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# A control model for object virtualization in supply chain management



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## ABSTRACT

Due to the emergence of the Internet of Things, supply chain control can increasingly be based on virtual objects instead of on the direct observation of physical objects. Object virtualization allows the decoupling of control activities from the handling and observing of physical products and resources. Moreover, virtual objects can be enriched with information that goes beyond human observation. This will allow for more advanced control capabilities, e.g. concerning tracking and tracing, quality monitoring and supply chain (re)planning. This paper proposes a control model for object virtualization in supply chain management, which is based on a multiple case study in the Dutch floriculture. It includes a typology of distinct mechanisms for object virtualization, which discerns reference objects and future projections next to the representation of real physical objects. The control model helps to define feasible redesign options for the virtualization of supply chain control. It is also of value as a basis to define the requirements for information systems that enable these redesign options.

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## 1. Introduction

Virtual supply chains are often advocated as an agile alternative to static pipelines that efficiently push products to the marketplace, e.g. [1–3]. A key driver of virtual supply chains is the virtualization of products and resources as enabled by new information and communication technologies. In virtual supply chains, the control and coordination of supply chain processes are based on virtual objects instead of on the direct observation of physical objects. This allows for the decoupling of physical flows and information aspects of supply chain operations [4,5].

Virtualization has been an important topic in research already for a long time. Traditional research streams particularly focus on virtual machines, e.g. [6], virtual reality, e.g. [7], virtual organizations, e.g. [8], and virtual teams, e.g. [9]. Another perspective is the virtualization of physical objects as digital representations, which is addressed especially by the literature on Product Information Management including Product Lifecycle Management and Intelligent Products, e.g. [10–14]. This perspective has recently received much interest, specifically due

to the emergence of the Internet of Things (IoT) concept. In the IoT, physical entities have digital counterparts and virtual representations; things themselves become context-aware and, as a result, they can sense, communicate, interact, and exchange data, information and knowledge [15]. As such, virtualization goes beyond simulation of objects, because virtual objects are used dynamically in the operational control of a company, which assumes a tight integration with operational information systems.

The introduction of virtual objects as a central means for planning, orchestration, and coordination has the potential to revolutionize supply chain management (SCM). Virtualization removes fundamental constraints concerning place, time, and human observation. As a consequence, SCM would no longer require physical proximity, such that the actors responsible for control and coordination are not necessarily also the ones handling and observing the physical objects. This allows for them to be at totally different locations. Moreover, virtual objects do not only represent actual states, but can also reproduce historical states and simulate future states. A final interesting angle is that virtual objects can be enriched with sensor data about object properties that cannot be observed (or not accurately) by the human senses, e.g. temperature information or X-rays. The representation of these data in virtual objects enhances its fitness for use, which allows for

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advanced control capabilities, including tracking and tracing, quality monitoring and (re)planning functionalities.

In the context of SCM, the objects are transferred between many different partners from primary production to the market. As a result, virtual objects are composed of information from different companies and need to provide multiple views for different organizations. All of these have distinct purposes for their usage, which may cover applications in the complete supply chain, including stock control and replenishment, production planning & control, product design, transport control, logistic planning & scheduling, quality inspection, asset management and commercial applications [16,17].

At this point, however, the research on how virtualization of physical objects can impact supply chain control is still in its infancy. It can be noticed that the available SCM literature on virtual supply chains takes no account of object virtualization, but it mainly considers virtualization from an organizational perspective. Cases in point form the work by Chandrashekar and Scharj [1], Ho et al. [18], Gunasekaran and Ngai [19] and Manthou et al. [20]. On the other hand, there are many papers in the product information management and IoT literature that present examples or discuss opportunities for supply chain applications, e.g. [10,11,15,21–23]. However, virtualization is not the main topic in most of these papers. The underlying mechanisms of how the virtualization of physical objects impacts supply chain control remain rather implicit. Moreover, related product information management and IoT literature seem to focus on the representation of real objects. From other research fields, in particular from the Virtual Reality domain, we can infer that also *imaginary objects* and *future representations* are relevant.

This paper proposes a control model, i.e. a systematic classification of concepts for modeling the virtualization of control in a supply chain context. The model builds on the concept of virtual objects as addressed before by the Product Information Management and IoT literature. Its novelty especially lies in our explicit identification and definition of the distinct mechanisms behind object virtualization as to make an impact on supply chain control. The objectives of the control model are threefold. First, it should help to define feasible redesign options for decoupling the handling and observing of physical objects from the control activities based on virtual objects. Second, the control model will be defined as an information model, which can be used as a basis to define the requirements for information systems that enable the aforementioned redesign options. As such, it will contribute to the switch from control systems that rely on their own, often tacit, object information to control systems that rely on explicit virtual objects. The latter are automatically derived from the information of external observers. A final objective of the paper is to assess the value of the control model for SCM. For that purpose, the control model will be based on case studies of virtualization practices in horticultural supply chains. The horticulture is an instructive sector because it is characterized by a high variety and volatility of supply chain processes. These characteristics impose great demands on the diversity and dynamics of virtualizations.

In the remainder of this paper, we first give an account of the applied research method in Section 2. Subsequently, Section 3 introduces the theoretical background and presents a generic control model for supply chain virtualization. Section 4 summarizes the mapping of the studied cases. Section 5 describes the main results of this paper. It defines the distinct mechanisms for object virtualization that are applied in the mapped cases and elaborates the control model accordingly. Next, Section 6 describes how the control model is applied to the cases. The paper concludes by summarizing the main findings, discussing the specifics of our main contributions, and addressing future challenges.

## 2. Methodology

The research reported upon in this paper is based on a design-oriented methodology, which is increasingly applied to management sciences, inspired by Simon [24]. Design-oriented research focuses on building purposeful artifacts that address heretofore unsolved problems and which are evaluated with respect to the utility provided in solving those problems [25,26].

The design artifact developed in the present paper is a control model, i.e. a systematic classification of concepts for modeling the virtualization of control in a supply chain context. A control model represents the control functions needed to ensure that a system's objectives are achieved, even if disturbances occur (see Section 3.2). One of these control functions is a decision-making function, which decides on specific control actions based on a decision-making model. The majority of the literature on supply chain modeling focusses on the development of such, mostly quantitative, decision-making models [27]. The virtualization of control does not affect the decision-making models, but it in particular influences the interactions between the control functions of a control model. For this reason, our control model concentrates on the definition of control functions and information flows among these functions. The designed control model is defined as an information model. Information models provide systematic representations (visualizations, descriptions) of software architectures from different viewpoints and at various levels of abstraction. As such, they support different stages of software engineering: requirements definition, design specification and implementation description. The control model of the present paper can be used as a basis for the requirements definition phase.

Design-oriented research is typically involved with 'how' questions, i.e. how to solve a certain problem by the construction of a new artifact [28,29]. A case study strategy usually fits best for this type of questions, because artifacts intended for real-life problems are influenced by many factors [29]. Case studies can deal with such complex phenomena, which cannot be studied outside their rich, real-world context [30–32].

The present research has conducted an extracting multiple case-study, which is a type of best practice research that aims at uncovering technological rules as already used in practice [29]. For the purposes of this paper, the cases should reflect the diversity and dynamics of virtualizations in a supply chain context, i.e. a heterogeneous selection based on theoretical replication logic [30,32]. For that reason, we have chosen to focus on the Dutch floriculture. After all, in this sector trade relations change frequently, product quality is variable because flowers and plants are living products, product variety is high, products are distributed via diverse marketing channels, and demand is volatile. Furthermore, the availability of virtualization practices was expected to be high, because the Dutch floriculture is working actively on the virtualization of its supply chains [5].

The case study was carried out as part of the DaVinc<sup>3</sup>i project in close interaction with the involved business partners, which represent the majority of the Dutch sector, including auction, traders, growers and industry associations, [33] [[www.davinc3i.com](http://www.davinc3i.com)]. The selection of the cases is based on an investigation of virtualization practices as reported in Verdouw et al. [5], who identified in total 34 of these. For the present paper this list was updated with eight additional practices by consulting the industry partners of the Da Vinc3i project. The identified practices include technologies that are preconditions for virtualization of supply chains, such as identification codes, object sensing technologies, and standards for data exchange. The paper at hand has focused on practices that are directly related to virtualization applications. Specifically, we have chosen to focus on Business-to-Business applications. The practices in this domain can be classified into

Tracking & Tracing applications, Quality Monitoring applications, and B2B market information systems [5]. Within these categories, seven cases in total were selected based on their relative importance in the sector, as indicated by the industry partners of the Da Vinc3i project, and their accessibility for the researchers (see Appendix A).

The research method involved four phases: (A) literature review and generic design, (B) case study mapping, (C) elaborate control model, and (D) case study analysis (see Fig. 1).

In the first research phase, the problem context was analyzed in more detail and the object system was conceptually defined based on a review of the literature on virtualization, supply chain management and control. Next, the results of the literature review were used to design a generic Control Model.

The second research phase covered the mapping of the cases on the concepts as defined in the generic Control Model. The data were collected through structured open interviews with key informants of the seven cases, as well as through desk research and observations of the company's operations and systems. In total, 22 industry experts were interviewed: five traders, one grower, six experts from the auction, two transporters, three experts from industry associations, and five consultants. The structure of the questionnaire corresponds with the developed object system definition and comprised four main parts:

- (i) introduction: problem context, objectives, status, etc.;
- (ii) network: involved supply chain roles/actors;
- (iii) objects: hierarchy of the involved objects including product and resources/assets;
- (iv) processes, control and virtualization: the supported business processes and application domains, the ways of monitoring, planning, etc. and the way in which objects are virtualized and used for control purposes.

The interview reports were reviewed and commented upon by the respondents. Finally, the interview reports and desk material were aggregated into structured descriptions of the investigated practices following the concepts as defined in the generic Control Model of the first research phase.

In the third phase, the structured descriptions of the mapped cases were used to elaborate the generic control model as designed in phase 2. We started this phase by identifying the distinct mechanisms for object virtualization that are applied in the mapped cases. Based on these findings, four generic mechanisms were defined and modeled. These were incorporated in the generic control model that was designed in phase 2. As such, this generic

control model served as an analytical vehicle for theoretical generalization of the case study findings [32].

Finally, the fourth research phase applied the elaborated control model to the cases. The purpose was to determine if the cases can be adequately captured by the control model. In this way, the conceptual validity of the designed control model was evaluated, which means that it was checked whether the model concepts correspond with reality [34,35].

The remainder of the paper introduces the results by following the research steps as described above.

### 3. Theoretical background

#### 3.1. Object virtualization

Basically, the word “virtual” is used in contrast to “real” and “physical”. This means that it has an essence or effect without a real-life appearance or form (World English Dictionary). Virtualization is used in reference to digital representations of real or imaginary real-life equivalents. As such, virtualization removes fundamental constraints concerning [5]:

- *Place*: virtual representations do not require geographic presence, i.e. physical proximity, to be observed, controlled or processed;
- *Time*: besides the representation of actual objects, virtualization can reproduce historical states, simulate future states or imagine a non-existing world;
- *Human observation*: virtual representations can visualize information about object properties (such as temperature information or X-ray images) that cannot be observed by the human senses.

Although dealing with the same basic concept, virtuality has been applied to different domains and the concept has been used in different meanings and with different focuses. Verdouw et al. [5] distinguish the following perspectives: virtual organization perspective, virtual team perspective, virtual machine perspective, virtual reality perspective, and virtual things perspective. This paper mainly considers virtualization from the latter perspective, which is related to the Internet of Things (IoT) concept.

IoT provides a vision of a world in which the Internet extends into the real world embracing everyday objects by utilizing the power of combining ubiquitous networking with embedded systems, RFID, sensors, and actuators [36,37]. The interaction between real/physical and digital/virtual objects is an essential concept behind this vision. In the IoT, physical entities have digital

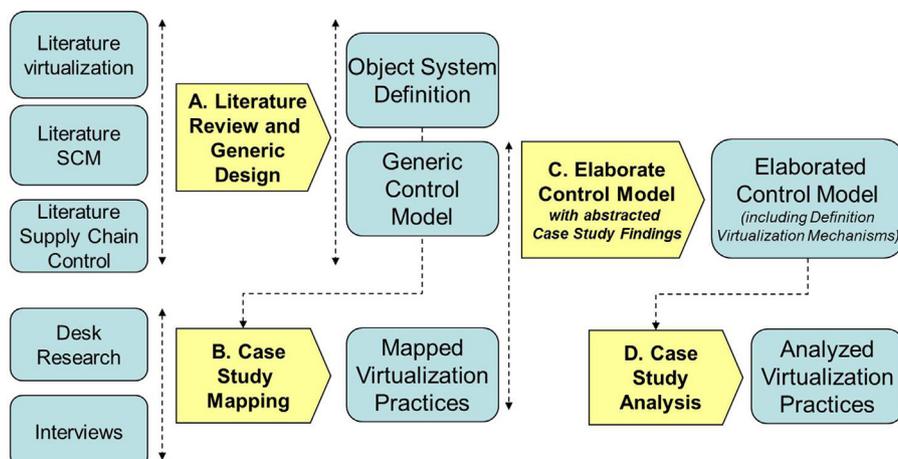


Fig. 1. Research phasing.

counterparts and virtual representations; things become context-aware and they can sense, communicate, act, interact, exchange data, information and knowledge [15]. In other words, each physical object is accompanied by a rich, globally accessible virtual object, which contains both current and historical information on that object's physical properties, origin, ownership, and sensory context [38]. The Internet acts as a storage and communication infrastructure that holds a virtual representation of things linking relevant information with the object [39]. As such, virtual objects serve as central hubs of object information, which combine and continuously update data from a wide range of sources.

The principles behind the IoT vision were already addressed before in the domain of Product Information Management. This literature stream considers products as central objects in enterprise and supply chain systems. All product-related information can be accessed by any user in the supply chain in any stage of the Product Life Cycle [11,12,14]. The representation of each physical product in a virtual counterpart has been proposed to handle the amount and complexity of the resulting product-related information [11,21,40]. Furthermore, the concept of Intelligent Products extends the virtual representation with services that equip products with information handling, problem notification or decision making capabilities [10,41–43]. However, although the virtual representation of physical products is addressed both in Product Information Management and IoT literature, it can be noticed that virtualization is not the main topic in most of these papers. Especially, the underlying mechanisms of how virtual objects can be used in supply chain control remain rather implicit.

### 3.2. Supply chain control

Control is a basic concept in system dynamics. It ensures that the system's objectives are achieved, even if disturbances occur. The basic idea of control is the introduction of a controller that measures system behavior and corrects if measurements are not compliant with system objectives [44]. In a supply chain, the control system plans, controls, and co-ordinates a connected series of business processes while aiming at realizing supply chain objectives, within the constraints from the supply chain configuration and the restrictions set by higher management echelons [45,46].

Supply chains are 'in control' if the performance of its business process remain in a steady state. Therefore, the activities of these processes must include the cybernetic control functions necessary to demonstrate 'cybernetic validity'. Basically, this implies that they must have a feedback loop in which a norm, sensor, discriminator, decision maker, and effector are present [47,48]. Fig. 2 depicts these control functions in a basic control model. The object system executes activities that transform input into the desired output. In Supply Chain Systems these are the business processes of the involved actors that transform input material to final products at the end customer's location. The sensor function measures the actual performance of the object system. The discriminator function compares the measured performance with the norms that specify the desired performance (system objectives concerning e.g. quantity, quality and lead time aspects) and signals deviations to the decision-making function. Based on a control model of the object system, the decision-making function selects the appropriate intervention to remove the signaled disturbances. Finally, the effector implements the chosen intervention to correct the object system's performance.

### 3.3. Impact object virtualization on supply chain control

In virtual supply chains, the control of supply chain processes is based on virtual objects instead of on direct observation of physical

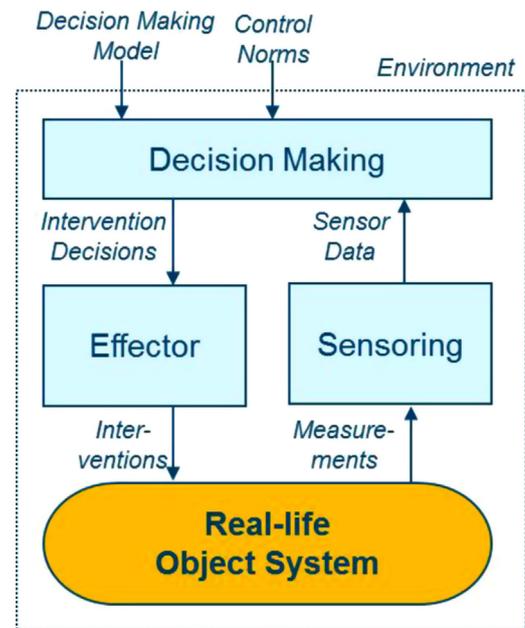


Fig. 2. Basic control model.

objects. This allows for the decoupling of physical flows from information aspects of supply chain operations [4,5]. Decoupling of control means that the measurements of the object system's state are translated into a virtual object. We define a virtual object as a digital representation of an object, with a unique identification, that can be trusted, possesses the property of integrity, is timely available, and can be used for the intended purpose.

The introduction of virtual objects in the control model is visualized in Fig. 3. The control cycle starts with measuring the object system's state by the sensor function and with acquiring relevant external data. The sensor data and external data are then translated into a virtual representation of the controlled object system. The virtual object includes all information relevant for the supported purposes of usage (i.e. control objectives) as specified in a meta model. Dependent on a specific purpose of usage, a virtual view may then filter irrelevant information and present it in such a way that it can be processed optimally by specific users (model-based transformation) on the basis of a meta model. The next control function is the decision-making function, which compares a virtual view on the object system with a specific control norm. Next, the decision-making function selects appropriate interventions for deviations based on its Decision Making Model, similarly as in conventional control systems. Lastly, the selected intervention is communicated with the effector function, either directly or via the virtual object using remote actuator systems.

## 4. Case mappings

The present research has involved a multiple case study in the Dutch floriculture. The case study started with covering the mapping of the cases on the concepts as defined in the generic Control Model (see Fig. 3). This section first provides insight in the context of the cases by introducing the main sector characteristics. Next, we will summarize the mappings, i.e. the structured descriptions of the investigated practices following the concepts as defined in the generic Control Model.

### 4.1. Characteristics of floricultural supply chains

The floricultural industry comprises of cut flowers and pot plants production, mainly in greenhouses. Europe is the leading

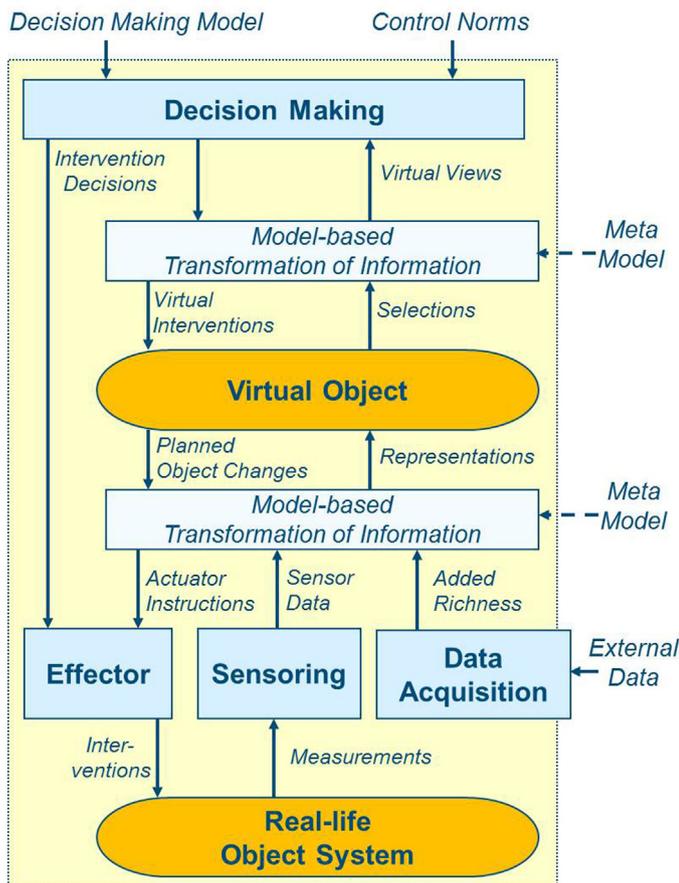


Fig. 3. Generic model for control based on virtual objects.

floricultural producer in the world. The Netherlands is by far the largest producer, accounting for approximately 40% of the total European production value [49,50]. The Dutch floriculture is concentrated in so-called Greenports. The Netherlands has an intricate and high-quality network of floricultural companies, ranging from breeders and growers to sales experts and export firms, representing every aspect of the business [33,51]. The main actors in the floricultural supply chains are:

- **Growers:** there are about 3000 floricultural producers in The Netherlands [52]. The number of growers is declining, while their individual size is increasing.
- **Auction houses/producer organizations:** the world's largest flower and plant auction is located in The Netherlands (FloraHolland) where the flower auctioning system originally started.
- **Traders,** in particular wholesalers, exporters, and importers; these organizations are closely connected to retail and have a crucial role in logistics orchestration. There are about 2200 Dutch traders [52], dealing with many (inter)national customers. Most important import countries are Kenya, Ethiopia, Israel, Ecuador and Germany. Most important export countries are Germany, United Kingdom, France, Italy and Belgium.
- **Logistic Service Providers (LSPs):** in particular transportation and storage/transshipment activities are often outsourced a logistics service provider. In some cases, the providers execute additional activities like quality control, handling and packaging.
- **Suppliers of Logistic Assets:** important containers in floriculture include CC trolleys of Container Centralen and auction trolleys of Flora Holland.
- **Retailers:** the main retail channels are florists, supermarkets, garden and Do-It-Yourself (DIY) centers, and street market. The

relative shares between these types of retailers differ a lot between European countries. In general, web shops are becoming increasingly popular.

The floricultural industry is characterized by high uncertainty of both demand and supply [53]. Supply uncertainty is high, because chains are vulnerable to product decay, weather conditions, pests, traffic congestion, and other uncontrollable factors. Further, also demand uncertainty is high, which is amongst others due to weather-dependent sales, changing consumer behavior, and increasing global competition. This results in high variability of supply capabilities and demand requirements in terms of volume, time, service levels, quality and other product characteristics.

Furthermore, there is a high variety of supply chain configurations in the floricultural sector [54]. The extent to what processes are order-driven differs a lot, not only among different companies but also within firms. For the spot market, products are made to stock and distribution is either to order (usually via traders) or anticipatory (usually via auctions). For other cases, flowers and plants are often produced to forecast, while assembling, labeling and packaging are order-driven. There are also differences in the supply chain network of pot plants and cut flowers in particular due to the fact that a flower after being cut can decrease 15% in value a day in case not delivered to the customer, whereas the quality of ornamental plants may even increase if they are cared properly.

#### 4.2. Mapping the investigated cases

Seven cases in total have been studied in the research, which were all mapped on the concepts of the generic Control Model:

1. **Plant-to-Customer:** pilot project on the benefits of RFID in plant supply chains;
2. **Hubways:** development of a digital platform that supports the exchange of cargo, capacity and information on the level of the logistics between floricultural stakeholders in The Netherlands;
3. **Freshtrack:** tracking and tracing system for transportation of flowers based on barcode scanning of boxes at various critical stages in the chain;
4. **Smart Agri-Food trial:** pilot in a plants supply chain to combine RFID and sensor technologies for quality controlled logistics and retail store replenishment;
5. **Cold Chain Score Card:** quality monitoring system based on data loggers for the transportation of flowers in conditioned containers;
6. **Cool Chain Monitoring:** cool chain application that monitors the entire cool chain temperature based on data loggers;
7. **Virtual Auctioning:** remote auctioning system (called KOA) that allows to buy, anywhere in the world, real-time via Internet on all the FloraHolland auction clocks.

See Appendix A for a further description of these cases.

Table 1 summarizes the case study findings on the categories of Network, Process, Virtual Object, Object Data, Presentation, Update Frequency, and Control Purposes. It shows that most practices support business processes in the upstream supply chain, which implies that the main involved actors are growers, auction houses, traders, transporters, and other logistics service providers (LSPs). The main supported business processes of the cases 1–6 are packing, sorting, storage, distribution and transportation. Case 7 focusses on sourcing, procurement, marketing and sales.

The objects that are virtualized differ per case and range from individual products to shipments and batches. Most cases virtualize objects on different aggregation levels and, as a consequence, involve a hierarchy of virtual objects.

**Table 1**  
Overview of the virtualization of control in the investigated cases.

Case	Network	Processes	Virtual object	Object data	Presentation	Update frequency	Control purpose
Case 1. Plant-to-Customer	Grower, Trader, Transporter/LSP	Packing/sorting, storage, distribution/transportation	Plant tray, trolley	RFID, external data	Static and dynamic features in text	Event-driven	Monitoring (track & trace), deviation Mgt (alerts)
Case 2. Hubs	Grower, Trader, Transporter/LSP, Auction	Distribution/transportation, sourcing/procurement	Shipments (transportation orders)	Barcode scanning, RFID, external data (EDI, backend systems), manual entry	Static and dynamic features in text, visualization status (colors)	Event-driven	Monitoring (track & trace), deviation Mgt (alerts), planning
Case 3. Freshtrack	Growers, Transporters, Traders, Auction	Distribution/transportation, sourcing/procurement	Box, pallet/container	Barcode Scanning, external data, manual entry	Static and dynamic features in text, visualization status (colors)	Event-driven	Monitoring (track & trace), planning
Case 4 Smart Agri-Food trial	Grower, Trader, Transporter/LSP, Auction, Retailer	Packing/sorting, storage, distribution/transportation, returns management	Product, tray, trolley	Barcode (product), RFID (trolley), sensors (temperature, humidity, light), external data	Static and dynamic features in text, condition trajectories and simulations in graphs, product pictures	Event-driven	Monitoring (track & trace), deviation mgt (alerts), planning
Case 5 Cold Chain Score Card	Grower, Trader, Transporter/LSP	Packing/Sorting, Storage, Distribution/Transportation	Box, Container/shipment	Temperature sensors, manual entry, external data	Static and dynamic features in text, temperature trajectories and remaining degree hours visualized in graphs	Afterwards	Monitoring (track & trace), deviation mgt (alerts), prevention/compliance
Case 6 Cool Chain Monitoring	Grower, Trader, Transporter/LSP, Auction	Packing/sorting, storage, distribution/transportation, sourcing/procurement	Box, container/shipment	Data logger (temperature, humidity sensors), external data, manual entry	Static and dynamic features in text, condition trajectories visualized in graphs	Afterwards	Prevention/compliance
Case 7 Virtual Auctioning	Grower, Trader, Auction, Retailer	Sourcing/procurement, marketing/sales	Product, batch	External data, manual entry, camera	Static and dynamic features in text, product picture	Event-driven	Intervention (commercial transaction), Monitoring (available supply)

In all cases the object data are gathered by a combination of methods, including AutoID (RFID and barcode scanning), sensors, data from other systems (via EDI and interfaces with backend systems), and manual entry.

The virtual objects are presented in all cases in the system as text fields with static and dynamic features. In addition, most cases include basic visualizations like graphs and status information in colors. The use of vision technologies is still limited in the investigated cases.

In most cases (nos. 1–4, 7), virtual objects are updated when a specific event occurs, e.g. when the objects are read by an AutoID device. In two cases (nos. 5 and 6), virtualizations are generated after arrival of the object at its destination. The continuous updating of virtual representation is not present in any of the analyzed cases.

The usage of virtual objects for control purposes differs per category. The cases 1–3 use virtualization mainly for monitoring (track & trace), deviation management (alerts), and logistics planning. The cases 4–6 use the information also afterwards to improve control systems (prevention) or to provide evidence for claims and for demonstrating compliance to regulations. Case 7 uses virtual products to monitor available supply and for bidding.

In summary, the analysis of the cases shows that virtual objects are composed of information from different companies. Also, virtual objects need to provide multiple views for different organizations, each having a distinct purpose for its usage. The next section will define the distinct mechanisms for object virtualization based on these findings and will elaborate the control model accordingly.

## 5. Control model for object virtualization in a supply chain context

This section develops a control model for object virtualization in a supply chain context, as based on the generic Control Model on the one hand and on the structured descriptions of the mapped cases from the previous section on the other. As argued in the introduction, the control model can be used to define feasible redesign options for the virtualization of control. Furthermore, it can serve as a basis to define the requirements of the information systems that enable these redesign options. To this end, this section first identifies the distinct mechanisms for object virtualization that are applied in the mapped cases. Subsequently, each mechanism is further defined and modeled. Finally, the resulting models are incorporated in the generic control model that was presented in Section 3.3.

### 5.1. Typology of virtualization mechanisms

Virtual objects are composed of information from different companies. They need to provide multiple views for different organizations, which have distinct purposes for their usage. These different types of usage are based on distinct mechanisms of object virtualization. Based on the mapped cases, two dimensions of object virtualization are defined, i.e. the reality dimension and the time dimension.

The *reality dimension* is concerned with *the extent to which virtual objects exist in the real world*. From an IoT perspective, virtual objects are mainly considered to represent real physical objects by using technologies such as RFID and wireless sensor networks. However, for many of the applications mentioned above, objects first come into existence as a conceptual entity. Once the conceptual entity is materialized, the real object can be connected to the virtual object. In this case, reference objects are virtualized instead of real physical objects. An example is the usage of imaginary resources for planning purposes, which specify the type

of resources and the properties necessary to do the job. Think of, for example, a virtual lorry having a certain capacity in specific temperature compartments. When the plan becomes actual, a physical lorry is chosen to do the job for the virtual one (having at least properties that match required ones). Another example is the usage of virtual products in web shops, including standardized pictures and required product specifications. After the conclusion of the transaction, real products are allocated to the transaction, meeting the requirements as specified through the virtual product. These examples show that an object potentially comes into existence in different stages of its lifecycle. First, a conceptual stage can be distinguished in which an object is to be identified and described. Then, a physical stage is entered, in which the object comes into existence, stays 'alive', and may be maintained. Finally, the disposal phase takes place, in which the physical object is disposed, but the conceptual object may remain for some period.

The second dimension is the *time dimension* of virtual objects. The majority of IoT applications represent the current and historic state of objects. However, for many of the supply chain applications mentioned above, including planning, future states of virtual objects are needed in addition. These can be projected using predictive analytics, such as forecasting and simulation tools. For example, the planned route of a container shipped by different transportation modes (e.g. road, sea, road) can be visualized and rescheduled based on the expected congestion (e.g. road, sea, rail). Another example is the dynamic pricing of products as based on forecasted demand.

Based on the two dimensions that we discussed at this point, four virtualization mechanisms can be identified (see Table 2):

1. Virtual representation of real objects;
2. Virtual projection of real objects;
3. Virtual representation of reference objects;
4. Virtual projection of reference objects.

The next sections further define these virtualization mechanisms. Also, a conceptual model for each mechanism is introduced (a more elaborate description can be found in Appendix B). The chapter concludes with combining these models into an integrated control model for object virtualization.

5.2. Virtual representations of real objects

In the mechanism to be discussed, virtual objects represent the current and historic state of objects that exist physically in the real-world. The physical objects are equipped with tags for identification, usually barcodes or RFID transponders, and with sensors that measure dynamic properties of physical things. The virtual object uses these sensor data to generate a representation of the object based on a meta model, which might be implicit. Usually, the sensor data are combined with external data to enrich the virtual representation. Fig. 4 visualizes the conceptual model of this mechanism.

A represented virtual object comprises the unique identification (ID), as well as actual and historic properties of the real-life object that are relevant for the supported purposes of usage. In

**Table 2**  
Typology of mechanisms for object virtualization.

Time dimension	Reality dimension	
	Real objects	Reference objects
Current/historic state	Virtual representation of real objects	Virtual representation of reference objects
Future state	Virtual projection of real objects	Virtual projection of reference objects

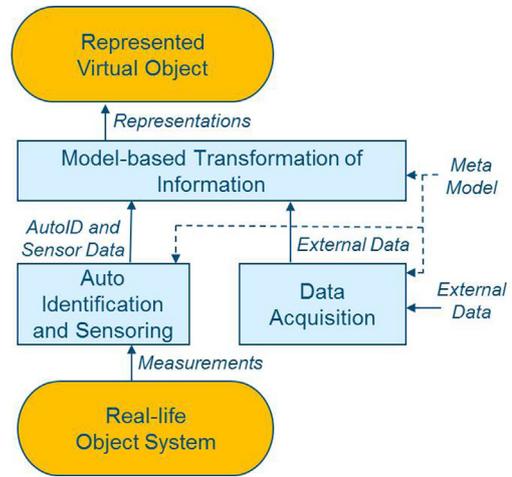


Fig. 4. Virtual representation of real objects.

other words, it consists of a unique ID and a complete set of attributes and values (attribute-value-pairs) that are derived from sensor and external data based on a meta model. Major elements of the meta model may encompass:

- A description of properties of the object at different points in time. Such properties denoting the state of an object can be described by a relation O-State ( $O_{ID}$ ,  $A_{ID}$ ,  $A_{ID\_Value}$ ,  $TI\_of\_State$ ,  $L_{ID\_of\_State}$ ,  $ORG_{ID\_of\_State}$ ,  $BOM_{O_{ID}}$ ). Each tuple of that relation denotes for an Object its object identification ( $O_{ID}$ ), the name of a valid attribute measured ( $A_{ID}$ ), the value of that measurement ( $A_{ID\_Value}$ ), the Time stamp of that measured value ( $TI\_of\_State$ ), the location of the object at that time ( $L_{ID\_of\_State}$ ), the owner of the object at that time ( $ORG_{ID\_of\_State}$ ), and relations with other objects ( $BOM_{O_{ID}}$ ). The attributes are concerned with different types of information, including numbers or strings, but also visual information such as pictures and geographical maps. They can be directly measured by sensors (e.g. temperature) or they can be derived from measured attributes by functional relations or transformation rules. The values can be concerned with one moment in time ( $t = 1$ ), but usually also include a historic trajectory ( $t_{n-1}$ ).
- Domains for attribute values. Each attribute has an associated domain from which the values for an attribute are drawn. Furthermore, the meta model includes definitions of the instruments, procedures and norms (calibration) for measurement of the attributes (including Auto ID, sensors and external data). An example is a standardized procedure to take representative pictures from products for web shops.
- A description of dynamic behavior, a transition, that depicts state changes of objects involved over a time frame. It must be possible to represent that a(n) (set of) object(s) are subject to some transformation function that takes place at a certain location, starts at a certain point in time, and has a timeframe (start and end). This can be denoted by a relation TRAN ( $TRAN$ ,  $O_{ID}$ ,  $TF$ ,  $TRF$ ,  $L_{ID}$ ). Each tuple then denotes the ID of the Transformation, the ID of the object affected, the timeframe of execution ( $TF$ ), the ID of the transformation function applied, and the location of the object at start. This approach allows many objects to participate in one transformation. A transition is to generate a number of states of the objects affected within the timeframe identified. As such, the model just presented allows for the representation of historic and current states of objects of interest and thus for the creation of virtual representations.

For a more elaborate description of the mechanism we refer the reader to Appendix B.

### 5.3. Virtual projection of real objects

In the second mechanism, virtual objects project the future state of objects that exist physically in the real-world. The future state is forecasted by using a prediction model. This model uses the information of the current and historic state of the objects, measured by sensors and AutoID devices, usually in combination with external data, e.g. weather forecasts or congestion information. The virtual object uses the prediction information and the actual information about the object to generate projections of the object based on a meta model. Fig. 5 visualizes the conceptual model of this mechanism.

The conceptual model of this mechanism is highly similar to the previous mechanism, i.e. virtual representations of real objects. The main difference is that the projected virtual object includes the *future state* of objects instead of merely the actual and historic state. Consequently, the values of simulated attributes are concerned with one moment in the future ( $t_1$ ) or with a future time frame ( $t_0 - t_1$ ). In order to capture this in the meta model of the previous section we add:

- A description of projected properties of the object at different points in time. Such properties denoting the future state of an object can be described by a Relation PO-State ( $P_{ID}$ ,  $O_{ID}$ ,  $A_{ID}$ ,  $A_{ID\_Value}$ ,  $TL\_of\_State$ ,  $L_{ID\_of\_State}$ ,  $ORG_{ID\_of\_State}$ ,  $BOM_{O_{ID}}$ ).
- A description of projected dynamic behavior, which depicts state changes of objects involved over a time frame in the future. A projection is similar to a transition, with the connotation that one can have a number of transitions to simulate the object's state for different future scenarios. This approach allows many objects to participate in one projected transformation.

For a more elaborate description of the mechanism, please consult Appendix B.

### 5.4. Virtual representation of reference objects

In the third mechanism, virtual objects represent the state of reference objects that are not (yet) connected to objects that physically exist in the real-world. An important advantage of not making the connection is the flexibility in the allocation of real objects to a specific task or transaction, because it allows for interchangeability of real objects. For example, for planning purposes, only the aggregated availability of lorry capacity might be known beforehand. The decision which particular truck and trailer have to do the job can be postponed until the moment just

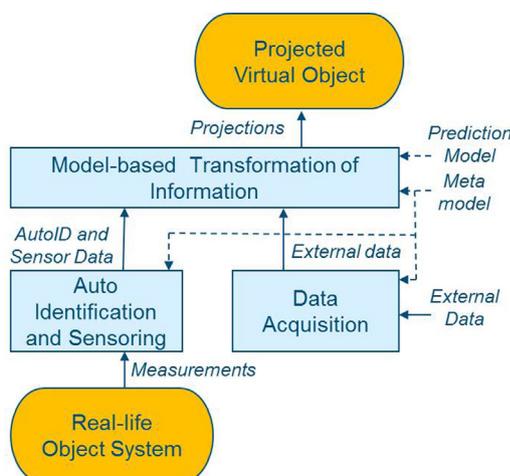


Fig. 5. Virtual projection of real objects.

before the shipment. Another example is a web shop that offers the same product from several manufacturers. In that case, the decision which supplier will supply the product for a specific customer can be postponed to the moment when the transaction takes place. Fig. 6 visualizes the conceptual model of this mechanism.

The key distinctive feature of this mechanism is that it specifies a typical object from the perspective of defining user requirements. The representation of a reference object consists of a set of attributes and values (attribute-value-pairs) that are derived from external data based on a meta model. The virtual reference object should include a specification of the variety of sub classes that are equivalent for the intended purpose of usage.

One can distinguish two main approaches to represent a reference object. First, a representative physical object can be selected and virtualized (typical objects). For example, many web shops use pictures of representative products. In the second approach, the reference object is a combination of desired features (conceptual object). These desired features can be based on past experiences or they can be the result of a design process.

In order to capture this in the meta model of the previous section we add the inheritance of object states from reference objects, which could be defined as relation RO-State ( $RO_{ID}$ ,  $O_{ID}$ ,  $A_{ID}$ ,  $A_{ID\_Value}$ ,  $TF\_of\_State$ ,  $ORG_{ID\_of\_State}$ ,  $BOM_{O_{ID}}$ ). Contrary to real objects, a reference object does not have a location. However, also the state of a reference object has a certain time, which indicates when the reference object is valid. As a consequence, also reference objects need transition functions to define the allowed dynamic behavior of a reference object, i.e. valid time frames. A more elaborate description can be found in Appendix B.

### 5.5. Virtual projection of reference objects

In the fourth and final mechanism, virtual objects project the future state of reference objects that are not (yet) connected to objects that physically exist in the real-world. Just like virtual projection of real objects, the state of the reference object is forecasted by using a prediction model. Based on this information, a projection is generated in conformance to a meta model. However, in this mechanism *reference data* are used as input instead of data from real objects. Fig. 7 visualizes the conceptual model of this mechanism.

The virtual object in this mechanism is based on reference data, i.e. sets of attributes and values (attribute-value-pairs) that are derived from external databases. These reference data can be

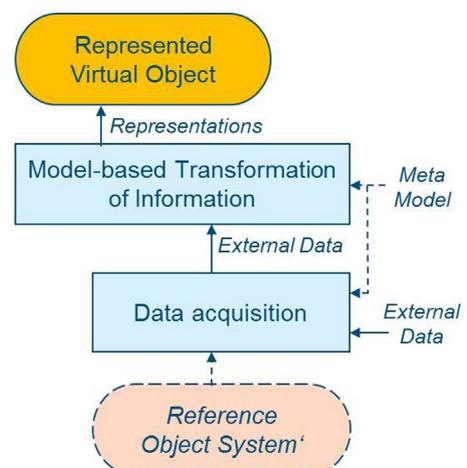


Fig. 6. Virtual representation of reference objects.

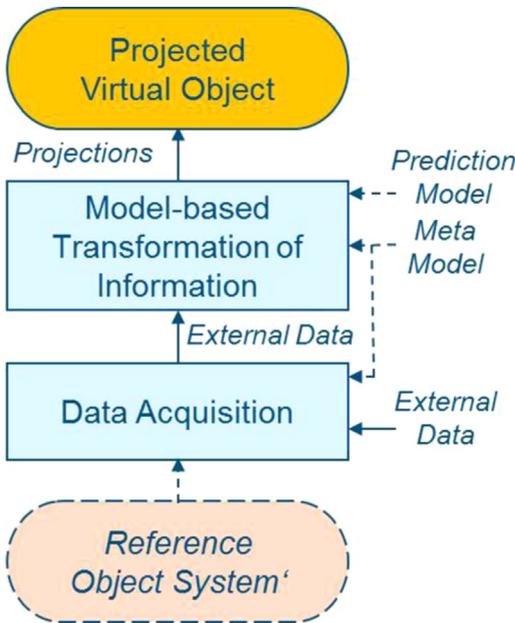


Fig. 7. Virtual projection of reference objects.

measured from representative physical objects, e.g. in a lab setting, or they consist of desired features that are based on past experiences or research. A simulation model uses these reference data to project the state of the reference object. Just like virtual projection of real objects, this can be done in two ways: (i) by the

transformation of reference values of attributes to future values or (ii) through a calculation of the future values of derived attributes. In order to capture this in the meta model, a projected reference object is defined as a relation PRO-State ( $P_{ID}, RO_{ID}, O_{ID}, A_{ID}, A_{ID\_Value}, TI_{of\_State}, ORG_{ID\_of\_State}, BOM_{O_{ID}}$ ). This relation is a combination of a projected object (PO-State) and a reference object (RO-State). Consequently, all required concepts are already included in the meta model as defined in the previous sections.

5.6. Integrated control model for object virtualization

The previous sections have defined four distinct mechanisms of object virtualization in the context of SCM. Fig. 8 incorporates these mechanisms into the control model. It adds the two dimensions of object virtualization that are defined in this section.

First, a reference object system is depicted, next to the real-life object system, which can be used to represent virtual objects that are not (yet) connected to objects that exist physically in the real-world. Such a virtual reference object specifies a typical object from the perspective of defining user requirements, either by combining and visualizing wanted features or by virtualizing a representative physical object. Virtualization of reference objects allows for postponement of the allocation of real objects to a specific task or transaction and consequently it increases control flexibility.

Second, a projected virtual object is added next to the represented virtual object. Such virtual objects project the future states of objects using predictive analytics, including forecasting and simulation tools. This allows for more proactive control, such as preventive alerts (early warning) and dynamic planning and scheduling.

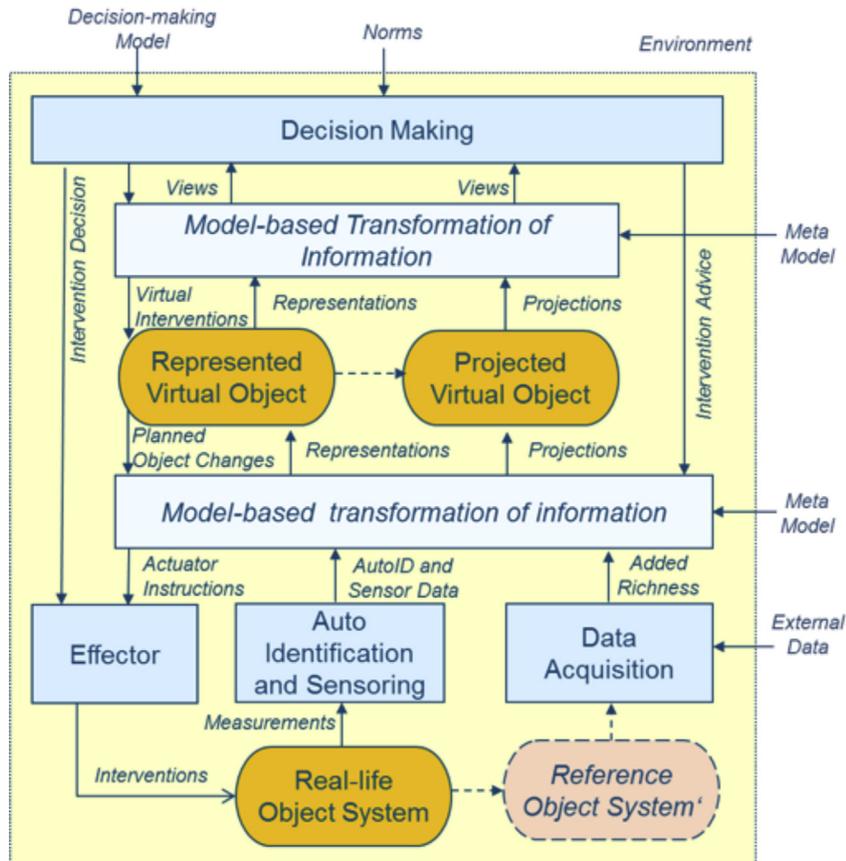


Fig. 8. Integrated control model for object virtualization.

## 6. Virtualization practices in floricultural supply chains

The previous section was concerned with the design of a control model for object virtualization in a supply chain, including the definition of four distinct virtualization mechanisms. This section will provide an analysis of the mechanisms that are practiced in each of the cases. It will then describe how the designed control model is applied in the case studies.

### 6.1. Mechanisms for object virtualization as practiced in the cases

Case 1 Plant-to-Customer [vanplanttotklant.nl] represents the properties and the actual location of plant trays and trolleys to monitor logistics and alert in case of deviations. If a trolley passes a RFID reader, the system displays a list of the related orders and visualizes any discrepancies with what should be loaded on the trolley. Users along the supply chain can track trolleys and monitor the status of the related orders via the web to determine when the trolleys could be expected to arrive. The main experienced benefits are (i) a reduction of manual activities, including data entry and physical inspection; (ii) less errors because users are alerted immediately in case of any missing, incorrect or extra products, (iii) shorter lead times by reducing waiting times, and (iv) more efficient management of trolleys and plant trays pools. Moreover, the up-to-date information on predicted arrival of shipments allows for a better scheduling of loading, unloading and repacking activities. As a result, the participating companies have been able to optimize their logistical processes, making surprise surges in order arrivals less likely to occur [57].

Case 2 Hubways [hubways.nu] virtualizes the actual status of shipments of plants and flowers by sharing transport order information in a digital platform according to domain-specific standards. Tracking and tracing information is displayed to authorized users, allowing them to easily follow the status, location and timeframe of specific transport orders. Users receive alerts in case of deviations and they can use the up-to-date information for transport planning. As a result, the efficiency of logistics operations can be improved because many administrative tasks, inspections, corrections and searches are no longer necessary. Transporters will also have more time for scheduling shipments, which allows them to provide a higher service level and to handle more transport orders in a shipment. As a result, the number of trips between floricultural market places in The Netherlands (currently over 1800 each day) can be reduced considerably, which has a positive effect on the utilization of transport capacity, sustainability and traffic congestion.

Case 3 Freshtrack [floraholland.com] represents the properties and the actual location of flower boxes, pallets and containers based on barcode scanning, external data and manual entry to monitor logistics and alert in case of deviations. The system is based on unique GS1 bar codes at box level, which are scanned at various critical stages in the chain. Freshtrack provides up-to-date information about who is handling the flowers, what is the source and destination, what are the expected arrival times, etc. The system enables users to monitor logistic processes throughout the supply chain and to streamline planning and administrative processes. As a result, disturbances can be corrected promptly, lead times can be reduced, which results in efficiency improvements and higher quality of perishable flowers and plants.

Case 4, the floricultural pilot of Smart Agri-Food [smartagri-food.eu], addresses a combination of all four virtualization mechanisms. The basis is the virtualization of plants, trays and trolleys along the supply chain, including location, quality conditions (e.g. light, relative humidity, and temperature) and expert quality assessments. The information is based on RFID,

sensors and external data and can be used for tracking and tracing and for alerting users when norms are violated, especially concerning timelines and quality conditions. Furthermore, the quality monitoring system includes product reference information, like standardized pictures and optimal treatment instructions. The future quality of the reference plants is also projected in decay prediction models, which are based on tests in plant labs. These models are then applied to real plants to depict its future quality based on operational sensor data and information about the initial product quality. Together, the application of these virtualization mechanisms allows users to remotely monitor, plan and optimize plant quality starting at the post-harvest phase at the producer up until the selling phase at retailer stores. As a result, the participants expect that the end-quality of the products can be improved, waste can be reduced and logistic costs can be decreased.

Case 5 Cold Chain Scorecard [55] is concerned with a Quality Management System for sea freight in conditioned containers, which includes three different virtualization mechanisms. First, the location and conditions of flower boxes and containers are virtualized to monitor flower quality at critical points in the cool chain. Second, the system projects the future quality of reference flowers and plants in quality decay prediction models that are based on flowering tests. Third, the quality decay models are used to project the future quality of the flowers that are being transported. The main benefits are better tracking and tracing, insight in the remaining vase life of flowers and a better orchestration of product quality in the cool chain for sea freight. As a result, the number of so-called total failures is reduced (sea containers of flowers that are wasted completely due to bad quality conditions) and the quality of flowers for the end customer is improved.

Case 6 Cool Chain Monitoring [floraholland.com] represents the actual conditions of flower boxes and containers in the entire cool chain from departure from the nursery to arrival at the international trading platform. The system is mainly based on data loggers that travel with the products along the entire supply chain and that are read after arrival. By doing so, the system provides a precise record of the conditions products experienced during transport. For example, users can see if products have been subjected to temperature fluctuations that could have an adverse effect on their quality and shelf-life, or if they have suffered due to transport delays. The system is also very useful in the event of claims, because it has the registration details to explain the loss of quality.

Case 7 Virtual Auctioning [floraholland.com] virtualizes batches of plants and flowers, which are being traded on the virtual auction clock, based on product pictures, external data and manual entry. Buyers can connect live to any auction clock of FloraHolland. They can see the products that are being traded (including the supplier information, quality attributes, etc.) and they can place a bid on the virtual auction clock. Often they have established a special dealing room on their premises for this purpose. Growers, on their turn, can monitor the sales progress in real-time. As the products cannot be seen physically at the clock, the quality of product information, including images and supplier information, is of vital importance. For this reason, the quality attributes are standardized and there are strict procedures for supply and verification of product information and pictures. Growers have to provide a product picture that is representative for that particular lot. If a grower does not provide a lot-specific picture, the system shows a photograph from a database with standard product reference information. FloraHolland has also implemented additional incentives to provide high-quality product information, e.g. publication of a reliability index during the auctioning process and early auctioning of products with correct information (may result in higher prices).

The main advantage of virtual auctioning is that is the products need not to be physically present at the auction clock, which implies that commercial processes can be decoupled from logistic processes. Consequently, logistic disruptions do no longer influence the commercial process and products can directly be transported from producers to customers. This not only improves logistics efficiency, but also results in a more optimal cool chain e.g. by a decrease of transshipments.

Table 3 summarizes the virtualization mechanisms that are practiced in the different cases. It shows that the first mechanism, i.e. the virtual representation of real objects, is dominant. It is practiced in all cases for different objects and different purposes. Each of the other three virtualization mechanisms are applied in two cases. The second mechanism, i.e. the virtual representation of reference objects, is applied to add product reference information to a quality monitoring system (case 4) and to a virtual auctioning system (case 7). The third mechanism, i.e. the virtual projection of reference objects, is applied in case 4 and 5 to depict the future quality of reference flowers and plants. These reference projections are then used to determine the typical quality decay behavior of specific varieties in quality decay models. The fourth mechanism, i.e. the virtual projection of real objects, is applied in case 4 and 5 to depict the future quality of flowers and plants, based on quality decay models that use operational sensor data. None of the investigated cases have integrated the projected objects in their planning and scheduling systems. Although most practices focus on the representation of real objects, projection and virtualization of reference objects are considered by the respondents of all cases as promising opportunities.

6.2. Application of the control model to the cases

The research has applied the control model to the cases. It is beyond the scope of this paper to exhaustively deal with the applied models for all cases. Therefore, we describe the model of case 5 as an illustrative example. Case 5 is concerned with the quality management system of a Dutch flower importer that

**Table 3**  
Mechanisms for object virtualization as practiced in the cases.

Time dimension	Reality dimension	
	Real objects	Reference objects
Current/historic state	Case 1 Plant-to-Customer Case 2 Hubways Case 3 Freshtrack Case 4 Smart Agri-Food trial Case 5 Cold Chain Score Card Case 6 Cool Chain Monitoring Case 7 Virtual Auctioning	Case 4 Smart Agri-Food trial Case 7 Virtual Auctioning
Future state	Case 5 Cold Chain Score Card Case 4 Smart Agri-Food trial	Case 5 Cold Chain Score Card Case 4 Smart Agri-Food trial

monitors the temperature of flowers at critical points in the cool chain for sea freight. We have selected this case because it includes three different mechanisms and it is an operational system (contrary to, for example, the pilot system of case 4). Fig. 9 shows how the case can be adequately captured by the control model.

In this case, three virtualization mechanisms are applied: virtual representation of real objects, virtual projection of reference objects, and virtual projection of real objects.

First, the case virtualizes the location and conditions of flower boxes and containers to monitor flower quality at critical points in the cool chain. To do so, it combines data from temperature sensors, batch data from the backend system of the trader (amount of boxes, flower variety and other product information, destination, planned route, etc.), and data about the actual location that are entered manually via a web interface by the different supply chain actors. The temperature sensors are placed in three representative boxes per container. Based on these data from different sources, model-based transformation determines the consolidated temperature, location trajectory, and other information (flower variety, amount, etc.) of each box. This information is used to create a Virtual Flower Box in the flower supply chain

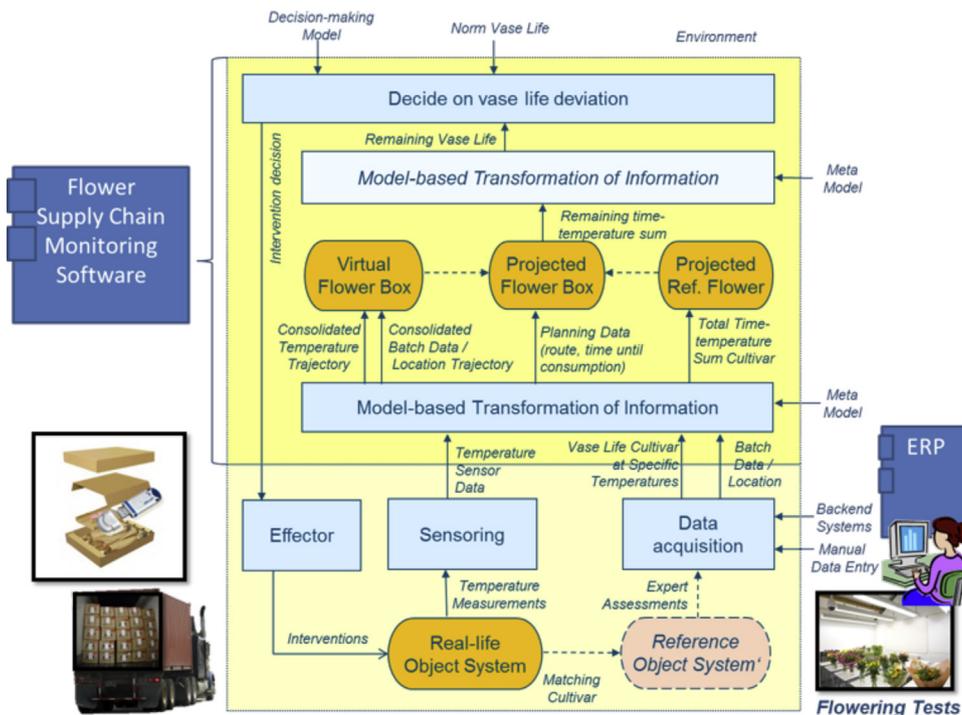


Fig. 9. Applied control model for case 5 Cold Chain Score Card.

monitoring system, which presents static and dynamic features in text and temperature trajectories as visualized in graphs (in hours from start shipment).

Second, the case uses the results of tests on the flowering behavior of flowers for different temperatures (static data). In these tests, different transport conditions are simulated for representative flowers of specific varieties that serve as reference objects. After a simulation, the remaining vase life of a specific flower variety is determined by using cameras that register the flowering behavior at room temperature. The tests are used to define quality prediction algorithms based on a time–temperature sum model, which assumes a cultivar dependent fixed vase life of non-stored flowers. According to this model the remaining vase life can be found by subtracting the recorded time–temperature sum after harvesting, divided by the room temperature, from the vase life of non-stored flowers [56]. The quality prediction model is used to project the decay of the reference flowers in time. The quality decay is also visualized in videos of the flowering process using pictures of the flowering tests (see for example: <http://www.flowerwatch.com/wwwUK/video.asp>).

Third and finally, the quality decay models are used to project the future quality of the flowers that are being transported. To do so, the virtualizations of the real flower boxes (including temperature trajectory and variety) are combined with the projected reference flower of the variety concerned (in particular the total time–temperature sum) and the planning information of the batch (in particular the remaining time until consumption). Subsequently, the remaining vase life is defined by using the decay algorithm for model-based transformation of information. The decision function then compares the remaining vase life with the norm, which is determined by customer requirements. In case of deviations, an appropriate intervention is selected based on an implicit decision-making model (i.e. in the mind of the decision-maker) and implemented manually by the effector function.

The application of the control model has shown that the existing virtualization practices of the cases can be captured adequately in the designed model. The control model proves to be a valuable tool to explicitly define the virtualization mechanisms that are used in the cases.

## 7. Conclusions and discussion

With the maturing of IoT technologies, it is becoming increasingly important to clarify the potential impact and opportunities of object virtualizing for supply chain control. We have argued that the virtualization of products and resources, as enabled especially by IoT technologies, allows for the decoupling of physical flows and information aspects of supply chain operations. As a consequence, SCM would no longer require physical proximity, such that the actors responsible for control and coordination are not necessarily also the ones handling and observing the physical objects. Moreover, virtual objects can be enriched with information that goes beyond human observation, including the historical and predicted state of objects and sensor data. The representation of these data in virtual objects enhances its fitness for use, which allows for advanced control capabilities, including tracking and tracing, quality monitoring and (re)planning functionalities.

The main contribution of the paper is that it has proposed a control model for object virtualization in SCM. The model builds on the concept of virtual objects as addressed before by the Product Information Management and IoT literature. It especially adds a typology and definition of the distinct mechanisms of how virtual objects can be used in supply chain control. The typology distinguishes two dimensions of object virtualization, i.e. the reality dimension and the time dimension. The first dimension

discerns the existence of reference objects that are not (yet) connected to objects that exist physically in the real-world. Virtualization of reference objects is important in SCM, because it allows for postponing the allocation of real objects to a specific task or transaction and, consequently, it increases control flexibility. The second dimension distinguishes the projection of futures virtual objects next to the representation of current objects. The virtualization of projected objects allows for a more proactive supply chain control, such as preventive alerts (early warnings) and dynamic planning and scheduling.

The control model is derived from an in-depth case study of seven Dutch virtualization practices in floricultural supply chains. The case studies have shown that the designed control model is useful to explicitly define the virtualization mechanisms that are used in practice. The respondents also acknowledge the value of the other mechanisms for further virtualization of supply chain control. As such, the control model is useful to define feasible redesign options for decoupling the handling and observing of physical objects from the control activities based on virtual objects. Furthermore, the application of the control model to the cases resulted in information models, which adequately capture the practiced virtualization mechanisms. These models are useful as a basis to define the requirements for information systems that enable the aforementioned redesign options. However, it was beyond the scope of the present research to implement the designed control model in operational control and information systems. Future research is needed to further validate whether the implemented design can be used for its intended purpose.

Furthermore, we have studied cases in one particular sector, i.e. the Dutch floriculture. The floriculture is an interesting sector for the purpose of the present research, because it is characterized by a high variety and volatility of its supply chain processes, which imposes challenging demands on the virtualization of products and resources. We expect that the designed control model is applicable for other sectors as well, among others because the use of a generic control model as a starting point, but further research is needed to provide evidence for this.

Other future work is related to further development of the control model. In particular, we plan to elaborate the Control Model into a more detailed reference information architecture, which will further apply the virtualization mechanisms to specific supply chain processes and which will elaborate distinct architectural views on the virtual objects for different types of users. In this context, visualization plays an important role to create views with a high fitness for use. Promising enabling technologies include advanced image processing and vision systems technologies (including high-speed/low-cost solutions, 3D, and internal features such as ripeness) and the mixture of real and virtual objects in augmented reality (including mobile applications). Furthermore, the reference architecture should support the communication of relevant object information within the supply chain network. Information about relevant physical objects must be available, accessible, and shared in a timely and secure manner with other organizations in order to enable adequate response within allotted timeframes. This in particular requires (i) solid infrastructures to communicate information of objects while safeguarding property, access and usage rights, (ii) standards for a seamless identification and exchange of product and logistics data, and (iii) trustworthy authorization and security mechanisms.

## Acknowledgements

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## Appendix A. Introduction of the mapped cases

### A.1. Case 1 Plant-to-Customer

The Plant-to-Customer project [[www.vanplanttotklant.nl](http://www.vanplanttotklant.nl)] has analyzed and demonstrated the benefits of RFID in plant supply chains based on a pilot implementation including growers, a trader and logistic service providers [57]. The system uses passive ultrahigh-frequency (UHF) RFID tags to track trays of plants from two growers in the Netherlands, through the hands of logistics providers and exporters, to transport companies' distribution centers, before the trays are then shipped to retailers. The software compares the products on the trolley with the order and displays a list, along with any discrepancies, on a screen mounted above the grower's dock doors. Users can also access the information via the web to determine when the trolleys were shipped, and thus when they could be expected to arrive.

### A.2. Case 2 Hubways

The Hubways project [[www.hubways.nu](http://www.hubways.nu)] aims to implement a digital platform that supports the exchange of cargo, capacity and information on the level of the logistics between floricultural market places and their stakeholders in The Netherlands. The core of the platform is the management of transportation orders, which can be created either automatically via electronic messages or manually based on purchase orders. Furthermore, additional services are provided for tracking and tracing the status of transport orders, billing, transport planning, etc.

### A.3. Case 3 Freshtrack

Freshtrack is an international Tracking and Tracing web application of FloraHolland that shows the location of flowers in the chain [[www.floraholland.com](http://www.floraholland.com)]. It also provides up-to-date information about who is handling the flowers, what is the source and destination, what are the expected arrival times, etc. The system enables users to adjust planning, anticipate sales processes and integrate logistic & administrative processes. Freshtrack is based on unique GS1 bar codes at box level. These bar codes are scanned at various critical stages in the chain, such as when the products leave the nursery; when they are with the cargo transporters; at the departure airport and upon arrival at the international trading platform.

### A.4. Case 4 Smart Agri-Food trial

As part of the European Smart Agri-Food project [[www.smartagrifood.eu](http://www.smartagrifood.eu)], this pilot has analyzed and demonstrated the possibilities of Future Internet technologies for dynamic Quality Controlled Logistics in floricultural supply chains. In this

approach, logistic processes throughout the supply chain are continuously monitored, planned and optimized based on real-time information of the relevant quality parameters (such as temperature, humidity, light, water). The pilot has developed a prototype system, that leverages the trader's logistic tracking system of a plants trader, which is based on the ultrahigh-frequency RFID tags that are attached to the complete pool of plant trolleys. The pilot is now being upgraded in an operational software system as part of the successor project Flspace [[www.flspace.eu](http://www.flspace.eu)].

### A.5. Case 5 Cold Chain Score Card

This quality management system of a Dutch flower importer monitors the temperature of flowers at critical points in the cool chain [55]. It uses data loggers that are read several times during its journey from international growers via freight forwarders to the Dutch importer. The data are stored in a web application that calculates the remaining degree hours of a shipment. Authorized users can view and update the status of shipments in this database.

### A.6. Case 6 Cool Chain Monitoring

Cool Chain Monitoring is FloraHolland's international cool chain application that monitors the entire cool chain from departure from the nursery to arrival at the international trading platform [[www.floraholland.com](http://www.floraholland.com)]. During transport, information about temperature and other transport conditions is recorded by data loggers. When the products arrive at the international trading platform, the data loggers are read and the data are uploaded to a web application, where it is immediately available. By doing so, the system provides a precise record of the conditions products experienced during transport. For example, users can see if products have been subjected to temperature fluctuations that could have an adverse effect on their quality and shelf-life, or if they have suffered due to transport delays.

### A.7. Case 7 Virtual Auctioning

Virtual auctioning system called KOA (Remote Auctioning) that allows to buy, anywhere in the world, real-time via Internet on all the FloraHolland auction clocks [[www.floraholland.com](http://www.floraholland.com)]. Buyers can connect live with the auction clocks. They can see the products that are being traded, (including the supplier information, quality attributes, etc.) and they can place a bid on the virtual auction clock. There are strict procedures for supply and verification of product information and pictures. Besides the product information of the growers, there are databases with high-quality standard product reference information.

## Appendix B. Definition conceptual model in relational database notation

M1	Mechanism 1: virtual representation of real objects
Formalization	Relation O-State ( $O_{ID}$ , $A_{ID}$ , $A_{ID\_Value}$ , $TI\_of\_State$ , $L_{ID\_of\_State}$ , $ORG_{ID\_of\_State}$ , $BOM\_O_{ID}$ )
Explanation	<ul style="list-style-type: none"> <li>• A description of properties denoting the state of an object at different points in time.</li> <li>• Transition functions are needed for historical state trajectory (Time Frame)</li> <li>• See Table below for a definition of the relevant concepts</li> </ul>

M2	Mechanism 2: virtual projection of real objects
Formalization	Relation PO-State ( $P_{ID}, O_{ID}, A_{ID}, A_{ID\_Value}, TI\_of\_State, L_{ID\_of\_State}, ORG_{ID\_of\_State}, BOM_{O_{ID}}$ )
Explanation	<ul style="list-style-type: none"> <li>• A description of projected properties denoting the future state of an object at different points in time.</li> <li>• Each tuple of this relation denotes then for an Projection with P_ID as identification, an Object its object identification (<math>O_{ID}</math>), the name of a valid attribute measured (<math>A_{ID}</math>), the value of that measurement (<math>AID\_Value</math>), the Time stamp of that projected value (<math>TI\_of\_State</math>), the projected location and owner of the object at that time (<math>L_{ID\_of\_State}</math> and <math>ORG_{ID\_of\_State}</math>) and the projected relations with other objects (<math>BOM_{O_{ID}}</math>.)</li> <li>• Projection functions are needed to simulate multiple future state trajectories (TF). A projection is similar to a transition, with the connotation that you may have more than one to simulate the object's state for different scenarios.</li> <li>• See table below for a definition of the relevant concepts</li> </ul>
M3	Mechanism 3: virtual representation of reference objects
Formalization	Relation RO-State ( $RO_{ID}, O_{ID}, A_{ID}, A_{ID\_Value}, TF\_of\_State, ORG_{ID\_of\_State}, BOM_{O_{ID}}$ )
Explanation	<ul style="list-style-type: none"> <li>• Inheritance of values from reference objects.</li> <li>• A reference object does not have a location</li> <li>• However, it has a time in which it is valid</li> <li>• Transition is needed to define the time frame in which the reference object is valid</li> <li>• See Table below for a definition of the relevant concepts</li> </ul>
M4	Mechanism 4: virtual projection of reference objects
Formalization	Relation PRO-State ( $P_{ID}, RO_{ID}, O_{ID}, A_{ID}, A_{ID\_Value}, TI\_of\_State, ORG_{ID\_of\_State}, BOM_{O_{ID}}$ )
Explanation	<ul style="list-style-type: none"> <li>• Combination of M2 and M3, no additional concepts required.</li> </ul>

**Formalization of the concepts.**

Concept	Relational database notation	Explanation	Mechanism
$O_{ID}$	$OID = \{OID(id) id = 1, \dots, NOID\}$	Unique identification of objects	All
$A_{ID}$	$AID = \{AID(id) id = 1, \dots, NAID\}$	Unique identification of attributes	All
$A_{ID\_Value}$	$AT = \{AT(a) a = 1, \dots, NAT\}$	Objects have measurable properties that one can represent through attribute, value pairs. Where value pairs are drawn from some domain. Properties of objects are recorded in the form of numerical sensor readings or measurements or pictures or other images.	All
$TI\_of\_State$	$TI = \{TI(t) t = 1, \dots, NT\}$	Time: (represented) states of object at a certain moment of time	All
$L_{ID\_of\_State}$	$L_{ID} = (L_{ID}(loc\_id) loc\_id = 1, \dots, nL_{ID})$	Locations, physical objects are at a certain location, identified by a unique location identifiers such as a global location number (GLN) or global position system coordinates	M1, M2
$ORG_{ID\_of\_State}$	$ORG_{ID} = (ORG_{ID}(org\_id) org\_id = 1, \dots, nORG_{ID})$	Organizations, objects have a certain owner, identified by a unique organization identifier	All
$BOM_{O_{ID}}$	Each object may have a bill of material (simple only stating that another object is part of the object. Concept is BOM. Instance is $BOM(O_{ID}(id))$ , BOM of an object with object id $O_{ID}(id)$ . In its simplest form a BOM denotes that a resulting O-Object consist of (parts of) another I-Object. $BOM\_Relation (O-O_{ID}, I-O_{ID})$	Objects may have constituent parts, objects on their own. That constituent parts idea can take different shapes: <ul style="list-style-type: none"> <li>• Undivided objects are assembled into the object. Also sensors and labels are part of that list.</li> <li>• Parts of objects have been used to create the object.</li> <li>• Depending on the shape just mentioned the id's of the constituent parts may be preserved on the physical object or not.</li> </ul>	all
Domain	$DA = \{DA(d) d = 1, \dots, NDA\}$	Domains. Each attribute has a number of values/shapes it can take.	All
Transition	$TRAN = \{TRAN(tran) tran = 1, \dots, NTRAN\}$ Relation: $TRAN (TRAN, O_{ID}, TF, TRF, L_{ID})$	Transition: Key elements of a transition are Objects, the time frame of transition (TF), the location where the transition starts to take place (beware of a movement) and the transition function. A transition thus may incorporate many objects that participate, a location at start, have a timeframe and a transition function. The results of a transition are state changes of attributes (a few or many). That state changes can be observed and noted in the O-state relation(s).	M1, M3

Transition Function	TRF = {TRF(trf) trf = 1, ..., NTRF}	Transition: A transition function transforms objects over a time frame.	M1, M3
Time Frame	TF = {TF(tf) tf = 1, ..., NTF} Each TF(i) consists of a TI(j) denoting the beginning of a time frame and a TI(k) denoting the end of a time frame. With Val(TF(l)) <= Val(TF(k))	Time frame: a certain period of time in which transitions of objects take place.	All
P <sub>ID</sub>	P_ID = {P_ID(pid) pid = 1, ..., NP_ID}	Projected State of an object. We must be able to represent the projected states of objects. That can be noted in a simple relational table. Drawn values for A <sub>ID</sub> can be complex. Each projection however needs to be identified.	M2, M4
Projection Function	P_TRF = {P_TRF(ptrf) ptrf = 1, ..., PNTRF} P_TRAN = {P_TRAN(tran) ptran = 1, ..., PNTRAN} Relation: P-TRAN (P-TRAN, OID, TF, P_TRF, L <sub>ID</sub> )	Basically a Projection is the same as a transition with the connotation that you may have more than one. We must be able to represent that a(n) (set of) object(s) are subject to some transformation function that takes place at a certain location, starts at a certain point in time and has a timeframe (start and end). This can be denoted by again a Relation P_TRAN(P-TRAN, OID, TF, P-TRF, L <sub>ID</sub> ). Each tuple then denotes the ID of the projection, the ID of the Transformation, the ID of an object affected, the timeframe of execution (TF), the ID of the transformation function applied and the location of the object at start.	M2, M4
RO <sub>ID</sub>	RO_ID = {RO_ID(id) id = 1, ..., NRO_ID}	State of a Reference Object, can also be represented as a set of attributes and values. These attribute-value-pairs can either be derived from a representative physical object (typical object) or they can be defined as a combination of wanted features (conceptual object).	M3, M4

**Definitions**• O-State = object state. • PO-state = projected object state. • RO-state = reference object state. • PRO-state = projected reference object state. • O<sub>ID</sub> = object identifier. • P<sub>ID</sub> = projected object identifier. • RO<sub>ID</sub> = reference object identifier. • AT = attribute. • A<sub>ID</sub> = attribute identifier. • TI = time stamp. • TI-of-state = time stamp of a certain object state. • L<sub>ID</sub> = location identifier, e.g. Global Location Number or global position system coordinates. • ORG<sub>ID</sub> = organization identifier, i.e. supply chain participant that owns an object with a certain identifier at a certain moment of time. • BOM<sub>O<sub>ID</sub></sub> = bill of material of an object with a certain Identifier, used to describe the relations of an object with other objects, including constituent parts, at a certain moment of time. • DA = domain. • TRAN = transition. • TRF = transition function. • TF = time frame. • P\_TRF = projected transition function. • P\_TRAN = projected transition.

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