Supply Chains Management 4.0 in the Manufacturing Industry: from formal specification to digitalization

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Abstract

Industry 4.0 technologies provide new opportunities for innovation of supply chains. However, without the aid of models for the representation and understanding of relationships and interactions that develop among the active entities in the chain, these technologies do not unfold their full improvement potential. To help bridge the gap that exists between theoretical studies on supply chains and the implementation of management systems based on Industry 4.0 technologies, the paper proposes a top-down methodology. The methodology integrates the definition of formal specifications based on the concept of interaction type, the modeling and implementation of cyber-physical production systems, and the provision of digital services for the horizontal/vertical integration of processes. The case study discussed in the paper shows the application of the methodology to the supply chain processes of the automotive industry, highlighting the benefits deriving from the design, implementation, and use of new software applications based on the interaction type model, the Internet of Things and Cloud Computing technologies.

Keywords: Supply Chains, Horizontal and Vertical Integration, Industry 4.0, Supply Chain Management 4.0

1. Introduction

The increasing usage of Information and Communication Technologies in the logistics domain, and the advent of the fourth industrial revolution known as Industry 4.0, lead researchers to evaluate the impact of Industry 4.0 on logistics, supply chains, and supply chain management systems [1] [2]. In the manufacturing industry, the transformation toward Industry 4.0 is powered by nine foundational technology advances that have been applied for the realization of cyber-physical production systems aiming at more advanced planning, control, and automation of the production process as well as at the provision of new digital services [3]. This has led to benefits in terms of customized mass production, increased speed, better quality, and improved productivity [4]. Apart from the processing and assembly operations necessary to transform raw materials and semi-finished goods into finished products, a relevant part of the production process concerns logistics problems that must be solved in ordering materials, moving the work through the factory [5], and delivering the finished product. Therefore, there is ground for introducing Industry 4.0 concepts and technologies into supply chains (SC). Indeed, Industry 4.0 is predicted to bring new challenges and opportunities for future SC and new benefits are expected from the realization of smart and sustainable supply chain management in Industry 4.0 [6].

In recent years, an important research effort has been made by scholars to define the fundamentals of Logistics 4.0. In the review of Chauhan e Singh [7] of the 344 analyzed papers, 82% are conceptual studies while 8% concern empirical studies (case studies, surveys, and interviews); the review of the literature contributes 5% and the remainder contributes to works on mathematical models or experiments. From this review emerges that a relevant part of Logistics 4.0 is devoted to conceptual and theoretical aspects with little coverage on the design and implementation of a new generation of supply chain management systems. This lack is confirmed in [8] which finds limited research linking Industry 4.0 to SC, and in [1] which highlights the need for studies on the implementation of Industry 4.0 in supply chain networks.

Within the framework of research based on the Viable System Approach [9] [10], this work proposes a top-down methodology for the formal specification, modelling, and implementation of supply chain management systems based on the application of Industry 4.0 concepts and technologies to supply chain management systems. The main purpose is to offer a contribution to bridging the gap that exists between the works that explore conceptual or theoretical aspects related to the management of supply chains and the implementation of logistics systems based on Industry 4.0 technologies. The methodological steps show how to specify, design, and implement digital services that improve data sharing and collaboration across end-to-end supply chains in a Logistic 4.0 scenario. A relevant aspect of this research concerns horizontal/vertical integration of the processes that are carried out in the production chain of a manufacturing industry [11]. The study of the structure/system dichotomy, the consonance property, and the interaction type model from the system theory, allow us to gain a deeper understanding of how to increase the integration degree of systems and processes that implement the supply chain. This higher integration degree positively influences the important property of visibility in SC [12] that brings the benefit of improved collaboration across end-to-end supply chains.

The first confirmations on the benefits that can be obtained from the application of the methodology for the application of Industry 4.0 to supply chain management systems of manufacturing industries came from the case study discussed in the paper; the case study shows the implementation of digital services in a manufacturing industry where a new software application, based on the interaction type model, the Internet of Things and Cloud Computing, has been implemented to improve the supply chain management processes.

The paper is organized as follows. The theoretical background in Section 2 reviews the fundamental definitions of SC and SC management (SCM), discusses the systemic interpretation of a SC and evaluates the state of the art of Industry 4.0 SCM applications. The next three sections describe the top-down methodology for the formalization, design and implementation of a SCM system in the Industry 4.0 scenario. The steps for the formal specification of structure and dynamics of an SC are presented in section 3 on the basis of the interaction type concept. Then, a model of a cyber-physical system for the supply chain management of a manufacturing industry is introduced in section 4. On the basis of the two previous models, in section 5 we discuss the design step of a software framework for the digitalization of SC services. Finally, in section 6, we exemplify the implementation of a new software application for the SCM of a manufacturing industry starting from an interaction type model implemented by means of the Internet of Things and Cloud Computing technologies. The case study has been developed during the SMART INDUSTRY 4.0 project aiming at the horizontal/vertical integration of processes enacted within the SC of an Italian automotive industry. A discussion on the positive implications of this research and possible future developments closes the paper.

2. Theoretical background

The theoretical background is divided into three sections discussing fundamental definitions of SC and SCM, the systemic interpretation of a SC, and the application of Industry 4.0 technologies to logistics, SC, and SCM. Without claiming to be exhaustive, the following definitions are useful to develop our systemic vision in the study of SC and SCM.

2.1 Fundamental definitions

The essential constituents of a supply chain are the organizations that make it up, the relationships between them, the products, and services that flow along the chain with the aim of providing value to the end customer. The following definition is due to Lu [13].

Def.1: A SC is a group of inter-connected participating companies that add value to a stream of transformed inputs from their sources of origin to the end products or services that are demanded by the designated end-customer.

Typically, the participants to a SC do not belong to the same business ownership, and hence there is legal independence in between. In the framework of a SC, *logistics* includes all the activities required to move products and information to, from, and between partners [14]. The definition of SC proposed in [15] is different from the previous one as it takes into account the nature of the exchanges that take place along the supply chain:

Def.2: A SC is defined as a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer.

In this definition, the authors assume that the smallest SC, “a direct supply chain”, consists of three entities (e.g.: a company, a supplier, and a customer) that interact with each other in several ways; augmented forms of SC include other entities such as suppliers of the immediate supplier and customers of the immediate customer. It is worthwhile to underline that the terms logistics and SCM have been often used interchangeably. Larson and Halldorsson published a paper [16] in which four perspectives of logistics versus SCM are identified: Traditionalist, Re-Labeling, Unionist, and Intersectionist. In the traditionalist perspective, SCM is positioned within logistics, while the re-labeling perspective simply renames logistics into SCM because of the significant evolution of logistics. The unionist perspective treats logistics as part of SCM while the intersectionist perspective tries to make the two terms coexist by assigning them a different meaning. Today, the unionist perspective seems to gain more consensus because SCM is considered an overarching concept that links together multiple processes to achieve competitive advantage while logistics refers to the movement, storage, and flow of goods, services, and information within the overall supply chain [14].
Lambert [17][18] identifies eight essential supply chain management processes ranging from customer relationship management to returns management. He emphasizes that the SC is not a business function, it

is a network of companies and SCM is the implementation of cross-functional relationships with key customers and suppliers in that network. This point of view brings him to define SCM as follows:

Def.3. SCM is the management of relationships in the network of organizations, from end customers through original suppliers, using key cross-functional business processes to create value for customers and other stakeholders.

This is a high-level definition that focuses on the management of relationships and processes within the network of organizations. SCM is a wide research field that can be studied from several viewpoints. One of the most studied concepts in SCM is *Supply Chain Visibility* (SCV) because of its relevance for effective SCM. A systematic review of the supply chain literature is conducted in [19] to identify the characteristics and the effectiveness of SCV. The concept of SCV has also been used in [12] to explore its impact on sustainable SC ecosystems. A SC with a high degree of SCV is also known to be transparent. New [20] observes that people from company leaders to interest groups to consumers are interested to know something, if not everything, about a product's origins. Dorey [21] discusses how transparency, although involving risks and increased cost, has been implemented by important companies because it is capable of improving SC labor practices.
Compared with other definitions of SCV the following, proposed in [22], is more precise and suitable for the systemic interpretation of SC and SCM explored in the following.

Def.4. SCV is the identity, location, and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times for these events.

SCV has also been studied more or less explicitly from the context-awareness perspective. In [23], context-aware services in the SCM are proposed as a means to achieve more quick and timely responses, which will facilitate collaboration among SC partners. Recently, the notion of context-awareness has been also used to explore sustainable supply chain visibility [24].

2.2 Systemic interpretation of a supply chain

From a systemic point of view, a SC can be perceived as a set of elements and relationships among elements. In [25], the authors propose a systemic approach to SCM to take advantage of the benefits derived from collaboration. Their work is based on the combined application of the Beer's Viable System Model and the Goldratt's Theory of Constraints where the first allows the definition of the systemic structure of the SC and orchestrates the collaboration, while Theory of Constraints implements the systemic behaviour. Recently, a systems dynamics approach has been utilized to model an Industry 4.0-adapted SC by including the effects of different barriers and drivers of Industry 4.0 on SC dynamics [1]. As regards the modeling part of an SC, our work refers to the research line of the systems theory known as Viable System Approach. In particular, we will leverage two of its ten principles [26]:

- *Structures and systems*: Every organization is characterized by a structure constituted of a set of individual elements with assigned roles, activities, and tasks that are performed in compliance with rules and constraints. From the structure, a system can emerge by the activation of relationships into dynamic interactions with external supra-systems and internal sub-systems.

- *Consonance and resonance*: the term consonance refers to the potential compatibility between systems elements; it thus refers to a static vision of a potentially harmonious relationship. For system survival, real systems harmony needs to be achieved as resonance, which refers to elements operating in a distinctive fashion for a single purpose.

The first two definitions of the previous section, and indeed any definition of SC in the literature, share the fact that a SC is made of structure (static aspects) and system (dynamic aspects) where the structural aspects lead back to the participating organizations and the relationships between them while the dynamic aspects focus on the processes. One important aspect of the "structure and systems" principle is that the structure-system dichotomy allows to simplify the investigation of a phenomenon and recognize its scope and implications [27]. We will exploit this principle in section 3, first focusing our attention on the structure of a SC and then on its dynamic aspects. On the other hand, the awareness of the structural compatibility (consonance) between system elements and of the harmonious interaction among elements can be used to facilitate the design and implementation of an SCM system.
The works presented in [28] contribute to the debate on the structure-system dichotomy that animates the Viable System Approach community. The key concept of *interaction type* is interpreted as a bridge linking the relationship concept (structural) to that of interaction (systemic concept). We will use the interaction type model to deepen our understanding of *Def.1* and *Def.2* making it possible to specify the nature of exchanges that take place in a SC and how they can be formalized and analyzed to reach a better collaboration between the active entities of a SC.

2.3 Industry 4.0 and its application to supply chain management systems

The term Industrie 4.0 was first used in 2011 at the Hannover Fair and the topic has grown every year in industry and academia. [29] [30]. The final report of the Industrie 4.0 Working Group [31] highlights how the introduction of the Internet of Things (IoT) and Internet of Services (IoS) into manufacturing inaugurated the fourth industrial revolution. Another fundamental concept of Industrie 4.0 is that of Cyber-Physical Systems (CPS). Lee points out that CPS essentially are integrations of computation and physical processes where embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa [32].
The following definition, due to Hermann, Pantek and Otto [33], illustrates the key aspects of the Industrie 4.0 paradigm:

Def. 5. Industrie 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with humans in real-time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain.

In manufacturing, some authors prefer to use the terms Industrial Internet of Things (IIoT) [34] and Cyber-Physical Production Systems (CPPS) [35] [36], instead of IoT and CPS respectively, because they are more specific with respect to the industrial application domain. We shall use IIoT and CPPS in the case study as well as the term Industry 4.0 that is in common use nowadays.
The application of Industry 4.0 technologies to SC, still in progress, has an evolution similar to what has occurred for traditional logistics and SCM systems. First, the technologies of Industry 4.0 have been applied to logistics. In [37], the authors observe how since the inception of the Industry 4.0 era, there have been investigations about its application to logistics and SC. They discuss the evolution from

Logistics 1.0 to Logistics 4.0 and propose a model that illustrates the relationship between different eras of logistics. The term *Logistics 4.0* in [38] is referred to as the combination of using logistics with the innovations and applications added by CPS. The importance of CPS, IoT, and IoS in innovative logistics solutions is highlighted in [39] where a definition of Logistics 4.0 that mimics *Def.5* is proposed.

The term *Supply Chain 4.0* is introduced in [8] to emphasize the relationships between Industry 4.0 and SC identifying the key elements that would form the foundation for the Supply Chain 4.0. The authors also propose two inter-related frameworks: the Supply Chain 4.0 conceptual framework and the Supply Chain Maturity framework. Moreover, they suggest 24 further research directions for researchers interested in Supply Chain 4.0.

The wider scenario in which we can introduce Industry 4.0 technologies in SC is that of SCM systems; it concerns not only the movement of materials (the domain of logistics) and the harmonious collaboration between the participant in a SC (the domain of supply chain) but also, according to *Def.3*, the management of relationships in the network of organizations using key cross-functional business processes.

In fact, the fundamental concepts of *Def.2* and *Def.3* can be found in [40] where SCM includes all of the logistics management activities, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance, and information technology.

For what concerns the application of Industry 4.0 to SCM, the definition of *Supply Chain Management 4.0* (SCM 4.0) together with the technological elements for it are proposed in [41]. Again, the focus is on the application of IoT and IoS to build interconnected and transparent systems. A peculiar aspect of SCM 4.0 regards the use of mobile applications. As underlined in [42], there are opportunities to change or extend traditional SC with mobile technologies using, for example, smartphone apps, cloud platform, IoT, and IoS to create new mobile applications for SCM 4.0. The effects of Industry 4.0 on the SMC processes of procurement, production, warehousing, transportation, and fulfillment are analyzed in [43].

3. Formal specification of supply chains

Companies that operate in a SC context usually adopt SC models to specify the flow of goods and services along the SC. An industrial standard for the definitions of supply chain processes is the SCOR model, the
first cross-industry framework for evaluating and improving enterprise-wide supply-chain performance and
management [44] [45].

Although widely adopted, the SCOR syntax and semantics has been judged not well defined; therefore in [46] the mapping of SCOR supply chains onto graphs to formalize the semantics of SCOR is used to verify the correctness of SCOR models. Our proposal for the formalization of SC models is founded on the interaction type model [28].

3.1 The main concepts of the interaction type model

The fundamental feature of the interaction type model is that it constitutes a bridge linking the relationship concept to that of interaction. The structural and dynamic nature of the relationships between elements of a system is deepened providing details on the form and content of messages that allow cooperation between actors in a complex system such as a SC. The main concepts on which the model is based are the following:

- *Active entity:* an organization, an individual, or an automated component capable of performing a behavior during interaction with other active entities;
- *Relationship*: a logical or physical connection between the components of a structure. Through relationships, communication becomes possible, thereby sustaining the interaction between active entities;
- *Interaction:* a concrete action between two active entities in order to reach a goal;
- *Interaction type:* the structural element that gives form to one kind of interaction. This form qualifies one or more interactions in the sense that it provides an external shape or configuration to the interactions of that kind. The structure of an interaction type can be suitably represented by considering the structure of messages between active entities.

An interaction type can be simple or aggregate. A *simple interaction type* represents the structure of an atomic interaction between two active entities. Since an interaction can be seen as an exchange (of goods, energy, data, money, etc.), the interaction type concept is useful to provide formality to the notion of upstream and downstream flows of *Def.2*. A simple interaction type is defined as follows:

$$itName = \{activeEntity1, activeEntity2, goal, messageStructure, constraints\}$$

where *messageStructure* qualifies the nature of exchanges between *activeEntity1* and *activeEntity2* to reach a *goal*. The symbol *constraints* represents a set of constraints that act as a guard for the activation of interactions of that type. By means of it, we enable or not the activation of the interaction (the dynamic exchange) between active entities.
An *aggregate interaction type* is defined as a set of two or more interaction types. In the following definition, the symbol *goal* represents what can be achieved by means of the whole set of interactions in *setOfInteractionTypes*:

$$aitName = \{activeEntity1, activeEntity2, goal, setOfInteractionTypes, constraints\}$$

By means of *constraints,* we enable or not the activation of the interaction belonging to the aggregate. An aggregate interaction type has a hierarchical nature; this also means that a high-level *goal* can only be reached when goals (*goal1*,…, *goaln*) belonging to the low-level set of interaction types are achieved.
At a given level, an aggregate interaction type is the composition of interaction types at a lower level. The last level of the hierarchy contains only simple interaction types.

3.2. Methodology

In accordance with the Viable System Approach, a systemic structure is specified by identifying the components and the role that the components assume in the structure as well as the relationships that bind the components together. The aspect that is explored here concerns the study of how the interaction type model contributes to a deepened understanding of the structure and dynamics of a SC. The methodological proposal for the formal specification, design and implementation of a SC and a SCM 4.0 system of a manufacturing industry comprises the following steps:

1. Structure of a supply chain
   1.1. Identification of supply chain active entities
   1.2 Identification of relationships
   1.3 Specification of simple interaction types

1.4 Specification of aggregate interaction types
1.5 Horizontal and vertical integration
2. Dynamics of a supply chain
3. Design of the SCM 4.0 system
3.1 CPPS modeling
3.2 Design of the software architecture
4. Implementation

To explain the methodological steps, we will make reference to an augmented form of direct supply chain [15] where the participants are a supplier, a manufacturing industry, a customer, and a transport company. The design and implementation of a case study in the automotive sector in sections 4 and 5 respectively, shows how to fill the gap between the formal specification of a SCM system and the realization of a software application for SCM based on Industry 4.0 technologies.

3.2.1. Identification of supply chain active entities

<u>Active Entity</u>	<u>Role</u>
`Supplier`	provider of raw material
`Manufacturing Industry`	production of the final products
`Road Transport`	ground transportation
`Customer`	final consumer

3.2.2 Identification of relationships

The following list identifies the main relationships among participants. Each relationship is represented by its name and a couple of participants. The observable events in the SC happen in the context of the identified relationships where the `Manufacturing Industry` starts, for example, the procurement of raw material process and the delivery of the final product to the `Customer`. The name of each relationship evokes its main goal.

`R1. Raw material supply: (Supplier, Manufacturing Industry)`

`R2. Raw material withdrawal: (Supplier, Road Transport)`

`R3. Raw material transport: (Road Transport, Manufacturing Industry)`

`R4. Final product transport: (Road Transport, Customer)`

`R5. Final product supply: (Manufacturing Industry, Customer)`

3.2.3 Specification of simple interaction types

In this step, the exchanges between participants in the supply chain are examined in pairs, using the concept of simple interaction type. As the interaction type model states that the structure of a relationship can be specified by a set of interaction types (simple or aggregate), we first will depict an example of how two simple interaction types can define the structure of the relationship `Raw material supply`. The first interaction type named `Supply Order` represents all instances of supply orders that are submitted by the processing industry to the supplier to achieve enough raw material. The constraints must hold so that the supply can be considered valid by the participants whatever be the instance of `Supply Order`. The second interaction type, `Raw Material Audit`, specifies the check that the manufacturing industry puts in place to verify if the supply meets the request.

```
Supply Order =

  {Active entities: (Supplier, Manufacturing Industry),
   Goal: to achieve enough raw material,
   Message: supply order,
   Constraints:c1)Supplier and industry have an active supply agreement,
               c2)Delivery time < X days}
```

```
Raw Material Audit =

   {Active entities: (Supplier, Manufacturing Industry),
    Goal: to check if the supply is compliant with the request,
    Message: start of inspection verification,
    Constraints: c1)the raw material is in the industry availability}
```

The `Raw material withdrawal` relationship between `Supplier` and `Road Transport`, can be described by means of a single interaction type named `Withdrawal`. The specification assumes that the interaction between the participants can start when the `service order` released by industry is in the availability of both.

```
Withdrawal =

   {Active entities: (Supplier, Road Transport),
    Goal: to move the raw material from the Supplier to the industry,
    Message: service order,
    Constraints: c1) the service order,released by the industry,is available
                     to both the Supplier and the Road Transport,
                 c2) max. Y days, from reception of service order, to the raw
                     material delivery}
```

The model is flexible enough to represent several kinds of interactions. As stated by *Def.2*, in a supply chain several participants are involved in the upstream and downstream flow of products, services, finances and/or information. The following interaction type differs from the previous in that a finance flow is taken into account instead of a material flow. The active entities are generically represented by the variable `X` and `Y` to indicate that this structure is appropriate for any couple of participants. If `X` and `Y` acquire the values `Supplier` and `Manufacturing Industry` respectively, then `Payment` is the third example of interaction type that provides structure to the relationship `Raw material supply`.

```
Payment =

   {Active entities: (X, Y),
    Goal: to pay for a supply of goods or services,
    Message: Payment for the supply provided by X is required by Y,
    Constraints: c1) the invoice has already been sent from X to Y,
                 c2) the payment is due within 30 days from receipt of invoice}
```

3.2.4 Representation of hierarchies: aggregate interaction type

Relationships involving more than 2 active entities are often organised in a hierarchical form. The way to organize these hierarchies depends on the point of view of each active entity that the analyst must take into account when determining the structure of the SC.

Fig. 1.a) captures the points of view of the `Supplier` and `Manufacturing Industry` and reflects the fact that, during the movement of raw material, all the observable interactions among the involved active entities derive from the activation of the `Raw material supply` relationship. The interaction process starts at level 0 when a raw-material purchase is triggered by the `Manufacturing Industry`. In the context of the relationship `Raw material supply`, both active entities see their relationships with `Road Transport` as subordinate. Fig. 1.b) shows the same pattern that includes the names of interaction types that give structure to the multi-party relationships.

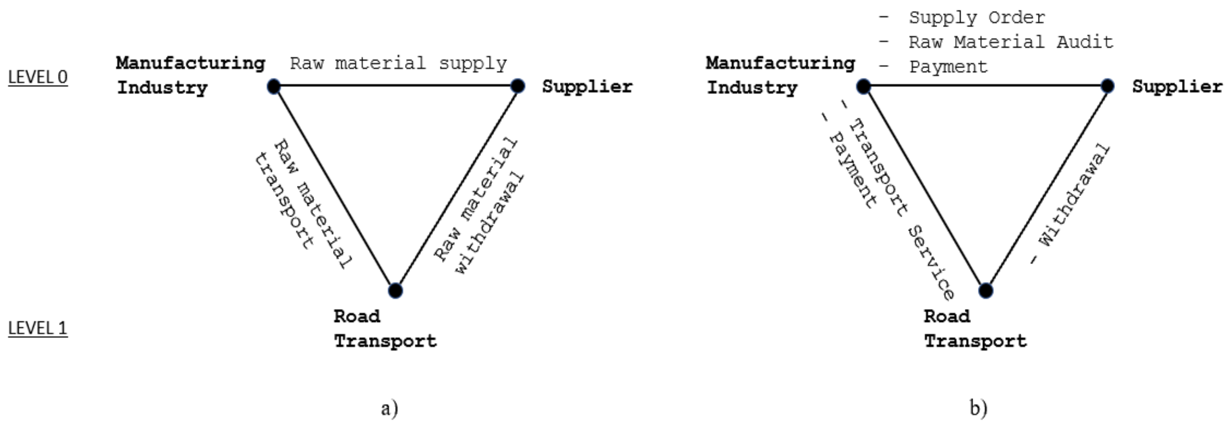


Fig. 1. a) Principal and subordinate relationships. b) Structuring the relationships using interaction types.

The aggregate interaction type `Raw Material Purchase` can be added to the three simple ones specified in fig. 1.b). It concerns the main aspects of raw material movement from the `Supplier` to the `Manufacturing Industry`.

```
Raw Material Purchase =

   {Active entities: (Supplier, Manufacturing Industry),
    Goal: to buy raw material supply,
    SetOfInteractionTypes: {Supply Order, Withdrawal, Transport Service,
                            Payment(Manufacturing Industry, Road Transport)
                            Raw Material Audit,
                            Payment(Manufacturing Industry, Supplier)}
    Constraints: select all, sequence}
```

Note that the aggregation expresses a high-level goal (`to buy raw material supply`) that can be achieved only when the set of low-level goals that appear in the set of its simple interaction types is reached:

```
1.    to achieve enough raw material;
2.    to move the raw material from the supplier to the industry;
3.    to check if the supply meets the expected quality;
4.    to pay for a supply of goods or services.
```

In the same way, the exchanges of messages between parties are not reported in the aggregation but in the specification of simple interaction types. The constraints `select all` and `sequence`, state that all the members in `SetOfInteractionTypes` must be activated from left to right as they appear in the set specification. Other circumstances could require the selection of one or more members in the set. In such a case, the constraint `choose(names)` can be used. This is the case, for example, when we have to decide a payment modality (cash on delivery, bank transfer, prepaid card) in the scenario of online purchases.

3.2.5 Horizontal and vertical integration

In the scenarios where the Industry 4.0 paradigm is used to innovate production systems [47] and SC [48], system integration plays an important role, especially for what concerns the Industry 4.0 capability to warrants vertical, horizontal and end-to-end integration [11] [49]. From a structural point of view, the horizontal integration across companies and the vertical integration from the enterprise level to the shop floor, up to the machine level, are the pillars on which to build collaboration between organizations, humans, and machines. Horizonal and vertical integration has many facets and can be studied from several points of view: SC, business process, production and handling systems, CPS, SCM software platform, data networks, and computing resources. This is why seamless integration of information flow between the horizontal layer and the vertical layer is very difficult to obtain. Mazak and Huemer observe that there is a lack of appropriate concepts for horizontal and vertical integration and that seamless integration of various stakeholders along the SC is needed [50]. In this sense, the interaction type model can provide a contribution to formally specify the structural elements of horizontal and vertical integration in a SC clarifying how the active entities interact with each other.
The point of view of horizontal and vertical integration for the SC of a `Manufacturing Industry` is shown in Fig. 2. In it, the interaction process is developed considering three levels. At level 0, we represent the relationships across the set of companies that operate "externally" to the active entity `Manufacturing Industry` and describe how a raw material purchase is delivered to the `Processing Industry` and how finished products are delivered to customers. At level 1, on the other side, we see an internal and vertical view of the company, where the interactions are developed internally with the structural relationships that bind the various `Manufacturing Industry` organizational units `(Inbound Logistics, Production, Warehouse, Outbound Logistics.` The active entity `Machine,` placed at level 2, receives from the Local Area Network the component of the production order known as “part program”; this is a set of instructions to be executed on the computer numerical control (CNC) processor of the machine tool so that the raw material can be transformed. The simple interaction types below exemplify how interactions happen in the SC.

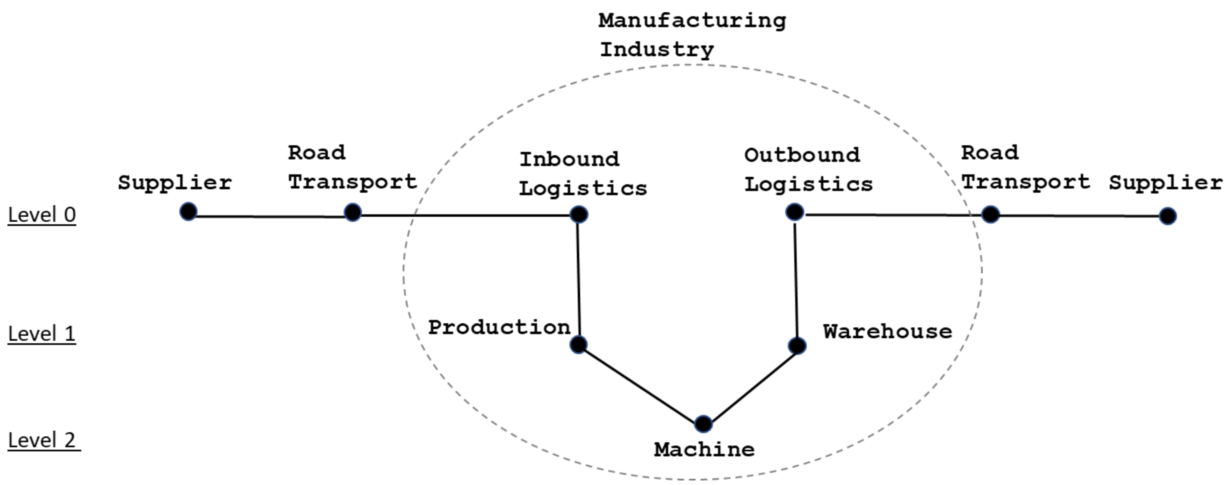


Fig. 2. Horizontal and vertical integration in a supply chain.

<u>Level 0 - Level 1</u> (vertical view)

```
Internal Material Movement =

   {Active entities: (Inbound Logistics, Production),
    Goal: move the raw material to the Production department,
    Message: authorization to move the raw material
    Constraints:
       c1) the raw material is available at the Inbound Logistics
       c2) the material is sent on the data established by the production plan}
```

<u>Level 1 - Level 2</u> (vertical view)

```
Loading Part Program =

   {Active entities: (Production, Machine),
    Goal: load the part program to the workstation control system,
    Message: part program,
    Constraints: c1)the part program is available at the Production department
                    and the data network is in operation}
```

<u>Level 0</u> (horizontal view)

```
Transport Service =

   {Active entities: (Outbound Logistics, Road Transport),
    Goal: to move finished products from the industry to the customer,
    Message: service order,
    Constraints:
       c1) the service order, released by the industry, is available to
           both: Outbound Logistics and Road Transport,
       c2) max. Z days from the withdrawal of finished product to delivery}
```

It is worth noting that the relationships that have entities active on two levels guide the analyst in changing focus from a horizontal perspective that considers the set of companies that operate "externally" to the active entity `Manufacturing Industry` to a vertical view of the company (and viceversa), across different organizational units of the `Processing Industry`.

3.2.6 Dynamics of a supply chain

For the study of the dynamic properties of a system, we discuss the way interaction type specifications rule systemic interactions that can be triggered as relationship activations between the active entities in the supply chain. A generic observer can understand when a structure initiates a behaviour (the structure in action) when an event generated by some active entity occurs. If the rules that specify the functioning of the system establish that the system must react to the event that has occurred, then the observer will perceive an action in response to the event and the dynamic evolution of the system state over time. The class of systems we are describing is that of discrete event reactive systems, and the active entity that generates the trigger event is the "initiator of the interaction". In the example below, two instances `i1` and `i2` of the simple interaction type `Supply Order` are observed at time `t1` and `t2` respectively; both are initiated by the active entity `Manufacturing Industry`, and the generated event corresponds to the reception of the message content of `i1` by the active entity `Supplier`. Although the interaction type that governs the exchange, `Supply Order`, defines the form of all messages that must be exchanged and the generic constraints that must be satisfied (the interaction structure), the information content of the individual interactions `i1` and `i2` is different because the need of those who initiated the interaction at time `t1` is different from that at time `t2`.

```
i1(t1) = {(Supplier, Manufacturing Industry),
     "to achieve enough raw material",
     "supply of 350 pieces of aluminium blocks 20x45 cm",
      c1 = contract deadline for the supply of aluminium blocks: 2022-06-30,
      c2 = the supply must take place within 15 days}

i2(t2) = {(Supplier, Manufacturing Industry),
     "to achieve enough raw material",
     "supply of two steel coils",
      c1 = contract deadline for the supply of steel coils: 2022-12-31,
      c2 = the supply must take place within 2 months}
```

4 A model of cyber-physical system for SCM

One of the key components for Industry 4.0 is that of CPPS [33]. CPPS are considered key components for SCM 4.0 systems too because of their capability to connect the physical and the virtual world together [51] so that computations are integrated with physical processes. The following definitions, due to Cardin [35], is suitable to qualify CPPS that comprise a manufacturing SC:

Def. 6. Cyber-Physical Production Systems are systems of systems of autonomous and cooperative elements connecting with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks, enhancing decision-making processes in real-time, response to unforeseen conditions and evolution over time.

The model of cyber-physical production systems for SCM of Fig. 3 is inspired by the previous definitions, and the interaction type model. Focusing on the manufacturing industry and then on the SC participating companies, the model is able to represent the following aspects. When there is need of raw materials to feed the production process, the Enterprise Rresource Planning (ERP) system issues a command message (thin arrow, cfr. interaction type `Supply Order`) to the cloud supply chain control system that delivers the message to the supplier. As the raw material is ready, an execution state message (dotted arrow) is sent back to the ERP system that, in its turn, activates the transport company for the transport service (crf. interaction type `Withdrawal`). Then, as shown by the solid arrows (material flow), the raw material proceeds toward the `Inbound Logistics` organizational unit, the production process takes place and the finished product is sent to the `Outbound Logistics`.

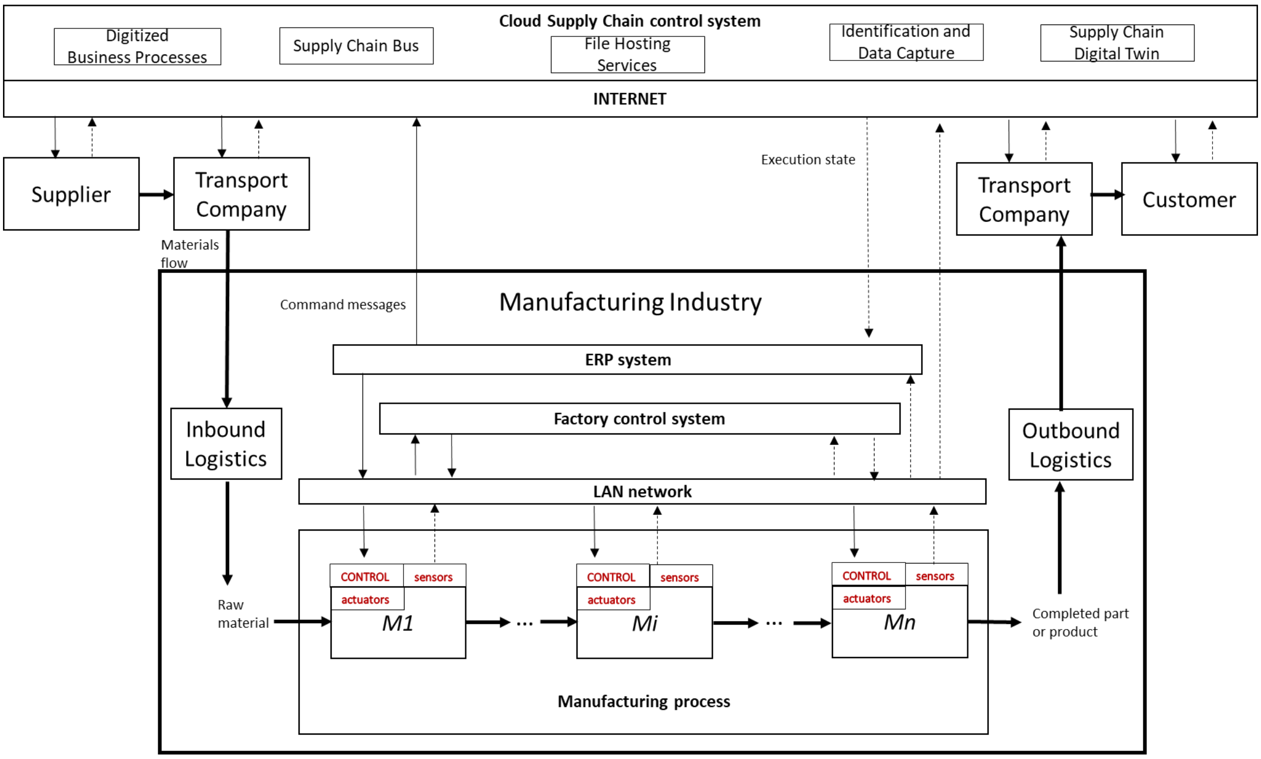


Fig. 3. A model of cyber-physical system for manufacturing SCM 4.0.

In a compex CPPS of autonomous and cooperative elements, the control logic is distributed so that well identified elements can be ruled by means of specialized control instructions. In the model of fig. 3, the manufacturing process is managed by a factory control system, such as the manufacturing execution system (MES), while the `Inbound` and `Outbound Logistics` are usually managed by the Inventory control system. The manufacturing process box represents the essential elements of a dedicated CPPS that supports the production. The machines in the set (a line, a cell, or even a single machine) are connected to each other and with other elements in the model (the factory control system, the ERP system, the cloud system) via the LAN network. Each machine is equipped with a control subsystem, whose main function is to execute part programs to operate the machine tool.

In the model, the cloud supply chain control system is placed one level above the other control to achieve the monitoring and control of the participating companies. This choice is compliant with that of [52] that proposes a novel cyber-physical logistics system with a multi-level CPS structure. The cloud supply chain control system is divided into more specialized subsystems which play the following role:

- Digitized Business Process. It contains the digitized representation of business processes that involve two or more companies in the SC. The SC business processes rule the exchange of materials, data, and finance between companies.
- Supply Chain Bus for the exchange of messages between software systems.
- Sharing of files and documents in the cloud.
- Identification and localization of goods in the SC.
- Digital twin for simulation modeling, optimization, and data analytics [53].

5 Design of SCM 4.0 software systems

Supply chain design and planning concerns the arrangement of assets in a network and how best to use production, distribution and storage resources to satisfy orders in an economically efficient manner [54]. In a systemic perspective, the design and planning can be guided by the consonance property (structural compatibility between elements in the SC) and the resonance property (harmonious interaction between active entities in the SC).

An important aspect of the design of a SC is its digitalization because of the resulting benefits [55] and this put into evidence the urgency of the translation of models of SC in a digital format [56].

In this section, the methodological step of "Design of a SCM 4.0 system" toward the digitalization of a SC is described with reference to the system developed at the STAMEC s.r.l., an Italian industry that produces mechanical molds for the automotive industry.

The architecture of a framework for the computerized representation and usage of the interaction type model in a SC is shown in figure 4. The architecture combines the interaction type model and the CPPS model of fig. 3 also providing examples of open source software components that have been chosen for the concrete implementation of the system. The interactions, which in the diagram are instances of the class *InteractionType*, are represented by the exchange of a message between two active entities. The latter are connected to each other through the *Relationship* class.

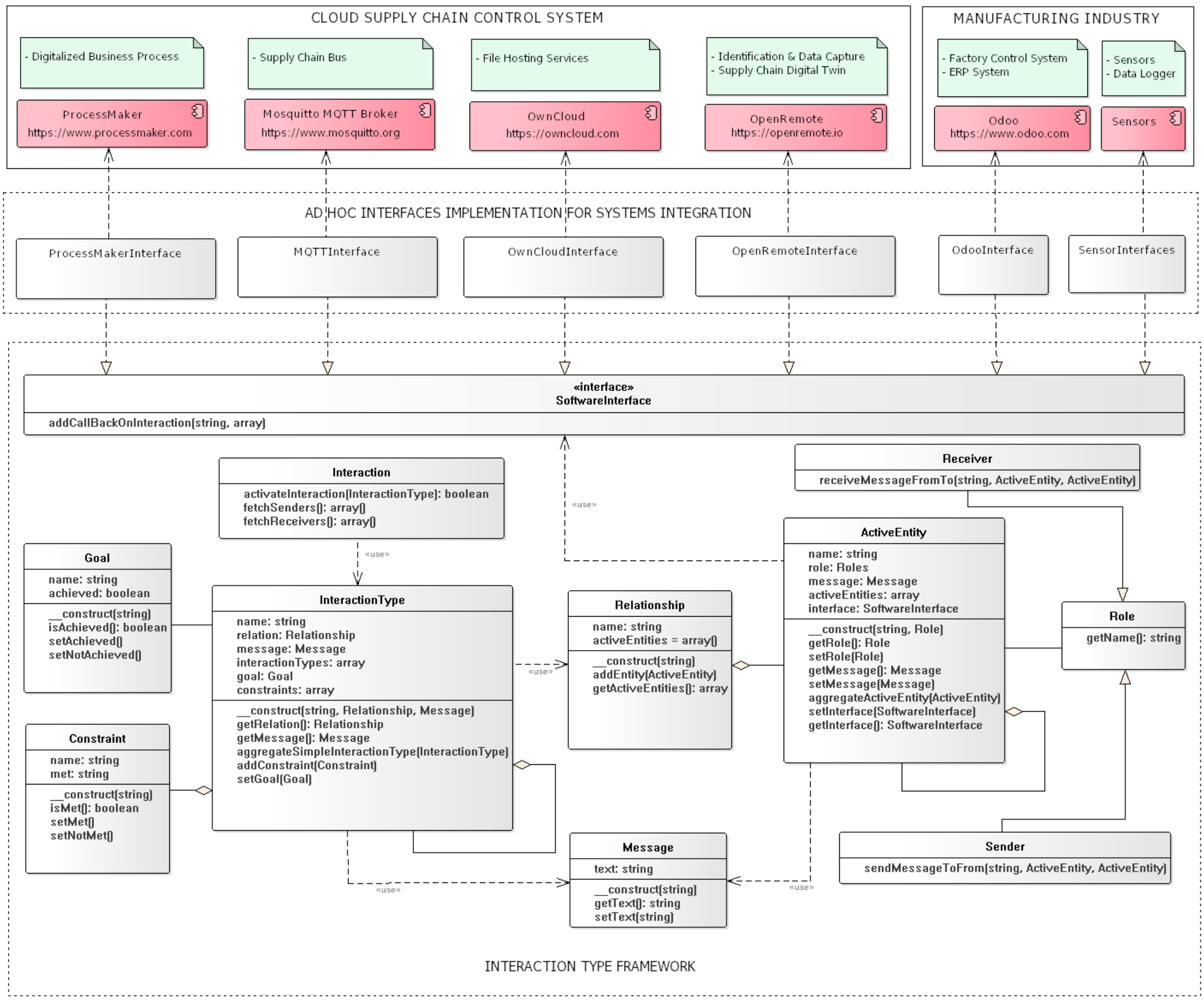


Fig. 4. UML Diagram of a framework for interaction of entities across a cloud supply chain control system.

Active entities and interaction types can both express hierarchies. Examples of hierarchies for an active entity are a manufacturing industry, that can be divided into its organizational units, and a machine tool that can be broken down into its subsystems. The hierarchy of interaction type was discussed in section 3 when we talked about aggregate types. It is therefore possible to consider the interactions between active entities that make up the SC at different levels. As it can be seen from Fig. 4, the manifestation of an interaction occurs with the instantiation of the *Interaction* class that activates the *InteractionType* class in which the relationship between its participating entities, the exchanged message, the goal to achieve, and the contraints that act as a guard on the interaction, can be retrieved through the classes *RelationShip*, *ActiveEntity*, *Message*, *Goal* and *Constraint*. Furthermore, an active entity can use software components, opportunely developed by implementing the *SoftwareInterface* interface, for interacting with objects and methods belonging to any component, module, software system, or Cloud service. For example, it is possible to associate an active entity with an interface developed for an MQTT broker for having MQTT capabilities inside the active entity (e.g publish data to a topic). Then, you can relate it with another active entity associated, in a similar way, with a software interface of an IIoT device (e.g. a GPS-equipped microcontroller to obtain geolocation data). The framework will be able to activate an interaction between them that results in the exchange of the measure, captured by the IIoT device towards the broker.

In the model of fig. 3, and in the case study of a real system such as that of fig. 4, the SCM 4.0 software system is structured as a network of software components, where each one assumes a part of control responsibility for the part of the process it has to manage. For example, to control the process execution at business level, it was decided to use a BPM software platform while we choose the approach that extends the interaction type framework when the control regards low-level components. For example, the communication between machine tools or the communication between IIoT and higher level components such as the MES required the creation of new ad-hoc code.

6. Implementation of digital services for SCM 4.0

In this section, we describe step 4 of the development methodology for SCM 4.0 software systems. The digitization of the SC processes can be done starting from their formal definition and can be achieved by a concrete design using the Cloud as a tool for exchanging information in the SC. We first describe the digitization of a purchase order process that is triggered, in the example, by the Odoo MES sending a Purchase Order (PO) to a supplier. The PO is processed and submitted to the supplier through the OwnCloud system that lives in the Cloud Supply Chain Control System. The formalization comprises three simple interactions that transfer requests from the MES to the Cloud using the Broker as a transfer channel and one aggregate interaction, which composes the previous ones for submitting the PO to the supplier.

```
Publishing PO to Broker (simple) =
{Active entities:(MES Scheduler, Broker Service),
 Goal: PURCHASE ORDER PUBLISHED,
 Message: "PO: list of parts to supply"
 Constraints:
    c1)MES scheduler fetch PO for publishing:True,
    c2)Broker service operative mode:True}

Subscribe to incoming PO (simple) =
{Active entities:(Cloud Subscriber, Broker Service),
 Goal: WAITING FOR PURCHASE ORDER,
 Message: "topic/PO"
 Constraints:
   c1)Broker service operative mode:True
   c2)Cloud MQTT client connects to Broker:True }

Deliver PO on Supply Chain (simple) =
{Active entities:(Broker Service, Cloud Receiver),
 Goal: PURCHASE ORDER DELIVERED,
 Message: "PO: list of parts to supply"
 Constraints:
   c1)Broker service operative mode:True:
   c2)Cloud MQTT client connects to Broker:True }

Notify order processing to Supplier (aggregate) =
{Active entities:(Cloud, Supplier),
 Goal: PURCHASE ORDER NOTIFICATION,
 Message: Cloud shared link to Order Document
 SetOfInteractionTypes:(Publishing PO to Broker, Subscribe to PO,
```

```
                    Deliver PO on Supply Chain) }
Constraints:
  c1)Select all,
  c2)Cloud generates Order document from PO deployed on Supply Chain:True
  c3)Cloud shares PO Order document with Suppliers:True }
```

This specification can be easily completed by adding the interactions involving the delivery of goods from the supplier to the industry. In the following, we show two different ways to implement the PO process. The first considers the usage of a BPM platform, as suggested by the “Digitized Business Processes” subsystem in Fig. 3, while the second shows how to transform the process specification into an executable program that extends the interaction type framework.

In fig. 5, there are three main entities represented in BPM notation: The manufacturing industry, the cloud SC control system, and the supplier. The comments on the right side of the diagram indicate which part of the specification has been implemented in BPMN.

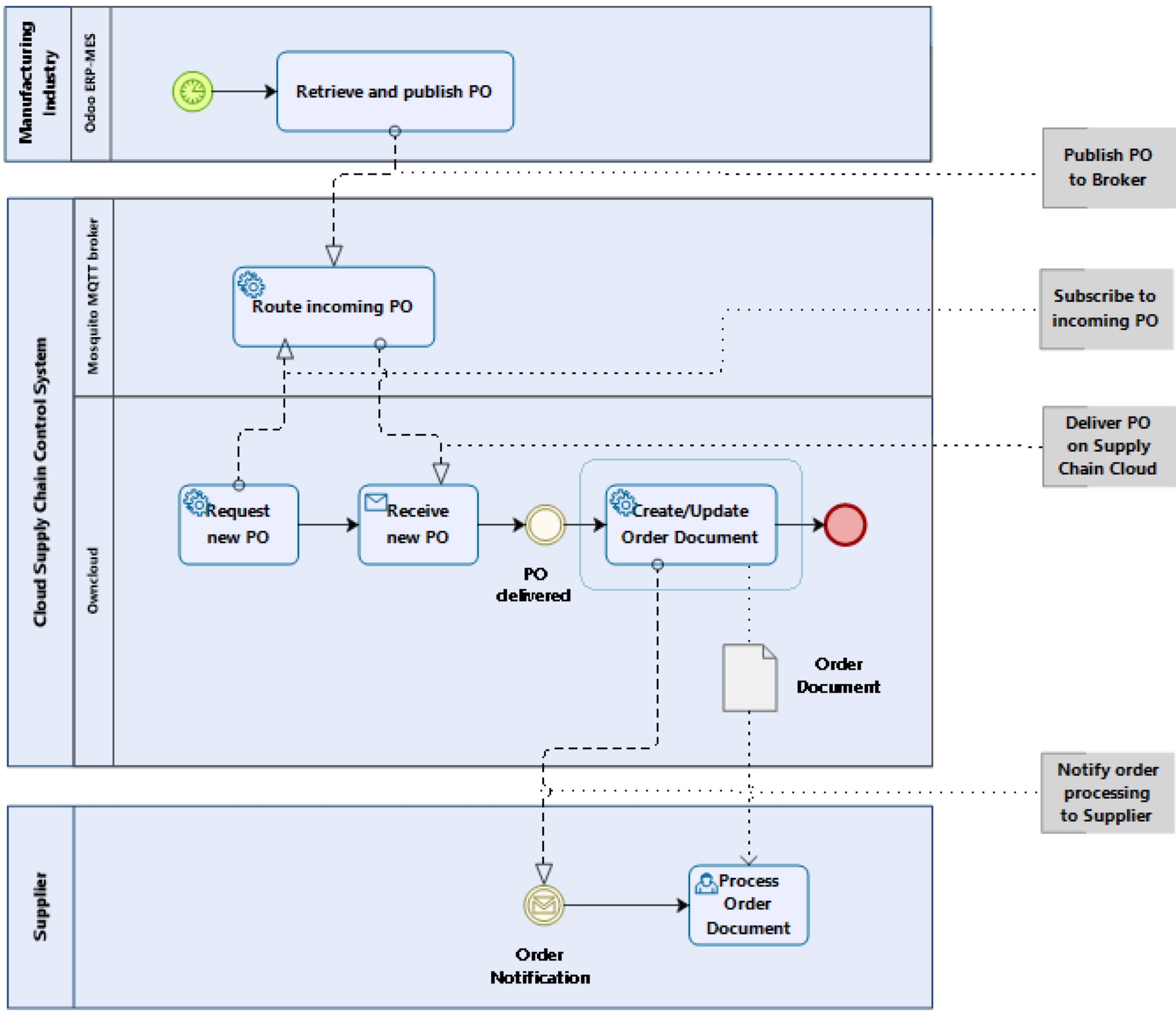
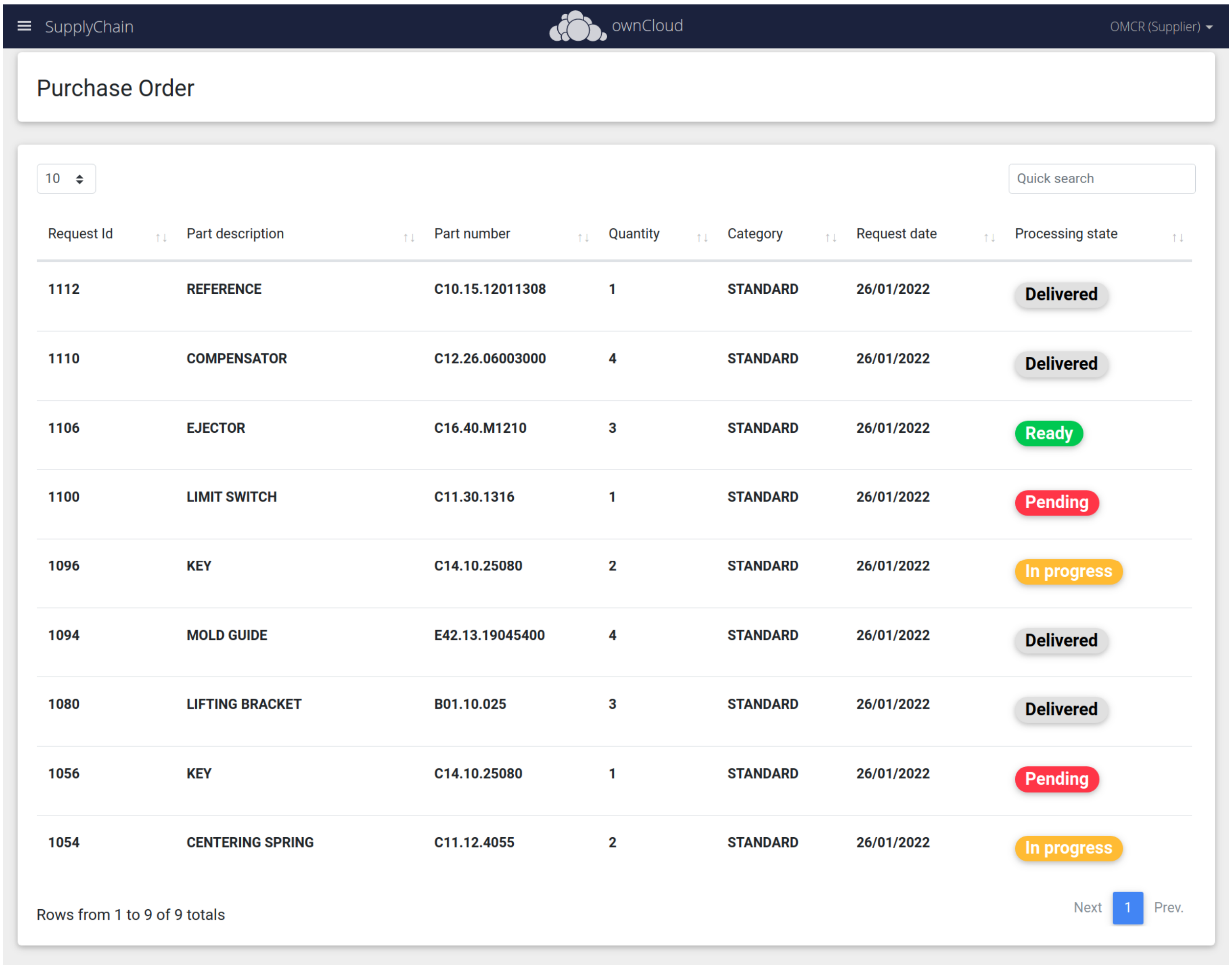


Fig. 5. Implementing the Purchase Request specification; usage of a BPM platform.

The second alternative is to implement the specification with an ad-hoc program. For simplicity, we report only the portion of code that shows the implementation of the interaction type `Publishing PO to Broker` between the Odoo MES and the MQTT broker.

```
/* Create the ActiveEntity MES using an ad hoc implementation of MesInterface. Then set the name and input/output parameters for a callback function of MesInterface that will be triggered on the activation of Interaction Type.*/
$mesInterface = new OdooInterface();
$mesInterface->addCallBackOnInteraction("retrievePartsToSupply",”listOfParts”);
$mes = new ActiveEntity("MES Scheduler");
$mes->setInterface($mesInterface);

/* Create an ActiveEntity representing MQTT by using an ad hoc implementation of MQTTInterface. Then set the name and input/output parameters for a callback function of MQTTInterface that will be triggered on the activation of Interaction Type */
$mqttInterface = new MqttInterface();
$mqttInterface->addCallBackOnInteraction("publishToBroker",”topic/PO”);
$mqtt = new ActiveEntity("Broker Service");
$mqtt->setInterface($mqttInterface);

/* Compose the relation between entities */
$relation = new Relationship();
$relation->addEntity($mes);
$relation->addEntity($mqtt);

/* Set Goal and Constraints */
$goalPOPublished = new Goal("PURCHASE ORDER PUBLISHED");
$constraintMesFetchPO = new Constraint("Mes Scheduler fetch PO for publishing");
$constraintBrokerUp = new Constraint("Broker service operative mode");

/* Set the message. Message text contains the list of parts to supply retrieved and stored into a list by using MesInterface. The list will be used to compose/update the purchase order */
$message = new Message();
$message->setText($mesInterface->getListOfParts());

/* Create and assembly the InteractionType */
$publishPOToBroker = new InteractionType("Publish PO to Broker" $relation,$message);
$publishPOToBroker->setGoal($goalPOPublished);
$publishPOToBroker->addConstraint($constraintMesFetchPO);
$publishPOToBroker->addConstraint($constraintBrokerUp);

/* Create,then activate, the interaction */
$interaction = new Interaction();
$interaction->activateInteraction($publishPOToBroker);
```

A high degree of SCV can be pursued both at the level of business processes (horizontal integration) and in the unfolding of activities from order to production (vertical integration). To show how SCV can be achieved, consider the two graphical user interfaces of Fig. 6 and Fig 7. The first is used in the context of the relationship between a manufacturing industry and a supplier; the second is used in the context of the relationship between the industry and the final customer.



Request Id	Part description	Part number	Quantity	Category	Request date	Processing state
1112	REFERENCE	C10.15.12011308	1	STANDARD	26/01/2022	Delivered
1110	COMPENSATOR	C12.26.06003000	4	STANDARD	26/01/2022	Delivered
1106	EJECTOR	C16.40.M1210	3	STANDARD	26/01/2022	Ready
1100	LIMIT SWITCH	C11.30.1316	1	STANDARD	26/01/2022	Pending
1096	KEY	C14.10.25080	2	STANDARD	26/01/2022	In progress
1094	MOLD GUIDE	E42.13.19045400	4	STANDARD	26/01/2022	Delivered
1080	LIFTING BRACKET	B01.10.025	3	STANDARD	26/01/2022	Delivered
1056	KEY	C14.10.25080	1	STANDARD	26/01/2022	Pending
1054	CENTERING SPRING	C11.12.4055	2	STANDARD	26/01/2022	In progress

Fig. 6. Cloud based processing of a Purchase Order delivered to the Supplier.

The digitized PO lists the parts to be supplied to the industry; it is an interactive document within the SC built on the base of horizontal integration at business process level. In fact, it allows the supplier to set the status of each requested supply in the list, using the change button shown in the last column. On the other side, the industry automatically receives notifications on ready or delivered parts allowing the MES actualization. In the example, the requests are shown with different colours and status indications with the following meaning:

1) order received: PENDING;
2) order accepted: IN PROGRESS;
3) ready for delivery: READY;
4) delivery notified to the industry: DELIVERED.

The report of Fig. 7 is an example of a graphical user interface built on the basis of horizontal and vertical integration. The report is accessible to the Customer through the Cloud and allows to monitor the progress of the product commissioned to the industry while the production process is in progress.

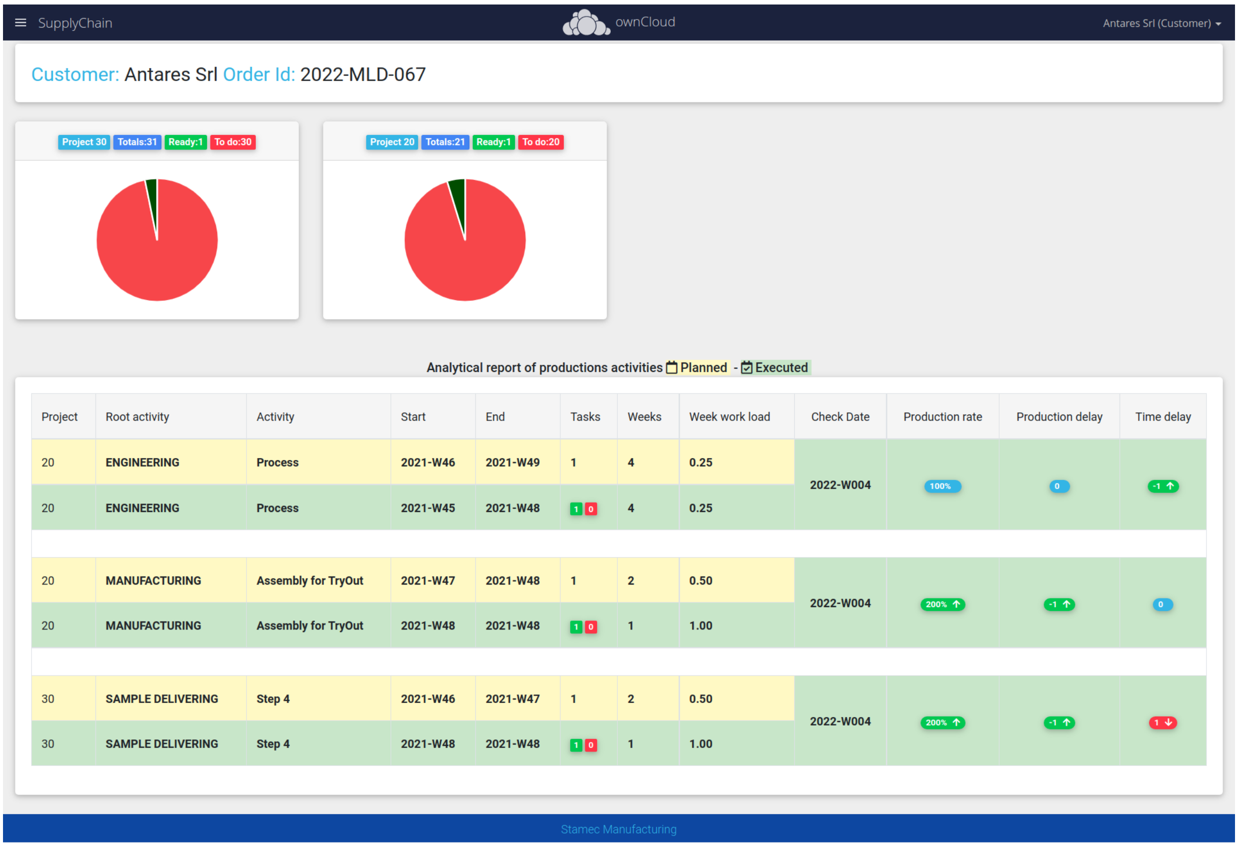


Fig. 7. Cloud based graphical user interface for production process monitoring.

The graphs representing the completion of all the sub-projects that contribute to the realization of the product requested by the customer are shown in the upper part of the report. This information expresses the number of total and processed components that make up the finished product and come from the interactions between the manufacturing company's MES and the Cloud. The following part of the report shows, in a table, the comparisons/deviations between the planned values (yellow background) and the actual values (green background), in relation to the times and capacity of all the processing phases carried out by the production machines. In this case, two sets of interactions were initially taken into consideration: those between the CNCs of the machines with the MES intermediate by the Broker and, subsequently, those between the MES and Cloud intermediate by the Broker. The two sets of interactions were then aggregated in the form of a single interaction capable of producing the report.

7 Conclusions and future research

The advent of Industry 4.0 has led in recent years to the emergence of interconnected ecosystems that require new software platforms to improve the collaboration and performance of these ecosystems. [57]. In this scenario, scholars are proposing the design of vertical and horizontal integration mechanisms that have a positive impact on people, infrastructures, technologies, processes, culture and goals [49]. Most works that have been published by scholars to define the fundamentals of Logistics 4.0 and SCM 4.0 concern conceptual studies or empirical studies. There exists a contribution on how to go from foundations to practical implementation in supply chain management [58] but it focuses exclusively on the technologies on cyber-physical systems and microservice architectures. Our proposal addresses a wider scenario where the SC is seen as a socio-technical system and where the integration must be studied not only at technological level but also at the level of business processes, organizations and goals.

To help bridge the gap that exists between theoretical studies on SC and the implementation of management systems based on Industry 4.0 technologies, this paper introduces a top-down methodology. To this purpose, the interaction type model is central because of its capability to formally represent interactions of any kind between human beings, hardware and software systems as well as between humans and software systems. The interaction type model, together with the definitions recalled in the paper and the principles of Industry 4.0 has inspired the CPPS proposed in section 4; the CPPS model has been then taken as reference for the development of the SCM 4.0 system implemented for an Italian manufacturing industry that operates in the automotive sector.
The principles of the Viable System Approach have been used as a guideline for this research. In particular, the structure/system dichotomy, allowed us to simplify the study of the SCM 4.0 system, first focusing attention on the structural aspects (active entities, CPPS, relationships, interaction types) and then on the dynamic aspects of the SCM 4.0 system. Furthermore, we pursued the realization of a high degree of consonance between subsystems as a prerequisite to obtain vertical and horizontal integration. This has been achieved by first defining formal specification of the SCM 4.0 system and then using IoT, IoS, and Cloud Computing for data capture, data sharing and digital service integration. We have evidence from implementation of the case study that this higher integration degree positively influences the important property of SCV that is known to improve collaboration across end-to-end supply chains, thus improving resonance among participants in the SC. For example, on the supplier side, the digitized process shown in Fig. 6, improved the collaboration between supplier and industry resulting in faster delivery of raw materials and compliance with delivery dates. The main benefits has been obtained on the client side. Before the digitalization of SC services, due to the criticality relating to the delivery of the finished mold, a customer representative made a periodic visit to the STAMEC company to check compliance of production with the agreed times. After the implementation of the system, the customer was able to check in real time the production progress, starting from data generated directly by the machine tools and forwarded by the broker to a shared area in the Cloud. The automatic identification of the delivered mold also allows one to trace the mold and connect it to related digital services (online manuals, routine maintenance control, breakdown maintenance request).

This work dealt with both theoretical and applicative aspects. The former concerns the systemic understanding of the SC and the processes that take place in it; the latter refers to the design and implementation of SCM 4.0 systems. The proposed methodology tries to reduce the gap that usually exist between theorical aspects and practical implementation and be considered both by scholars interested in the formalization of SCM 4.0 systems and by professionals interested in their implementation. As SCM 4.0 research is still in its infancy, several directions can be pursued to further contribute to its development and this is true for the findings of this research too. First of all, formal specifications require new software tools for the verification of structural properties and validation of the expected SC behavior. Another important aspect of SCM 4.0 design concerns the role of the Supply Chain Digital Twin subsystem. Recent research [59], advocates the use of Digital Twin for modeling, real-time optimization and data usage in SC collaboration. We believe that all these points, as well as the simulation of different alternatives of a SC, to evaluate the better implementation, must be further studied in the Industry 4.0 scenario. Finally, professionals could benefit from the availability of visual patterns to reduce the implementation effort of new SCM 4.0 systems. This approach is described in [60] to design Industry 4.0 software applications and could be further deepened in the SCM 4.0 scenario.

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