in F)$ and $p\circ$ to denote the set of outgoing flows with $p\circ = (f \mid (p, m) \in F)$, with $m \in P$.

When mapping flows onto product names, the designer must consider that thread diagrams are only concerned with products subject to buyer-supplier relationships (Bolstorff and Rosenbaum 2012). However, if a product is not subject to any buyer-supplier relationship, the product must not be specified in the thread diagram. This case materializes as a flow linking two *make* processes, with the former process producing the internal product and the latter process transforming that product. Therefore, flows of internal products between *make* processes carry no label. We add this requirement to the grammar specification through a constraint on the mapping *FProd* as of Definition 1. We first define an auxiliary function *CM* to determine the type of a process (so called *management process* in the SCOR terminology, Definition 2), and then provide the constraint (Constraint 1).

**Definition 2 (Management process):** *CM* is a function that maps each process category $c \in C$ onto a management process $m \in M$, with CM={*S1→Source*, *S2→Source*, *S3→Source*, *M1→Make*, *M2→Make*, *M3→Make*, *D1→Deliver*, *D2→Deliver*, *D3→Deliver*}.

**Constraint 1 (Flow with no label):** For each flow $f=(p_i, p_j)$ with $CM(PC(p_i))=\{Make\}$ and $CM(PC(p_j))=\{Make\}$ : $FProd(f)=\varnothing$.

*3.2.2 Transformation Rules*

Transformation rules describe the actions that modellers should take to transform existing thread diagrams into the new representation. The first rule ensures that actor labels are free of product-related information. The second rule is a syntactic convention. The third rule is required for fulfilling constraint 1. The fourth and fifth rules describe actions to ensure the correct labelling of incoming and outgoing flows considering the semantics of source, deliver, and make processes. We list the rules as follows:

(1) *Actors*: Replace the product-laden label by an abstract name (e.g., replace "Tire Retailer Europe" by "Retailer Europe").
(2) *Flows*: Use the product name in singular form (e.g., "Front suspension").
(3) Flows between *make* processes carry no label.
(4) In assigning product names to flows, consider that *source* and *deliver* processes transfer products but don't transform them. For *source* and *deliver* processes with exactly one incoming and one outgoing flow, the product names must be equal.
(5) In assigning product names to flows, consider that *make* processes transform incoming products into different outgoing products. For *make* processes with exactly one incoming and one outgoing flow, the product names must be different.

### *3.3 Demonstration*

We demonstrate how to transform diagrams into the new representation. The exemplar we utilize is an extension of the supply chain shown in Figure 1 when discussing the current approach. We consider the following setup: Three suppliers deliver tires, rims, and hubs respectively, which are then transformed by the manufacturer into wheels. In the diagram developed from the original grammar, the actor labels contain all the product information. Figure 2 shows the original representation and the new representation.

The transformation proceeded as follows. We replaced the four product-laden actor labels by abstract names (rule 1). For instance, *Tire Supplier* becomes *Supplier 1*, and

*Rim Supplier* becomes *Supplier 2*. We amended each flow by the product that is transferred by its preceding process (rule 2). For instance, the *Tire* label is placed on the outgoing flow of the *Supplier 1*'s deliver process. We placed no label on the flow between the two *make* processes of the *Manufacturer* (rule 3). We preserved equivalence of incoming and outgoing products for all three *source* processes because each process has exactly one incoming and one outgoing flow (*Tire*, *Rim*, and *Hub*, respectively; rule 4). Finally, we verified that the *make* process in the manufacturer tier actually transforms its incoming products into a different product (*Wheel* is the name of the new product; rule 5).

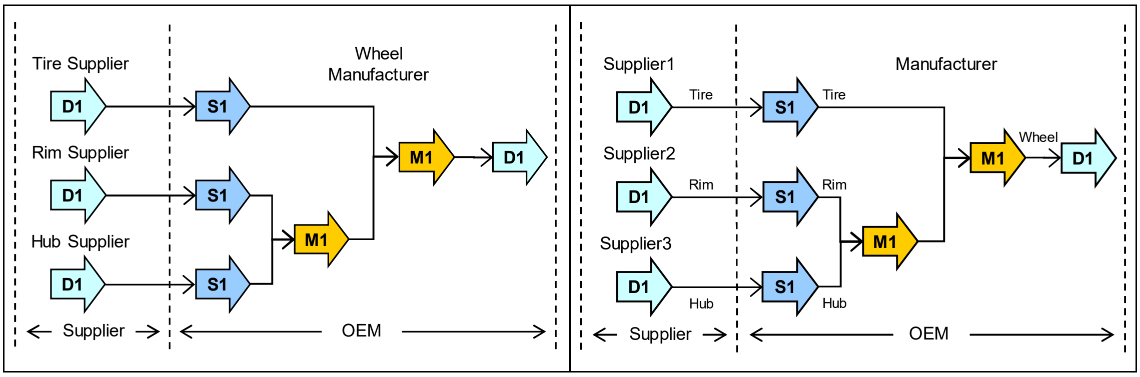


**Figure 2.** Diagrams created from the original (left) and the revised grammar (right).

## 4. Evaluation

To evaluate the proposed product representation, we conducted a laboratory experiment. Below, we discuss the hypotheses tested, the experimental method, and the results obtained.

### *4.1 Hypotheses*

We expect that the product representation using labelled flows will improve the user's understanding of the supply chain process model. We expect this effect to hold for tasks that require the user to retrieve specific product information from the diagram. Therefore, our first hypothesis is as follows:

> ***H1:*** *Product comprehension performance will be higher when SCOR thread diagrams represent products through labelled flows compared to actor labels.*

We also anticipate that labelled flows assist the user in first identifying the composite structure of the final product from the diagram and then reproducing this structure, e.g., in the form of a graph with nodes for products and arcs for relationships between products. We summarize this effect in our second hypothesis:

> ***H2:*** *Product modelling performance will be higher when SCOR thread diagrams represent products through labelled flows compared to actor labels.*

### *4.2 Experimental Method*

The experiment used a between-group design. This design allowed us to compare results obtained from the explicit-representation group (using two diagrams that represent products through labelled flows) against those obtained from the implicit-representation group (using two diagrams that represent products through actor labels). The between-group factor had therefore two levels, *explicit representation* vis-à-vis *implicit representation*.

#### *4.2.1 Participants*

The experiment is targeted at people who have some practical experience with SCOR thread diagrams and possess basic knowledge of businesses and supply chain management. The participants should have an understanding of the modelling constructs and be able to retrieve domain semantics from diagrams. In the experiment, we administered two tests for SCOR modelling knowledge to assess how well our participants met this requirement. The target group that would benefit the most from our approach are the novice analysts and our findings are generalizable only for this group. We selected students over practitioners to rule out confounding effects by participants who can bring their high levels of modelling or domain knowledge to bear. This setting is similar to prior modelling research that empirically evaluated the usefulness of alternate diagrammatic representations (e.g., Figl, Mendling, and Strembeck 2013; Mendling, Strembeck, and Recker 2012).

Our participants were 65 undergraduate students (36 males and 29 females) from the business school of a university in Western Europe. 47 participants were enrolled in a management program with IS major and 18 in an IS program. All participants were attending an *E-Business* course. The course introduced to SCOR thread diagrams through three classroom sessions. In addition, the participants had taken prior courses on conceptual modelling, business administration, and operations management. As this research deals with understanding diagrams, rather than supply chain design that would require practical experience with SCOR modelling, students from this specific course are a suitable surrogate for novice analysts. Thus, participants for the experiment were drawn from this group.

Participation in the experiment was voluntary and rewarded by adding three extra credit points to the final exam (total of 60 points). To further motivate the participants, a performance-based compensation of 20 Euros was paid to the best 20% of all participants within each group.

To evaluate the feasibility of the experiment, we ran a pilot study with 16 undergraduate students. The pilot study followed the same design as the main study, but participants worked with only one diagram for which they had to solve four product comprehension tasks. As expected, the explicit-representation group achieved higher scores ($M$=2.63, $SD$=0.92) compared to the implicit-representation group ($M$=2.06, $SD$=0.78), which suggests a medium size effect (Cohen 1988).

### *4.2.2 Measurements*

*Product comprehension performance (PCP)* was defined as the number of correct solutions to eight comprehension tasks; hence, we used an eight-item instrument for measuring PCP. Participants were asked to retrieve specific product information from the diagrams. The tasks are provided in Appendix C. In solving the four product comprehension tasks per diagram, participants had to classify diagram elements (task 2), provide frequencies (task 3 and 4), or describe product structures (task 5). Every task had a clearly defined solution and could be correctly answered by just studying the diagram (for both groups due to informational equivalence with respect to our dependent variables). To have additional assurance that understanding differences observed could be attributed to our experimental manipulation rather than other factors, task 1 for each diagram was equally easy to answer because it was not affected by the manipulation. These tasks were denoted as baseline tasks (Shanks et al. 2008). The baseline tasks were not related to product semantics but asked for the number of actors within the diagram. When presenting the results, we additionally checked to ensure that the groups did not differ on the scores for the baseline tasks.

*Product modelling performance (PMP)* was defined as the number of correct solutions to two modelling tasks (provided in Appendix C); hence, we used a two-item instrument for measuring PMP. Participants were required to identify the structure of the final products from thread diagrams and to sketch an image that best represents that structure. For instance, the correct solution for the first diagram must represent the nine products and their relationships. For each correct product we assigned a score of one-ninth, which sums up to a total score of one per diagram.

*Control variables:* We used control variables to account for individual factors. Prior empirical research suggests that several individual factors can affect diagram understanding (Figl 2017). Therefore, we wanted to make sure that our randomized assignment of participants to groups worked well so that we could rule out confounding individual-level factors in our between-group experiment. First, we assessed self-reported modelling knowledge by adopting a three-item instrument proposed by Mendling, Reijers, and Recker (2010). Second, we considered perceived usefulness as a key predictor of behavioural intentions to use SCOR. We measured perceived usefulness by a three-item instrument used in prior research (Shanks et al. 2008). For both variables, we adjusted the original items to the terminology of SCOR. Third, we administered two tests of modelling knowledge, which is a potential covariate of diagram understanding (Figl 2017). In the first test, we asked eight multiple-choice questions on the correctness of statements about the SCOR grammar. The second test provided an exemplar thread diagram for which the participants had to answer six syntactic comprehension questions.

### *4.2.3 Materials*

The materials included three parts and a supplement (which provided the grammar as shown in Table 1). The first part captured the participants' background (material provided in Appendix A). The second part included the tests of SCOR modelling knowledge (Appendix B).

The third part of our materials provided the *actual tasks materials* through two diagrams and six tasks per diagram (i.e., one baseline task, four product comprehension tasks, and one product modelling task; material provided in Appendix C, Figures C1, C2, C3, and C4). In developing the materials, we adopted guidelines for evaluating diagrams (Parsons and Cole 2005). First, the alternative diagrams were informationally equivalent with respect to our dependent variables. The diagrams provided sufficient information to complete all the tasks correctly. Second, our dependent variables PCP and PMP measured performance only with respect to the domain semantics contained in the diagrams. We created diagrams that were independent from particular domains as much as possible, i.e., by using generic labels for tiers such as "1st Tier Supplier" and "Distributor". However, we used domain words for products. Third, we used no subject matter experts as participants but novices. Fourth, the diagrams were available to participants as they worked on the tasks. The difficulty of the tasks required careful examination of each diagram.

We took care that the two diagrams contained manifestations of all grammar constructs and many of their possible combinations as follows: (1) some tiers had only one actor, while other tiers had up to five actors, (2) some actors only had either *source* or *deliver* processes, while other actors had *source/deliver* processes or *source/make/deliver* processes, (3) some processes had exactly one ingoing and one outgoing flow, while other processes had a total of up to four flows, and (4) flows existed between adjacent tiers as well as distant tiers. The diagrams contained each 5 tiers and 11 actors, while the numbers differed for flows (31 and 21) and processes (33 and 22).

#### *4.2.4 Procedures*

The experiment took place in a classroom setting. Our research objective as well as the manipulation were unknown to the participants. One of the five instructors explained the procedures and answered questions. Participants were randomly assigned to either the implicit-representation or the explicit-representation group. Limited seating capacity did not allow us to leave every second seat empty for all participants but only for one half of our participants. To further prevent copying, we counterbalanced the modelling knowledge tests (second part of our materials) and the actual tasks (third part). Thus, every two participants next to each other either first started with the knowledge tests or the actual tasks (and were assigned to different groups). In our data analysis, we additionally checked for potential order effects. The instructors made sure that there was no collaboration between participants. The experiment started simultaneously for all participants. The materials were provided on paper in two documents plus the supplement. The participants were given ample time to work through the documents. Once a participant had completed the first document (demographics plus either knowledge test or actual tasks, based on which part was administered first), an instructor collected the material and distributed the second document (again, either the knowledge test or the actual tasks). The time required was recorded by the instructors.

### *4.3 Results*

This section reports the results by first examining the conformance of the data with the assumptions of statistical tests. Then, we present the results from testing our hypotheses.

*4.3.1 Data Screening*

Table 2 shows participants' data and controls for the two groups. Overall, the self-reported modelling knowledge was moderate. Participants achieved, on average, high scores in both the grammar test (76% and 73%, respectively) and the diagram test (93% and 91%, respectively). A further inspection revealed that no difference in any variable shown in Table 2 was significant (using Mann-Whitney U-tests); hence, the assignment of participants to groups was effectively randomized.

**Table 2.** Participants' data and controls.

| | | **Explicit representation** (n=31) | | **Implicit representation** (n=34) | |
|---|---|---|---|---|---|
| **Variable** | **Scale** | **M** | **SD** | **M** | **SD** |
| Age | Years | 22.87 | 3.13 | 23.09 | 2.45 |
| Undergraduate credits | 0-180 | 117.23 | 30.07 | 108.53 | 42.64 |
| Self-reported modeling knowledge | 1-7 | 4.30 | 1.31 | 3.93 | 1.37 |
| Perceived usefulness | 1-7 | 5.54 | 0.94 | 5.06 | 1.55 |
| Grammar test | 0-8 | 6.06 | 1.53 | 5.85 | 1.52 |
| Diagram test | 0-6 | 5.58 | 0.77 | 5.44 | 1.13 |
| Time required | Mins. | 22.45 | 4.76 | 22.74 | 4.43 |

Next, we examined the reliability of our reflective multi-item instruments. To be able to combine several items into one variable, the Cronbach's alpha measure of internal consistency should be equal or greater than 0.7 (Nunnally and Bernstein 1994). We found sufficient levels of internal consistency for our dependent variables (i.e, 0.701 for PCP, 0.769 for PMP), and excellent levels for our psychometric control variables (i.e., 0.910 for self-reported modelling knowledge, 0.944 for perceived usefulness). Then, we checked the dependent variables PCP and PMP for normal distribution. Because we found departures from normality, we decided to use the Mann-Whitney U test for testing our hypotheses. This test can be used instead of the independent samples t-test, which assumes normal distribution of the dependent variable. The Mann-Whitney U test ranks all values and then calculates the sum of the ranks for each group. The test statistics indicate whether two groups differ based on the sum of the ranks.

In the final step of our data screening, we assessed correlations between the independent and dependent variables. Age and credits were not correlated with PCP/PMP, while self-reported modelling knowledge was. In addition, the scores in the grammar test were correlated with PCP/PMP, suggesting that abstract knowledge of the grammar helps in problem-solving with diagrams. Finally, task performance was not dependent on the time required.

*4.3.2 Hypotheses Testing*

Table 3 provides the results of our hypotheses testing. With respect to product comprehension performance (H1), participants using the diagrams created from the revised grammar (explicit representation) achieved higher scores than participants using diagrams created from the original grammar (implicit representation). Participants in the explicit-representation group also performed better in the product modelling tasks (H2).

**Table 3.** Results of hypotheses testing.

| | | **Explicit representation** | **Implicit representation** | **Test** | | |
|---|---|---|---|---|---|---|
| **Variable** | **Scale** | **M (SD)** | **M (SD)** | **U** | **p[1]** | **Effect Size[2]** |
| Product comprehension | 0-8 | 4.54 (1.90) | 3.18 (2.17) | 334.5 | .011 | Medium (0.31) |
| Product modeling | 0-2 | 1.63 (0.56) | 1.26 (0.78) | 330.0 | .009 | Medium (0.33) |

[1] Significant at *p*<.05 (Mann-Whitney U-test, 2-tailed).

[2] Effect size: Absolute r; medium for 0.3≤|*r*|<0.5 (Cohen 1988).

Regarding the two baseline tasks, the scores of the explicit-representation and implicit-representation groups were very similar (*M*=1.81 and *M*=1.76). A follow-up test showed no significant difference (*p*=0.661, Mann-Whitney U-test, 2-tailed). Thus, the seeding of baseline tasks that we assumed would not be affected by our manipulation, worked as expected.

Because of counterbalancing the modelling knowledge test and the actual tasks, order effects might have confounded the observed effects. Therefore, we tested for differences between participants that first started with the modelling knowledge test and participants that began with the actual tasks. For the implicit-representation group, all differences in grammar test, diagram test, and actual test were nonsignificant. For the explicit-representation group, the results were very similar except for one test becoming significant (product modelling). In summary, our results suggest that it is unlikely that learning or maturation has confounded the observed effects.

## 5. Discussion

In this section, we discuss the experimental results, implications, and limitations of our study.

### *5.1 Findings*

Our research set out to develop and empirically evaluate a product representation in supply chain process models that uses explicit labelling of product flows. Our laboratory experiment provides evidence that using the proposed explicit representation enhances product comprehension performance compared to using the implicit representation, in which products are represented through actor labels. Specifically, we find an effect of explicit labelling on the ability of diagram users to retrieve product information from diagrams. On average, product comprehension performance increased from 40% (implicit labelling) to 57% (explicit labelling). We believe this effect has practical significance considering that the diagrams were more complex (i.e., number of diagram elements and relationships) than those reported in case studies (Persson and Araldi 2009; Wang, Chan, and Pauleen 2010). We also find an effect on product modelling performance. Hence, using labelled flows, participants were more effective in sketching an image that best represents the structure of the final products. While product modelling tasks also test diagram understanding, they require further cognitive processing compared to product comprehension tasks. As expected from our theoretical analysis, product modelling performance in the experiment increased considerably from 63% to 82% (on average).

Based on our experimental results, we contribute to modelling research a novel product representation within supply chain process models, which enhances domain understanding by novice analysts. We add to the modelling literature by investigating a representational problem surrounding an essential construct of supply chain grammar, i.e., the construct for representing products. We provide a rigorous empirical evaluation of alternate product representations, which has not been carried out previously. Prior research is restricted to descriptive methods such as scenarios (Long 2014; Röder and Tibken 2006; Soffer & Wand 2007; Zdravković et al. 2011) and informed argument (Millet, Schmitt, and Botta-Genoulaz 2011; Verdouw et al. 2010) as well as case studies (Persson and Araldi 2009), which lack user participation and experimental control. We took rigorous measures to ensure internal validity, including implementing recommendations for creating the materials (Parsons and Cole 2005), and designing diagrams and tasks of various complexity and difficulty.

We believe that our study also makes a theoretical contribution. Our study is a further step to establish the boundaries of the cognitive theory of multimedia learning within modelling research (Mayer 2001; Mayer and Moreno 2003). The theory's spatial contiguity principle informed the development of our proposal and we find empirical support for its predictions. To that end, our study complements prior modelling research that tested predictions derived from the theory's principles, e.g., (Burton-Jones and Meso 2008; Figl, Mendling, and Strembeck 2013; Gemino and Wand 2005).

### *5.2 Implications*

Our research has two major implications for practice. First, we provide empirical evidence for the effectiveness of the explicit representation of products in SCOR thread diagrams. We observed considerable improvements in domain understanding. Because domain understanding from diagrams is an essential precondition for any decision-making process, our results are relevant for analysts and designers of supply chain processes and information systems. Further, the results are relevant for modelling practices, in particular with respect to choosing appropriate grammars and labelling styles. Although we considered the SCOR grammar due to its widespread application in practice, the flow construct under study is an essential part of any supply chain grammar. We believe that our findings bear potential to generalize to other grammars that concern product flow. Our approach to explicit product representation through labelled flows can be adapted to any modelling grammar that provides a construct for product flow. While our formal specification of the revised grammar and the complementing transformation rules are specific to SCOR, they provide a blueprint for revising other grammars.

Second, the transformation rules define how existing diagrams can be converted into the new representation without loss of information; hence, the rules help diagram owners in converting their current diagrams. These rules can also be implemented in modelling tools that automate the transformation or suggest labels for actors and flows conforming to the revised grammar. In addition, the modification only requires minimal additional training for diagram users, or none at all (as was the case in our experiment). Our results provide evidence that enriching flows with product labels does not increase the mental effort required for solving tasks, considering that the total number of labels per diagram increases greatly.

Our study results also have implications for future research. First, opportunities exist to evaluate our proposed product representation using other types of tasks (no extension of the representation). In our experiment, we administered tasks that allow assessing surface-level understanding of the domain because the tasks are directly concerned with domain elements represented in the diagram (Recker and Dreiling 2011). Fellow researchers can now assess deep-level understanding by using problem-solving tasks. Such tasks describe a problem in the domain and ask the user to provide explanations or solutions (Khatri et al. 2006; Leukel and Hubl 2018). Because the mental processes for answering product comprehension, product modelling and problem-solving questions are different, the effects of the proposed product representation on deep-level understanding should be explored (Khatri and Vessey 2016).

Second, the explicit representation could be extended to take product ontology into account. The meaning of words in a representation maybe different from the meaning that individual users ascribe to them. Specifically, how product names are interpreted by diagram users might depend on their prior domain knowledge and the task for which they use the diagram. Here, an ontology could be used for providing a formal specification of a set of product classes and their relationships (Fortineau, Paviot, and Lamouri 2013; Lee et al. 2006). In the presence of product ontology, product names on flows carry the semantics defined by that ontology. This semantics could help users in understanding diagrams. Future research could devise extended representations and empirically validate their usefulness.

Third, opportunities exist to study the effectiveness of alternate product representations for other types of tasks. For instance, researchers could use different problem-solving tasks (e.g., by asking for explanations or solutions for a problem in the supply chain domain) because differences in the mental processes for answering product comprehension, product modelling and problem-solving questions might affect the usefulness of diagrams, and thus should be explored (Khatri and Vessey 2016).

### *5.3 Limitations*

The limitations of our study must be noted. First, the nature of the laboratory experiment required us to study a small number of diagrams with varying complexity. This setting is similar to prior studies on diagram understanding (e.g., Agarwal, De, and Sinha 1999; Khatri et al. 2006; Mendling, Strembeck, and Recker 2012). The diagrams used were of moderate complexity so as to not confound them with many observed effects, which might require additional supply chain domain knowledge.

Second, our experiment used students, which may limit external validity. Students differ from business professionals in (1) their experience with the problem domain, and (2) their motivation to perform successfully. However, our participants had sufficient experience in the types of understanding tasks examined (acquired through attending SCOR modelling sessions). While they also completed relevant business courses, our analysis of confounding factors shows that task performance does not dependent on the individual's study progress. To overcome potential lack of motivation, we offered a considerable performance-based incentive. Our students are similar to novice SCOR users in the industry, who receive limited training in SCOR. Novice users need help in understanding SCOR diagrams and our research targets this population. In fact, using students over practitioners has been recommended to mitigate confounding effects of prior business knowledge (Burton-Jones and Meso 2008; Gemino and Wand 2005; Recker and Dreiling 2011). To allow researchers to replicate our evaluation with other groups of participants, we provide a detailed description of our experiment and the instruments used.

## 6. Conclusion

Process analysts and IT analysts increasingly use diagrammatic process models specific to the supply chain domain. Such models combine visual and textual information to assist users in acquiring an understanding of the domain semantics conveyed by the diagram. However, product representation in supply chain process models is insufficient. Current modelling approaches either lack in understandability by diagram users or expressiveness with respect to product semantics. They also lack empirical evidence for their usefulness. We address this gap in the literature by proposing a novel theoretically-derived product representation relying upon labelled flows; hence, product names are directly assigned to flows (explicit representation) instead of through other visual constructs (implicit representation). We provide a formal specification of this representation for so called thread diagrams defined by the Supply Chain Operations Reference (SCOR) model (APICS 2018) as well as transformation rules for existing thread diagrams. We report on a controlled laboratory experiment in which novice analysts had to solve understanding tasks with thread diagrams. Our experimental evaluation provides evidence for the usefulness of the proposed representation. We find improvements in solving product comprehension tasks as well as product modelling tasks, which are essential tasks for supply chain analysts. The contribution of our research is a novel product representation within supply chain process models, which enhances domain understanding.

**Disclosure statement:** No potential conflict of interest was reported by the authors.

**Funding:** The work by Joerg Leukel has been supported by the Bundesministerium für Bildung und Forschung [16KIS0083]. The work by Vijayan Sugumaran has been supported by the 2018 School of Business Administration Spring/Summer Research Fellowship from Oakland University, Rochester, MI, United States.

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## Appendix: Experimental Materials

### *Appendix A*

Demographics: Age (years); Program of study; Undergraduate credits.

Self-reported modelling knowledge and perceived usefulness: Please indicate the extent to which you agree or disagree with the following statements (7-point scale from "strongly disagree" to "strongly agree"):

- "Overall, I am very familiar with SCOR thread diagrams."
- "I feel very confident in understanding diagrams created with SCOR."
- "I feel very competent in using SCOR for supply chain modeling."
- "Overall, I think a thread diagram would be an improvement to a textual description of the supply chain."
- "I find thread diagrams useful for understanding the supply chain modeled."
- "Overall, I think the thread diagram improves my performance when understanding the supply chain modeled."

### *Appendix B*

Grammar test: Please indicate whether the following statements about SCOR thread diagrams are true or false. *(Three options: True, False, Don't Know; correct answers are given in brackets.)*

- Each process must be executed by an actor. *(True)*
- A *Make* process may be followed by a *Source* process. *(False)*
- Each process carries a 2-digit label. *(True)*
- An engineer-to-order product is of higher product specificity than a make-to-order product. *(True)*
- Tiers can be arranged from left to right as well as from top to bottom. *(False)*
- An S1 process may be followed by an M1 or D1 process. *(True)*
- Tier labels are optional. *(False)*
- An D2 process may be followed by an S2 or S3 process. *(False)*

Diagram test:

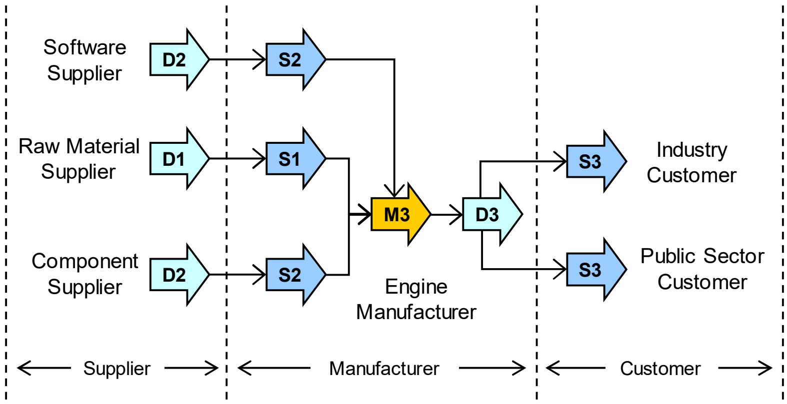


**Figure B1.** Exemplar diagram.

Consider the diagram shown above. Please answer the following multiple-choice questions (one correct answer per question) *([x] signifies the correct answers*):

(1) What is the number of actors in this supply chain? a) 4, b) 5, c) 6 [x], d) 7

(2) Which actor sells products to more than one actor? a) Software Supplier, b) Raw Material Supplier, c) Component Supplier, d) Engine Manufacturer [x]

(3) What is the product specificity of the Make process in the Manufacturer tier? a) Stocked product, b) Make-to-order product, c) Engineer-to-order product [x], d) Over-the-counter product

(4) Which statement is correct for the relationship between Software Supplier and Raw Material Supplier? a) The two are competitors, b) The two deliver products to Engine Manufacturer [x], c) The two deliver stocked products, d) The two deliver make-to-order-products.

(5) Which statement is correct for Industry Customer? a) Is a competitor of Public Sector Customer, b) Is the most important customer of Engine Manufacturer, c) Buys products from Engine Manufacturer [x], d) Sells products to private customers.

(6) Which statement is correct for the Make process in the Manufacturer tier? a) Transforms products into one final product [x], b) Transforms products into two different final products, c) Is a very complex and lengthy process, d) Produces a make-to-order product.

*Appendix C*

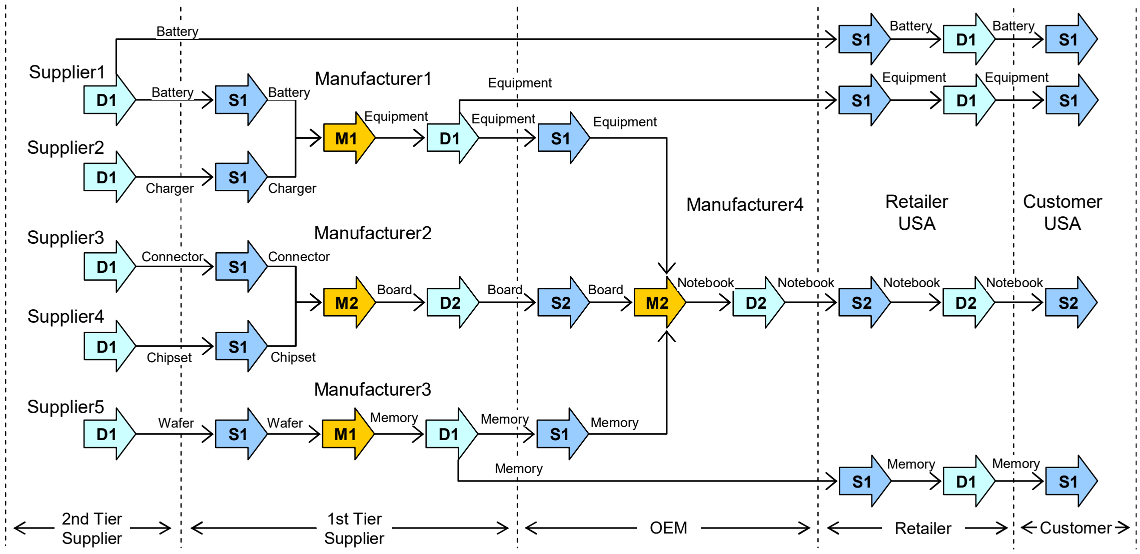


**Figure C1.** Diagram 1 for the explicit-representation group.

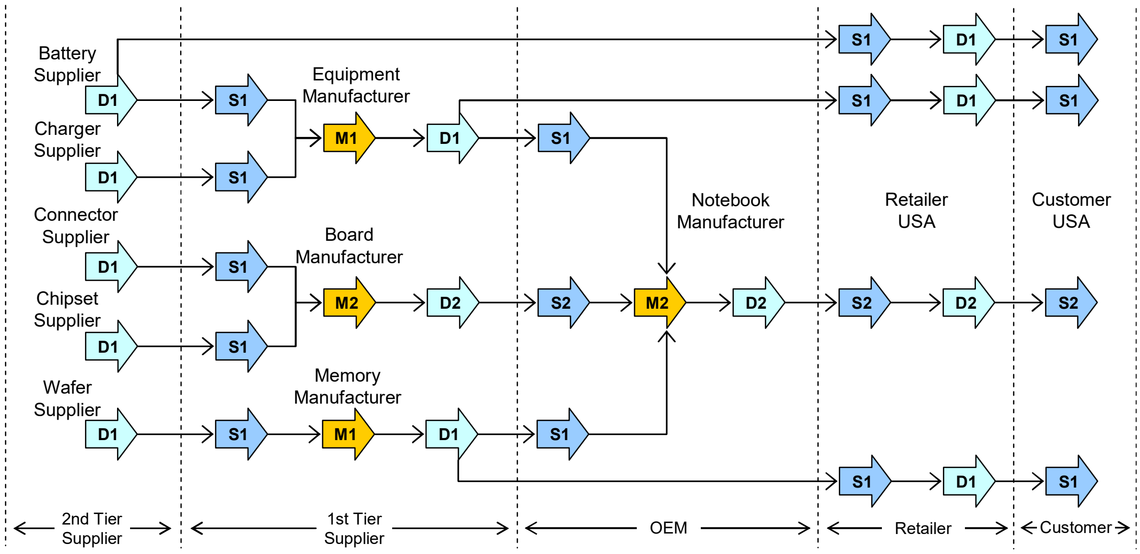


**Figure C2.** Diagram 1 for the implicit-representation group.

<u>Comprehension tasks on Diagram 1:</u> *(Correct answers are given in brackets)*

(1) Give the number of actors within this supply chain. *(11)*

(2) Give the product specificity of the deliver process within the OEM tier. *(Make-to-order)*

(3) Give the number of products that are subject to this supply chain. *(9)*

(4) Consider the product that is delivered by the D1 process of the actor Supplier2/Charger Supplier. Give the number of all other processes that are to some extent concerned with this product. *(12)*

(5) List all products that are sourced from the actor within the OEM tier and describe the structure of each of these products. *(Equipment: Battery+Charger, Board: Connector+Chipset, Memory: made of Wafer; 50% for products; 50% for structure; one-sixth each.)*

Product modelling task on Diagram 1: Sketch an image that best represents the structure of the final product. *(The answer must represent the nine products and their relationships; one-ninth per product.)*

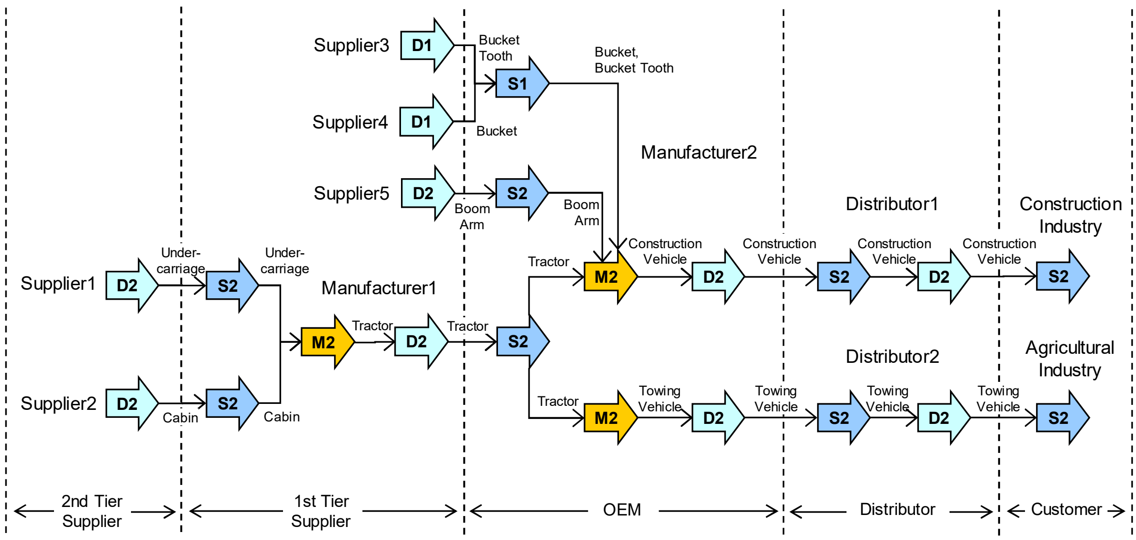


**Figure C3.** Diagram 2 for the explicit-representation group.

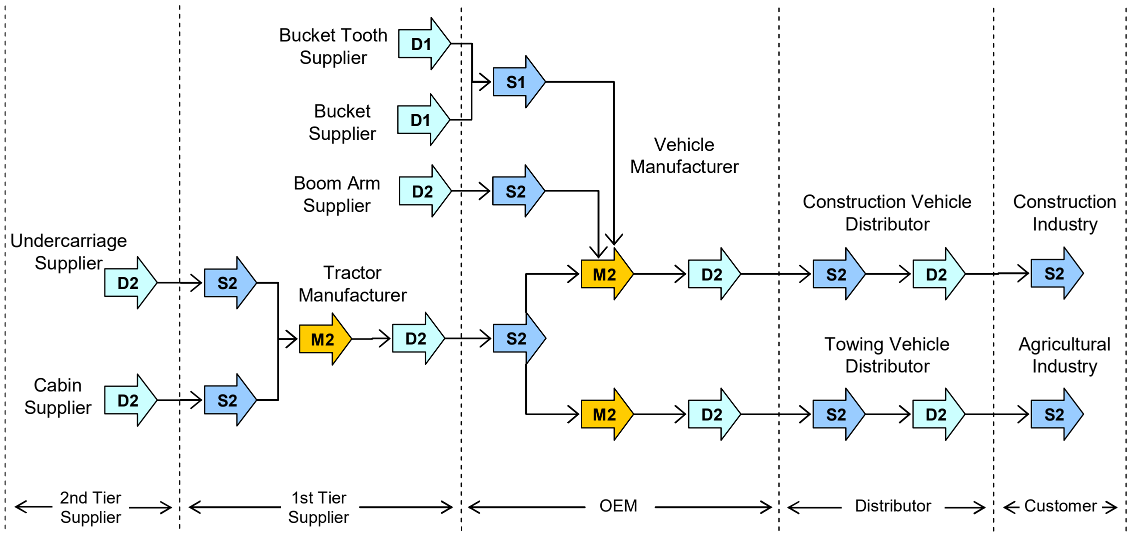


**Figure C4.** Diagram 2 for the implicit-representation group.

Comprehension tasks on Diagram 2: *(Correct answers are given in brackets)*

(1) Give the number of actors within this supply chain. *(11)*

(2) Give the number of processes that transform two or more different products into a new product. *(2)*

(3) Give the number of products that are subject to this supply chain. *(8)*

(4) Consider the product that is delivered by the D1 process of Supplier4/Bucket Supplier. Give the number of all other processes that are to some extent concerned with this product. *(6)*

*(5)* List all products that are sourced from the actor within the OEM tier and describe the structure of each of these products. *(Bucket: no structure, Bucket Tooth: no structure, Boom Arm: no structure, Tractor=Undercarriage+Cabin; 50% for products; 50% for structure; 1/4 each).*

Product modelling task on Diagram 2: Sketch an image that best represents the structure of the final products. *(The answer must represent the eight products and their relationships; one-eighth per product.)*