# Intelligent Autonomous Vehicles in digital supply chains: A framework for integrating innovations towards sustainable value networks

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## ABSTRACT

The principal objective of this research is to provide a framework that captures the main software architecture elements for developing highly customised simulation tools that support the effective integration of Intelligent Autonomous Vehicles (IAVs) in sustainable supply networks, as an emerging field in the operations management agenda. To that end, the study's contribution is fourfold including: (i) a review of software simulation tools and platforms used in assessing the performance of IAVs interlinked with sustainability ramifications in supply chain (SC) ecosystems, (ii) an integrated software framework for monitoring and assessing the sustainability performance of SCs defined by the utilisation of innovative IAVs in operations, (iii) a translation of the proposed SC framework into a corresponding software application through a robust five-stage stepwise process, and (iv) a demonstration of the developed software tool through its application on the case of an IAV system operating in a customisable warehouse model. Our analysis highlights the flexibility resulting from a decentralised software management architecture, thus enabling the dynamic reconfiguration of a SC network. In addition, the developed pilot simulation tool can assist operations managers in capturing the operational needs of facilities and assessing the performance of IAV systems while considering sustainability parameters.

## 1. Introduction

The Internet of Things (IoT) paradigm enables interconnection, intercommunication and interaction among supply chain (SC) actors that allow for the dynamic management of global network operations (Verdouw et al., 2016), hence promoting digital transformations in a cradle-to-grave perspective (Bechtsis et al., 2017). Nowadays, owing to the technological innovations, IAVs are characterised by inherent business logic and the technical capability to sense and autonomously interact with the surrounding environment in a manner that promotes reduced emissions, rational economic expenditure and increased societal benefits such as improved safety and accessibility (Koloz et al., 2013). To that end,

under the IoT umbrella, Intelligent Autonomous Vehicles (IAVs) constitute a radical innovation that could assist in the efficient management of production lines, handling of warehouse inventories and supporting intra- and inter-logistics services in a gamut of economic sectors including port container terminals (Angeloudis and Bell, 2011; Carlo et al., 2014), agriculture (Reina et al., 2015), healthcare (Kumar and Rahman, 2014) and industrial manufacturing (Ferrara et al., 2014).

Notwithstanding the emerging popularity of IAVs, academic research on the integration and sustainability assessment of autonomous systems in a SC context is lacking (Schmidt et al., 2015), while the extant literature only myopically refers to the confined applicability of IAVs on specific network echelons (Gu et al., 2010; Kumar and Rahman, 2014). The incorporation of IAVs in a SC context to promote digital transformations is associated with considerable capital requirements and technical challenges (Browne et al., 2012). In this regard, the use of software simulation tools to elaborate and proactively evaluate the operational

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performance and sustainability implications of IAVs for fostering the establishment of bespoke SCs is necessitated (Black et al., 2016). Simulation software tools provide the capability to make projections to the real world, assist SC actors in their decision-making process, including sustainability considerations (e.g., resource efficiency, vehicle emissions), whilst also tackling system uncertainties and complexities. These simulations can provide valuable managerial insights prior to the deployment of autonomous operations across a digital SC (Zeng et al., 2016).

Despite the plethora of commercially available simulation software tools enabling the analysis of manufacturing and distribution operations, such off-the-shelf solutions often provide limited flexibility in capturing customised working environments and corresponding IAVs. Moreover, commercial software packages contain built-in libraries that might be either outdated or limited in terms of range of covered IAVs (Briggs et al., 2017). To that end, considering the on-going innovations in the automations field, simulating IAVs with commercial software is typically governed by a magnitude of non-realistic assumptions. In particular, commercial software simulation tools do not provide the capability to capture an autonomous system's response to real-world environmental dynamics (Tsolakis and Bechtsis, 2017). A typical example is the impact of IAVs on operations and sustainability performance owing to multiple reconfigurations in the facility layout over time. Therefore, the understanding of the efficient use of IAVs in SC operations, from a sustainability perspective, and the use of software simulation to identify optimum deployment within a changing manufacturing context is the principal objective of this paper. The approach used builds on the established concepts of sustainability and Intelligent Autonomous Systems in the strategic management field (Mertens and Kanet, 1986; Seuring and Müller, 2008).

From both a theoretical and practice perspective, the study's contribution is fourfold including: (i) a review of software simulation tools and platforms used in assessing the performance of IAVs interlinked with sustainability ramifications in a SC ecosystem, (ii) an integrated software framework for monitoring and assessing the sustainability performance of supply networks defined by the utilisation of innovative IAVs in operations, (iii) a translation of the proposed SC framework into a corresponding software application through a robust five-stage stepwise process, and (iv) a demonstration of the developed software tool through its application on the case of an IAV system operating in a customisable warehouse model.

The remainder of this paper is organised as follows. In Section 2 the utilisation of IAVs in SC operations along with the associated sustainability ramifications are analysed, while in Section 3 a review of the available simulation software tools and platforms for evaluating and managing IAVs is provided. In Section 4 a novel framework proposes a software architecture for fostering the integration of IAVs in a SC context. The framework enables the sustainability performance assessment of customised supply networks that incorporate IAVs. Following, in Section 5 the applicability of the proposed framework is demonstrated through the actual development and application of a demonstration pilot simulation software tool focusing, at this initial stage of our ongoing research, on the environmental sustainability dimension. In Section 6 we provide simulation results on a conceptual warehouse along with a discussion. In the final Section 7 we wrap-up with conclusions and limitations while we further outline beyond state-of-the-art research avenues for incorporating IAVs in a sustainable SC context.

## 2. IAVs and sustainable supply networks in the digital era

The advent of digitalisation signals advances in industrial information and enterprise systems that further instigate changes in both the intra- and the inter-organisational boundaries that every large, medium and small sized company has to realise in order to compete in a globalised context (Xu, 2011). IAVs are documented to foster the sustainability performance of SC systems across the economic, environmental and social sustainability constituents (Craig and Dale, 2008; Kannegiesser et al., 2015; Wu et al., 2017), including: (i) increased productivity levels (Negahban and Smith, 2014), (ii) labour cost savings (Gosavi and Grasman, 2009), (iii) lower energy consumption (Acciaro and Wilmsmeier, 2015), (iv) reduced emissions (Geerlings and Van Duin, 2011), and (v) enhanced workforce safety (Duffy et al., 2003). However, research that motivates the integration of IAVs' sustainability ramifications onto the SC ecosystem is not sufficient. The aforementioned observation is further supported by the S2C2 tool provided by Bechtsis et al. (2017), a tool that evidently reveals opportunities for facilitating the adoption of IAVs into SC design and planning through identifying the key related decisions, as these are mapped on the relevant strategic, tactical and operational levels of the natural hierarchy. Opportunities can be identified basically on the procurement and on the sales (last-mile logistics) tiers covering all levels (i.e. strategic, tactical, operational and execution) as the incorporation of IAVs is observed to be limited. In Subsection 2.1 and Subsection 2.2 we exemplify the role of IAVs in a digital SC setting and we describe the key IAV-centric decision-making parameters that could impact SC sustainability.

### 2.1. Integrating IAVs in SC operations

By 2025 global economy is expected to serve a well-informed population willing to compensate for personalised goods and services (Ford and Despeisse, 2016). Indicatively, the European Commission has set the Industrial Landscape Vision for the 2025-time horizon to facilitate new production systems that will foster innovation and competitiveness through analysing and prioritising societal, technological, economic, environmental and policy drivers (EU Science Hub, 2016). In this context, industries in Europe invest in advanced manufacturing systems and sustainable production methods enabled by information and communication digital technologies (Scapolo et al., 2014). Enterprise information systems are basically analysed at design, architecture, integration, interoperability and networking levels and enable the 3C triplet, i.e. communication, cooperation, and collaboration, among SCs and network actors through the use of standards and technological innovations (Romero and Vernadat, 2016). Especially, standards promote innovation and can be a useful instrument for crafting policies towards shaping the industrial landscape of the future.

The term 'Synchronised Production & Logistics' is used to describe the operational level integration of manufacturing and logistics (including storage and transportation operations). Luo et al. (2016) define 'Synchronised Production & Logistics' as: "*Synchronising the processing, moving and storing of raw material, work-in-progress and finished product within one manufacturing unit by high level information sharing and joint scheduling to achieve synergic decision, execution and overall performance improvement*". However, an opportune decision-making process is required that could foster the effective adoption of automations towards synchronised production and logistics systems (Bechtsis et al., 2017). In particular, IAVs can be incorporated at all levels of an end-to-end SC, although their adaptation to the manufacturing shop floor tasks, (e.g., grasp, move, scan) and the warehouse facility layouts is the prevalent trend.

Typically, IAVs are elaborated extensively at an operational level and can greatly influence SC flows while promoting added value and innovation within a digital SC ecosystem. Furthermore, to

address the global SC challenges, all tiers of the supply network should function in a coordinated manner. Overall, automations can provide an integrated approach to an envisioned digital supply system where all decisions are evaluated in a holistic and systematic manner as conceptually depicted in Fig. 1.

The identification of the appropriate IAVs in a customised setting is a challenging task due to the complex nature of the related SC operations under specific sustainability, functional and budget constraints. To that end, simulation is suggested to be a viable scientific approach to tackle the aforementioned issues (Kavakeb et al., 2015), considering that this approach allows the study of a system without provoking any disturbance (Demirci, 2003), and to further explore conceptual scenarios and evaluate the associated impact in the real world (Yun and Choi, 1999). Particularly, considering a SC as a complex system characterised by data structures, operations, and product and information flows, IAVs are expected to exhibit direct reactive action to each SC echelon. To this effect, agent-based simulation could be used to proactively represent the operation of IAV systems within a SC setting. Generally, an agent is a software or hardware object able of performing specific tasks autonomously (Farahvash and Boucher, 2004). Particularly, Weiss (1999) provides the following definition: "*Agents are autonomous, computational entities that can be viewed as perceiving their environment through sensors and acting upon their environment through effectors*". Following that, sensors and effectors can be either physical, i.e. field devices which are represented by software files or data streams, or agents that can be: (i) autonomous, (ii) interacting, (iii) intelligent, and (iv) flexible. Therefore, multi-agent systems are recommended for simulating IAVs cooperating to tackle operational challenges that are beyond the capabilities or knowledge of each individual entity (Flores-

Mendez, 1999), especially within a sustainability context.

### 2.2. Leveraging IAVs for SC sustainability

Product and production life cycle must be aligned with sustainable SC and manufacturing activities in order to get a systematic and holistic approach that supports the decision-making process as: "*Sustainable manufacturing satisfies the (societal) demand for functionality while adhering to environmental, economic and social targets over the entire life cycle of products and services*" (Rödger et al., 2016). However, the realisation of efficient and sustainable SC operations through elaborating IAV systems denotes that a systemic multi-criteria decision-making process has to be considered in the relevant analysis tools (including simulation software and specifically agent-based approaches). To this effect, Bechtsis et al. (2017) provide a critical taxonomy of key decisions for facilitating the adoption of IAVs for the design and planning of sustainable SCs in the modern digitalisation era, while the related decisions are further mapped on the strategic, tactical and operational levels of the natural hierarchy.

Firstly, at the economic dimension, the strategic decision-making includes the determination of the capital requirements, the appropriate selection of data sharing schemes for communication and coordination with the SC environment, the design of the facility layout environment and the feasibility analysis. The determination of the exact vehicle type and fleet size along with the economic key performance indicators can be either at strategic or tactical levels, supporting the determination of maintenance costs and the integration with the proper sensors (both for vehicles and facility layouts). At the operational level, efficiency and performance must be taken into consideration while simultaneously fine-
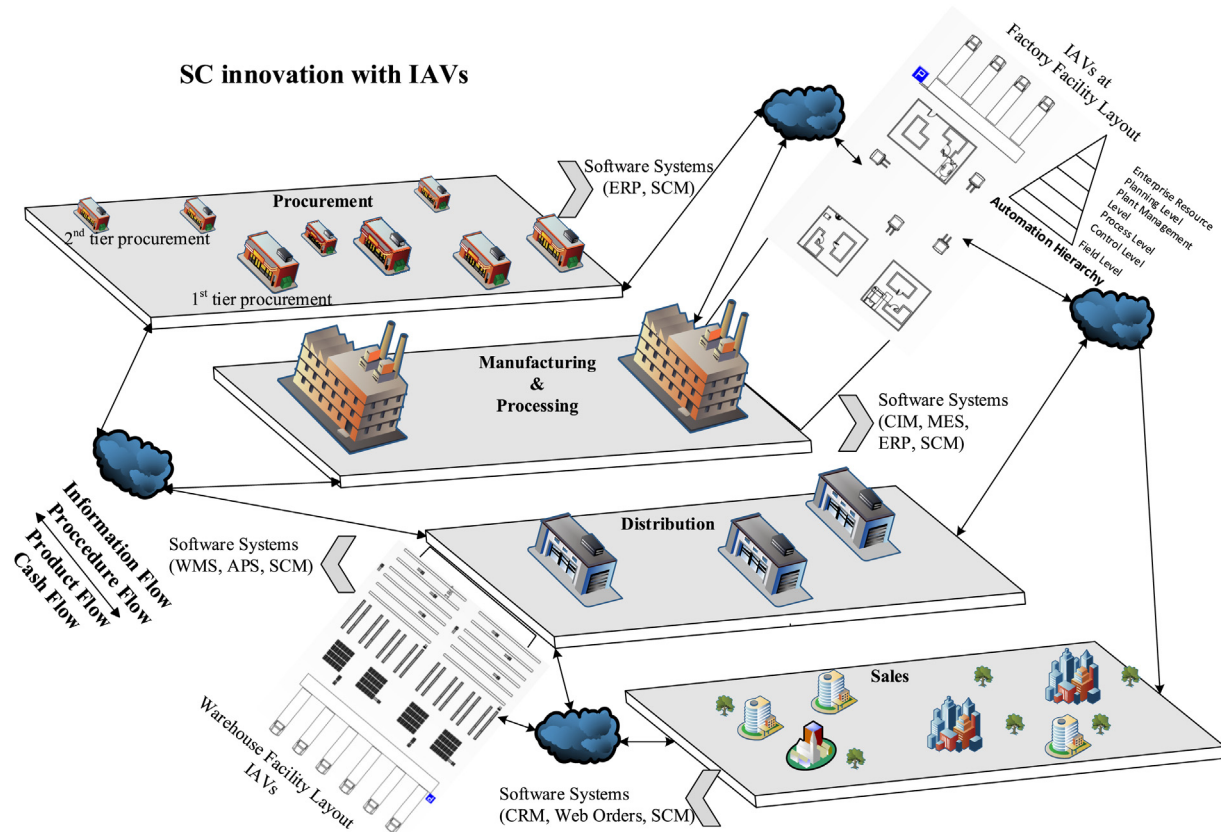


**Fig. 1.** Integration of IAVs for devising digital SCs.

tuning the navigation, routing, scheduling and dispatching algorithms based on the economic key performance indicators.

Secondly, at the environmental constituent, strategic decision-making focuses on the identification of the environmental goals towards establishing energy management and control policies. The determination of the required fuel type and the adoption of specific environmental key performance indicators are referring to the tactical level, along with the selection of the vehicles charging/refuelling strategy and the adoption of specific tools for the environmental assessment of the manufacturing plant. Following, at an operational level, the monitoring of the environmental efficiency performance on a daily basis along with the optimisation of the routing, scheduling and dispatching algorithms based on environmental criteria (e.g., minimisation of the total emissions) need to be considered.

Finally, at the social dimension, the SCs' workforce safety and accessibility, along with health and safety of the IAV operators, is prevalent. In addition, emphasis is provided to the continuous creation of skilled jobs, the constant improvement of ergonomics for the workers at the tactical level, the identification of opportunities for sensors' applicability to improve shop floor safety, and the adoption of tools for monitoring and assessing potential hazards. At an operational level, the fine-tuning of vehicles' social implications (i.e. accidents, hazards, noise level, ergonomics etc.) ensures the social performance of the system.

## 3. Simulation software for IAVs: a critical categorisation

Developing sustainable supply networks embracing IAVs, whilst considering the trade-offs among significant capital investments, operational constraints and derived sustainability benefits, implies that simulation approaches are needed in order to benchmark such systems. Simulation, from the early 1970's till today, is a continuously evolving field of research with undoubted contribution to the progress of manufacturing systems (Mourtzis et al., 2014).

A vast number of software tools available for simulating IAV operations are available, but their detailed technical analysis extends the scope of the present research study. In this section, we rather provide a representative categorisation of selected software applications that consider logistics operations in industrial manufacturing settings, deriving from a review of the related research publications. Generally, software tools and platforms used for simulating IAV systems in manufacturing and SC contexts can be clustered into the following five categories (see Table 1):

1. Discrete-event simulation software,
2. Robotics software,
3. Multi-agent software,
4. Dedicated software for IAVs in intra-logistics, and
5. Object-oriented programming languages for complex industrial systems.

Except for the abovementioned categories, traffic simulation tools are widely used for replicating the kinematics of passenger cars and urban logistics. Such tools can precisely simulate a vehicle's movement and use a business logic layer for scheduling all the necessary activities. Traffic simulation tools could be also used as dedicated tools for the management of IAV systems for intra-logistics operations in manufacturing plants. This categorisation is not based on an exhaustive list of all existing software tools and platforms, but rather acts as a synthesis of all major applications that we have identified as part of our on-going research.

The introduction of IAVs into the manufacturing sector triggered the development of associated simulation software. General purpose discrete-event simulation software usually involves the creation of robust components (i.e. blocks that can be programmed to perform specific actions) which can handle specific operations and communicate with each other in order to develop the simulation model. Moreover, general purpose discrete-event simulation software packages are used to represent manufacturing and industrial processes (Negahban and Smith, 2014), like for example: general system design and facility layout, material handling, cellular manufacturing, and flexible manufacturing system designs. Specific add-on modules assure compatibility with every aspect of the manufacturing activities, including intelligent intra-logistics vehicles, while blocks with custom functionalities can be developed as well.

In an industrial context, simulation software usually has 3D add-on functionalities for precisely representing the movement of machinery and other physical objects. In this regard, the emergent robotics and automation sector motivates the development of sophisticated robotics control software that includes advanced 3D graphics along with human-machine interface simulation techniques (Bechtsis and Moisiadis et al., 2017). Robotics software develops or incorporates modules for general purpose simulation activities while focusing on the robotic systems (including IAVs) as the main research activity.

In addition, multi-agent based techniques are prevailing in recent years due to the decentralised nature of IAVs, the complex SC environment with the multiple stakeholders and the mass customisation schemes. Existing commercial and open source multi-agent simulation software mainly refers to decentralised solutions that are more flexible and robust through avoiding the existence of a single point of failure and overriding any kind of

**Table 1**
Categorisation of software tools and platforms used for simulating IAV systems in SC ecosystems.

| Category | Software and Platforms | References |
|---|---|---|
| Discrete-event simulation software | ARENA | Ho and Liu (2006); Hsueh (2010); Jaoua et al. (2012); Rocha et al. (2010) |
| | SIMIO | Jain and Foley (2016); Pegden (2007) |
| | Flexsim | Kavakeb et al. (2015); Kesen and Baykoç (2007) |
| | Promodel | Leite et al. (2015); Lu and Wiens (2002) |
| | PetriNets | Hernández-Martínez et al. (2015); Meng (2010) |
| | AutoMod | Le-Anh and De Koster (2004); Moorthy et al. (2003) |
| Robotics software | Webots-MATLAB | Emmi et al. (2013); Ioannidis et al. (2011) |
| | ROS - middleware C++ | Myrsky et al. (2012); Vasijević et al. (2016) |
| Multi-agent software | AnyLogic | Hao and Shen (2008); Leriche et al. (2015) |
| | JADE | Chen and Chen (2010); Ribeiro et al. (2015) |
| Dedicated vehicle control software packages for intra-logistics | openTCS | Eilers and Rossmann (2014) |
| | Vendor Specific | AGVE Group, Egemin, JBT Corporation and other |
| Object-oriented programming languages | C++ | Başak and Esra Albayrak (2015); Cimino et al. (2010); Gaskins and Tanchoco (1989); Shah et al. (1997) |
| | JAVA | Martínez-Barberá and Herrero-Pérez (2010); Michalos et al. (2016) |

disturbances. Software tools in this category enable the development of more flexible solutions in the context of mass customisation that may not always be optimum.

Dedicated simulation software packages for IAVs and intralogistics take into consideration every aspect of a vehicle and allow for a detailed consideration of vehicle parameters and kinematics, vehicle surrounding (i.e. working facility layout), network parameters (communication with software modules and other vehicles), and real-time interaction with the working environment. It is worth mentioning some commercial autonomous vehicles vendors with dedicated software for the management of an intralogistics vehicle fleet like for example the AGVE Group traffic control solution, the Egemin Transport Intelligent Control Center and the JBT Corporations Self-Guided Vehicle Manager Software.

Finally, the use of general purpose object-oriented programming languages is continuously increasing in intra-logistic services due to the one-to-one correspondence between the physical objects and their digital representations. Every object is represented by a discrete class and each class follows the object-oriented concepts like encapsulation, abstraction, inheritance, polymorphism. As a result, objects can be easily extended, diversified and reused, while the maintenance requirement of the software significantly decreases.

Overall, the use of simulation methods in manufacturing sectors and SC management is continuously growing and they could assist in the analysis of the expected sustainability impact of alternative IAV systems. Nevertheless, the emerging need for more efficient and customisable simulation techniques motivates the development of hybrid methods integrating simulation methods with agent-based simulation and artificial intelligence (Negahban and Smith, 2014).

## 4. Proposed simulation framework

The proposed framework represents an inclusive simulation software structure for the integration of IAVs onto the digital SC ecosystem in a holistic and systematic manner. The framework is divided into three tiers of abstraction following the general principles of the ISA95 model of the non-profit community MESA (Manufacturing Enterprise Solutions Association). Particularly, the ISA95 model divides a classical production pyramid into: (i) business planning and logistics, (ii) manufacturing enterprise system, and (iii) control, and defines data structure and services at each corresponding tier (Verdouw et al., 2010; Witsch and Vogel-Heuser, 2012).

Fig. 2 depicts a high-level representation of the proposed simulation software framework. At the first tier, integration and interoperability of system agents in the context of a digital SC ecosystem is the main focus. At the second tier, the functional role of IAV systems towards promoting innovations and sustainability in digital SCs is more transparent. More specifically, the IAV entities are the enablers for the mass customisation scheme by providing the interface between the automation layer and manufacturing information systems. The third tier is the bottom level of the framework and is beyond the scope of the current research. In particular, at the third tier of abstraction all manufacturing equipment, from simple sensors and programmable logic controllers to sophisticated manufacturing equipment (e.g., cranes, drilling machines etc.), are considered in order to ensure operationalised interconnection, intercommunication and interaction with IAVs.
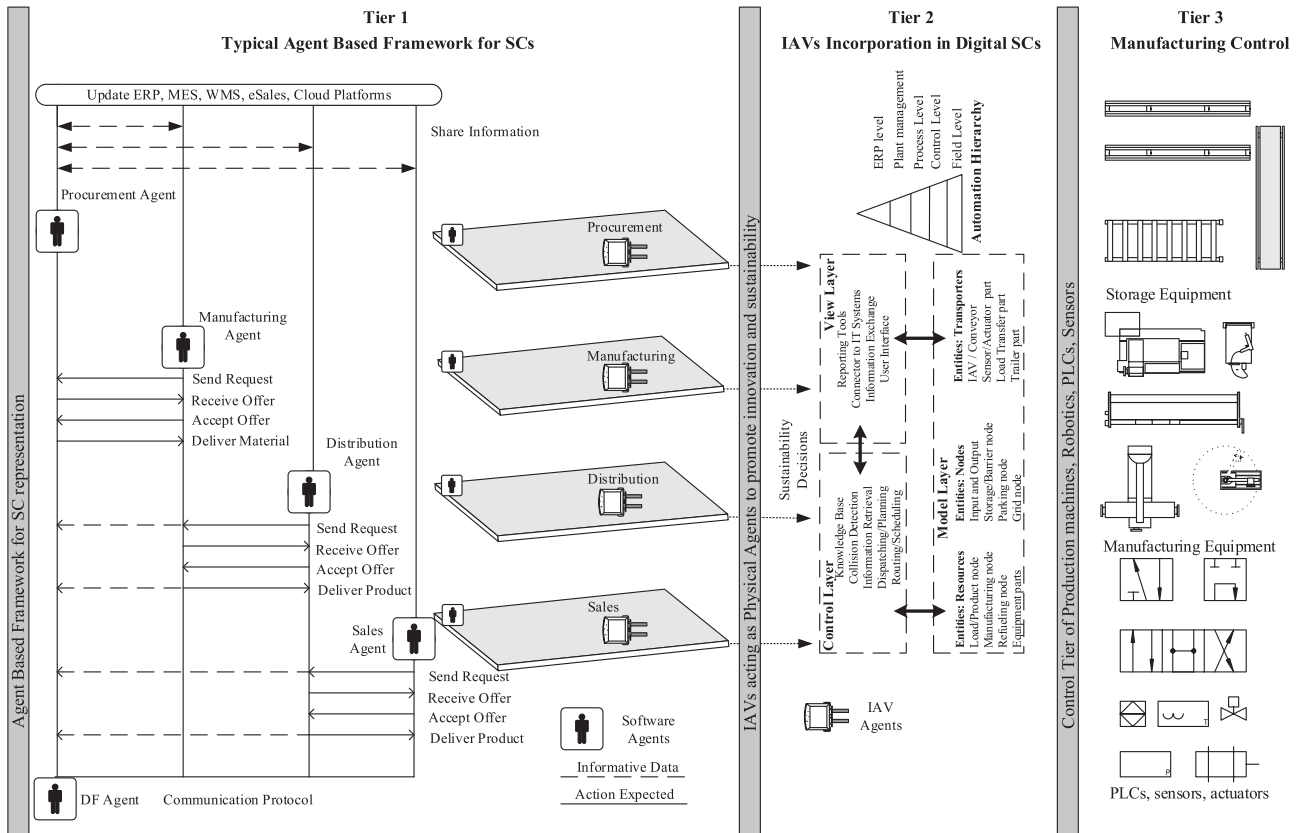


**Fig. 2.** High-level representation of simulation software framework for IAVs.

## 4.1. First tier of abstraction

The first tier of the proposed framework is based upon the implementation of software agents for promoting collaboration and negotiation among the high-level entities of a SC (Jiao et al., 2006), supported by an added layer of integration with the SC's information systems. Multiple agents register dynamically to the network in order to seize resources (raw materials, work in progress, finished products), manage the flows (information, procedures, cash, product) of the digital SC using the appropriate communication and coordination protocols. Directory facilitator agents can be used as a reliable source of information for the existence of ready to use agents and for keeping the agents' types and skills.

Each agent possesses de facto knowledge about the real-world environment and tries to enrich this knowledge by exchanging information and negotiating with other agents. Software agents organise the typical flows while updating their knowledge base and the SC's information systems at every tier. Agent communication and message exchange follow Extensible Markup Language (XML) based ontologies in order to provide a clear context to all conversations and follow specific standards. Furthermore, the framework implements specific interfaces with enterprise resource planning and manufacturing oriented information systems. The business to Manufacturing Markup Language of the ISA95 model is an XML based solution for ontology driven conversations that defines the context of each message exchange (Cupek et al., 2016).

At the same time, IAVs provide feedback to the software agents directly from the physical entities of the manufacturing environment. IAVs are considered highly critical entities for the system as they enable the dynamic reconfiguration of the production life cycle according to the market needs and can be considered as the control unit that supervises the shop floor processes and data. To this effect, IAV agents organise the intra-logistics, share information and interact dynamically with the software agents in real-time.

The framework illustrated in Fig. 2 assumes that the IAV systems implement the basic principles of a ready to use Cyber-Physical System (Lee et al., 2016), characterised by: real-time smart connection of the entities, conversion of data streams to information, a flexible cyber level, a cognition level for decision-making, and a dynamic reconfiguration level of the system. The detailed description of the second tier of the framework is hidden at high level interactions of the software agents as IAV agents provide the production data to the first tier and establish a two-way real-time communication with the shop floor.

## 4.2. Second tier of abstraction

The middle tier integrates the IAVs into the SC ecosystem and seamlessly links the automation hierarchy levels. IAVs are among the enablers of the Industry 4.0 revolution by acting on behalf of market demand for end-to-end automation as they can be effective and efficient through providing flexible manufacturing, preparation activities for production and logistics for supporting mass customisation, overnight rearrangement of inventories, reporting activities, and monitoring and calculation of key performance indicators for the SC ecosystem. From an environmental and social point of view, IAV systems result in minimised waste flows and damaged products, enhanced energy optimisation, minimised property damage and human errors, and further prevent loss of life and fatalities in industrial manufacturing facilities. Below, we specifically discuss the key role of communication standards and the selected architectural backbone for the case of developing bespoke simulation software tools that integrate innovations in intelligent transportation systems, SC operations and sustainability ramifications.

### 4.2.1. The role of communication standards

IAV systems are covering the field, control, process, plant management and enterprise resource planning levels of the automation hierarchy (Monostori et al., 2016). In order to interoperate with many multi-disciplinary tiers, the role of communication standards is critical. Modelling techniques are necessary in order to increase the replicability of the framework and decrease ambiguities. Ontologies are creating the proper context for the entities, their properties and the underlying processes (communication, coordination and activities), enabling software tools to interpret data in a more sophisticated way. Indicatively, the CORA ontology and the underlying extensions proposed by Fiorini et al. (2015), under the umbrella of IEEE Robotics and Automation Society, describe an industrial environment with entities, their parts (sensing, actuating, communication and processing), their relationships and all the necessary variables. Modelling languages, like the MES Modelling Language, integrate all the views for describing manufacturing environments, the entities and the underlying interdependencies (Witsch and Vogel-Heuser, 2012). Especially, the MES Modelling Language allows for the capturing of the technological structure of a plant, the specifications of the production processes and the description of the functions and manufacturing processes as to fully capture an industrial environment. In the same vein, general-purpose modelling languages, like the OMG Systems Modelling Language (Hehenberger et al., 2016) and the Unified Modelling Language (Matsuda et al., 2016), can be used for the representation of Cyber-Physical Production Systems in order to describe the entities of an industrial environment along with their interconnection, functional requirements and characteristics.

Moreover, representing industrial processes with international standards leads to the automation of the sustainability assessment activities and to more accurate measurement of the sustainability impact of the production processes (Mani et al., 2013). IAV systems and simulation techniques can automate the recording and reporting of sustainability parameters, even at a product level, as every parameter is an inherent entity characteristic that is included in the entity's description. The proposed software framework interface allows for the monitoring of SC sustainability parameters in a bottom-up approach including the fuel consumption of the IAVs, the greenhouse gas emissions, the energy requirements of the manufacturing and storage equipment; hence, simulations support the evaluation of effluents and the assessment of controlled refuelling approaches.

### 4.2.2. Architectural backbone

From a technical perspective, the proposed software framework is based upon the Model View Control (MVC) approach. The MVC framework consists of three independent layers (Glöckner and Ludwig, 2013): (i) the Model layer that describes the entities and their relationships, (ii) the View layer that provides the user interface forepart and presents the current state of the model and the output data, and (iii) the Control layer that dynamically alters the model's state after receiving events from the user interface. The MVC architecture depicted in Fig. 3 separates the user interface, the business logic, the control structures and the data access methods, and is recommended for modelling complex environments. The business logic and the control policies can be easily modified in order to highlight the role of innovations and sustainable performance.

First, the Model layer uses entities to represent the physical structure of a SC system, including: (i) resources (products,

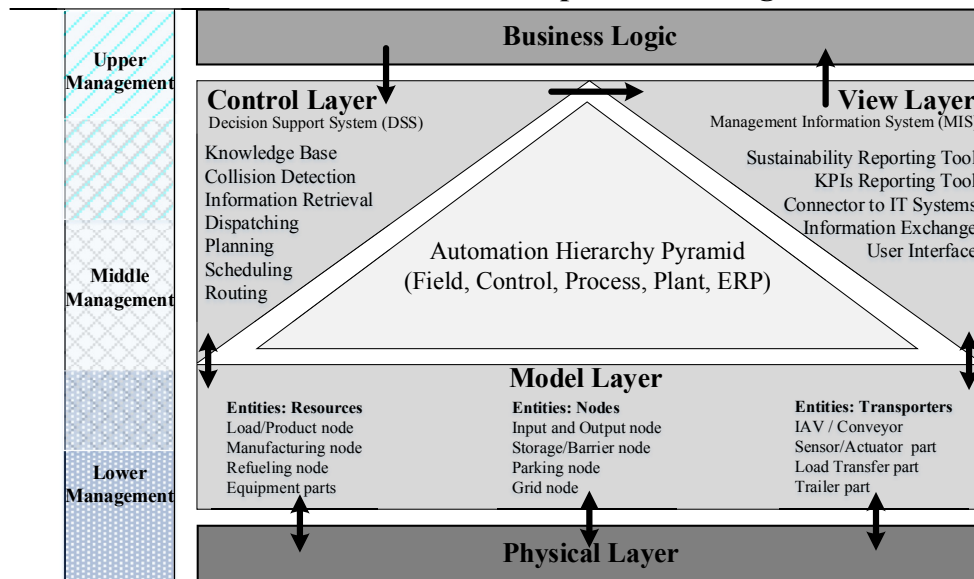## Tier 2: IAVs Incorporation in Digital SCs



**Fig. 3.** Technical structure of tier 2 – The MCV architectural specifications.

production machinery, sensors, actuators, equipment parts), (ii) facility layout nodes (input and output nodes, storage nodes, barrier nodes, divider nodes, refuelling nodes, parking nodes, grid nodes), and (iii) transporters (IAVs, conveyors, sensors, actuators, load transfer units, trailers). Each entity corresponds to a specific data scheme in order to extensively describe the properties of the entity. The data scheme is part of a predefined ontology. Sustainability parameters are enclosed in the ontology of the model in order to precisely measure and report the sustainability impact at each operations level.

Second, the View layer includes the user interface and the reporting tools. Particularly, the reporting tools are incorporated into our novel framework in order to enhance sustainability at all network echelons. Indicatively, economic viability, environmental impact and social implications that could be monitored with sensors are documented through the reporting tools. Interoperability to manufacturing and SC information systems can be established with the use of interfaces that can interlink with third-party software applications.

Third, the Control layer provides a plethora of algorithms for localisation, navigation, collision and deadlock prevention, dispatching, routing, planning, and task scheduling, while taking into consideration the entities' properties and the global optimisation parameters. The algorithms determine the vehicles' autonomy level that has been the subject of the Autonomy Level for Unmanned Vehicles framework (Huang et al., 2005). The Autonomy Level for Unmanned Vehicles framework recognises fully autonomous, semi-autonomous, tele-operated, remote controlled and automated robots (Fiorini et al., 2015). Sustainability focused optimisations are included in the implementation of the planning, scheduling and routing algorithms in order to minimise the sustainability impact of a SC. The Control layer is responsible for the characterisation of the system as hierarchical (central control) or decentralised (distributed control).

The second tier of abstraction can describe an IAV system in business terms and demonstrate its value at upper, middle and low management activities. Upper management activities involve the company's Business Logic and inform the Control layer (e.g., the Decision Support System) with specific procedures and goals, while

the results are presented in the View layer (e.g., the Management Information System), provide feedback to the board members and conclude to strategic decisions for optimising the Business Logic. The modeller can represent the physical hardware components as simulation entities in the Model layer while the Control layer acts as a middleware that enables communication with the modelling elements of the Model layer. The Control layer interfaces lower layer physical devices (facility layout nodes, resources like sensors, actuators and equipment parts as well as transporters) using the Model layer in order to coordinate their activities, enable their cooperation in the manufacturing area and present the underlying activities in the View layer. Low management decisions are usually made at the Physical level and can leverage the output of the DSS and the MIS where middle management activities prevail.

Following the key characteristics of the IoT, communication between the aforesaid three layers is critical in order to ensure operational excellence of IAVs and sustainable performance of modern SCs within a digital context. Therefore, collaboration and interoperation between the entities is handled by a middleware layer, including exchanging of messages and coordination among entities and activities. Data structures, information about the entities and the resulting sustainable performance for any system state (both historical and current state data) are stored in database structures. To this effect, feedback mechanisms are necessary to reconsider the operations of all entities and promote supply network sustainability.

### 4.3. Third tier of abstraction

The third tier is beyond the scope of the current research as it involves the functional details of the manufacturing and facility layout equipment, resources, third-party equipment standards, communication capabilities and interoperability issues of diversified devices. The second tier of the framework attributes each distinct equipment node or resource node with an interface that enables the input/output functions and the communication and coordination of the devices with the third tier. Resources and equipment with hardware and software interfaces enable the proper execution of the framework functions without the complete

knowledge of the third layer's individual components. Interfaces are focusing on an input/output basis, omitting technical details and functional requirements of third-party manufacturers' devices.

## 5. Demonstration of the pilot software simulation tool: development and modelling

The application of bespoke simulation software for assessing sustainability performance in SC operations is highlighted using a custom developed tool as a case study. Our modelling approach focuses on a decentralised multi-agent system for the control, communication and coordination of all the involving entities (Svensson and Danielsson, 2015). Design, control and integration with manufacturing environment through agent-based systems are widely studied and all decisions are made in real-time (Mes et al., 2008).

The developed simulation tool can model an IAV system operating at the second tier of the proposed software framework, consisting of two major modules: (i) the basic model building module for the modelling of the facility layout, and (ii) the vehicle management module for realising the IAVs' control layer and the environmental sustainability reporting. Both modules are in the pilot stage of development and are continuously being improved and expanded to allow greater functionality. The programming code for both the aforementioned modules was developed in the Microsoft Visual C# 2010 development environment.

The basic model building module allows the representation of the facility layout of a working environment. Thereafter, following a number of steps the user can simulate a number of specific fuel type autonomous vehicles in a customised facility layout. The simulation stepwise process, illustrated in Fig. 4, includes the following:

- Step #1 — 'Create Grid Layer'. The pilot software's interface resembles a grid with a menu for adjusting the parameters of the

model. The resolution of the grid layout could be adjusted in order to better represent the physical world, capture the physical entities and enable a precise movement for the transporters. Except for the basic menu functionalities (i.e. save etc.) the user can select entities (barrier or divider entities, loads, transporters, output gate) and insert them to a specific cell in the grid layout.
- Step #2 — 'Insert Map Layer'. The user can load the digital drawing of a facility layout. This enables the immediate transfer of the real world to the simulation environment, with the proper scaling.
- Step #3 — 'Insert Static Objects'. The user should use the basic menu to insert manually the facility's entry point, the storage separators, the loads (pallets with products), the refuelling points and the output gate.
- Step #4 — 'Insert Dynamic Objects'. At this stage, the user can insert the number and the fuel type of the desired transporters (autonomous vehicles), and select the preferred routing algorithm to pick up and deliver the load to the exit point. The research value of the algorithm is the ability to dynamically calculate optimal routes based on obstacles present in the layout. The user can then save the facility layout map along with the selected static and dynamic objects.
- Step #5 — 'Run Simulation, Assess the Model'. At this stage, the user can run the simulation based on the defined entities and view, in real-time, the environmental sustainability report and status of each autonomous vehicle.

The vehicle management component's interface allows the real-time reporting of the IAV's environmental sustainability performance through indicating the emissions of carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), total hydrocarbon (THC) and the total Global Warming Equivalent ($CO_2$ eq). The lift state is also dynamically presented as the vehicle operates in the
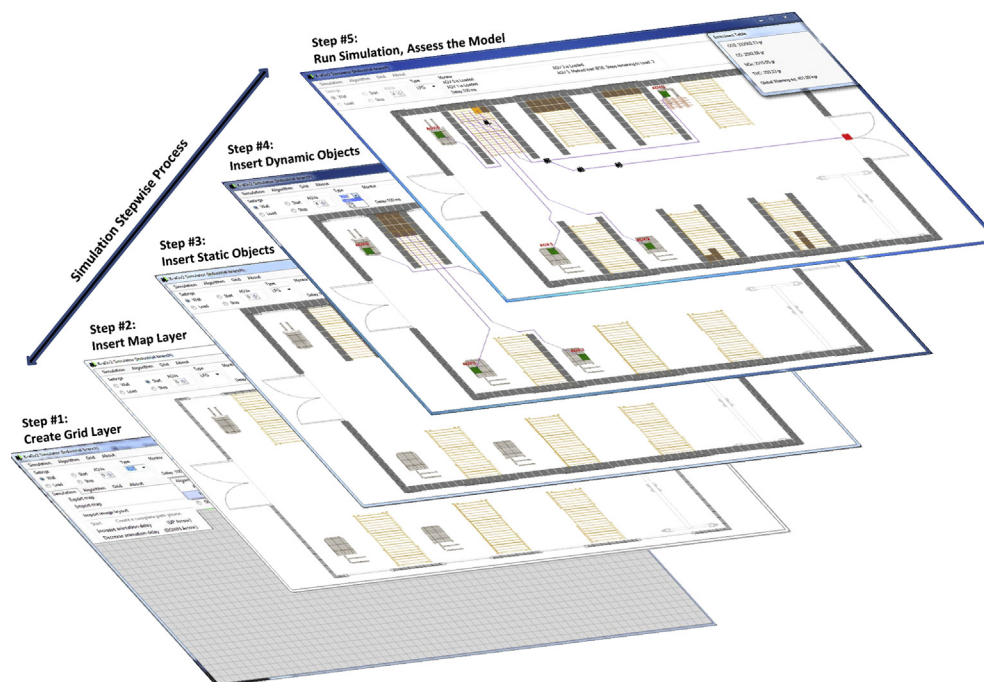


**Fig. 4.** Simulation tool: Model building module.

facility layout, taking into consideration the loading and the unloading kinematics of the vehicle and the type of the vehicle. At the current stage of software development, the user can choose between three distinct forklift types based on the used power source (Fuc et al., 2016): (i) liquefied petroleum gas, (ii) diesel, and (iii) electric. Both loaded (with 1t of load) and unloaded travel time is taken into account for the measurements. It must be stated that the transporters' movement towards the load and the output gate is automatically triggered by the Control layer. The transporter follows the shortest path in the facility using the A star (A\*) algorithm in order to optimise the total distance travelled in the facility, while avoiding the static and the dynamic entities.

## 6. Results and discussion

Existing research on IAVs in the SC domain is growing with industry needs pointing to more efficient and customisable simulation techniques. Considering also that IAVs are associated with significant capital requirements, simulation-based assessment of productivity and operational cost of IAVs could optimise SC material flows and thus justify a corresponding medium to long term investment. In this context, the present research sets out the process for the systematic development of simulation tools, from both architectural and practical aspect, that can support digital transformations in supply networks.

Firstly, the analysis of the reviewed software simulation tools and platforms provides useful insights indicating that the development of software for integrating IAVs in sustainable supply chains should use a decentralised approach to comply with emerging communication standards, while the developed software tools must be hardware independent and should interoperable with available third-party software applications.

Secondly, considering the findings of the software tools and platforms' review and categorisation, we propose a framework depicting an opportune software structure and key design elements for implementing interconnected IAVs across SC operations to evaluate the expected network's sustainability performance. The framework we propose is structured in a way that the analysis of IAVs can be directed towards sustainability evaluation for a range of facility layout designs, capacity scenarios, types of intelligent vehicles and routing algorithms, in order to provide more sustainable products, services and product-service combinations within the digital economy landscape (Vezzoli et al., 2012). In this regard, a software application could adapt to advances in environmental regulations and support firms in considering regulations as enablers for growth.

From a technical perspective, the proposed software framework enables practitioners and academicians alike to integrate commercial IAVs into the SC ecosystem by treating the vehicles' characteristics as member variables at the simulation Model layer (special features, capacity, velocity, acceleration etc.) through using the appropriate entities that fit the vehicles' characteristics (sensors, actuators, load transfer equipment, trailers etc.). The framework further enables the vehicle's navigation as well as dispatching, planning and scheduling activities at the Control layer and allows the comparative analysis of the derived sustainability performance in the View layer. Moreover, it is feasible to assess the sustainability performance of the same IAV units in multiple facility layouts by altering the shop floor entities at the Model layer of the framework. Sustainability ramifications comprise the fundamental basis of the proposed software framework as each entity at the Model layer has properties that capture the environmental, economic and social parameters. The Control layer embraces the actions that each entity can undertake considering that each action is associated with specific and measurable sustainability impacts.

Sustainability reporting is inherent to the system and is automatically and dynamically generated. Particularly, the framework provisions the precise sustainability metrics for the entities, the processing and the overall IAV kinematics. Although the proposed framework could address demand volatility, the tier approach separates low-level shop floor activities, high-level shop floor activities and SC coordination. The agent-based approach provides the system with decentralised management and enables the dynamic reconfiguration of the SC network and the shop floor. Agents can dynamically register and unregister without disrupting the stability of the system while IAVs can adjust the manufacturing schedule by taking into consideration multi-optimisation parameters.

Thirdly, the development of the demonstration pilot simulation software sets out a five-stage stepwise process recommended for the design of flexible tools that capture the characteristics of dynamic manufacturing contexts and support the effective integration of IAVs in operations. In this regard, at a first stage, a software application primarily needs to have a clear interface that allows a gamut of elements to be applied and imported. Following that, at a second stage, importing the layout of an industrial environment into the software should be simple and transparent to avoid challenges associated with advanced digital drawing skills. Importing ready-to-use layout maps allows, at a third stage, the manual insertion of static objects that represent the design specification elements of a facility including barriers, walls, loads, charging/parking stations, and input/output gates. This digital replication of the industrial environment along with its specifications could, at a fourth stage, inform about the available or required dynamic objects that define operations. More specifically, a simulation software should be able to capture real-world shop floor entities along with their properties, manufacturing machines, sensors, programmable logic controllers, actuators and finally the transport vehicles with their specific characteristics, properties and capabilities. At the last fifth stage, all entities have been recognised and captured in a software environment to proceed with simulating alternative scenarios and assessing IAVs' operations efficiency and sustainability performance.

In terms of demonstrating the applicability of the developed software, we used the case of a customisable warehouse facility as a simulation testbed. Table 2 summarises the simulated eco-indicator results according to the specific fuel type of utilised AGVs (Liquefied Petrol Gas - LPG, Diesel - DSL, Electric - ELE), taking into consideration the cumulative loaded and unloaded travel distances calculated in the presented model. Facility managers can identify the operational needs of the facility while considering environmental sustainability parameters.

## 7. Conclusions

This research sets out the process for the systematic design and development of simulation software tools for integrating IAV systems in digital supply networks, further enabling the simulation and sustainability assessment of the performed operations. The applicability of the proposed framework is demonstrated through a custom-built simulation software tool that is tested on the case of an IAV system operating in a conceptual and highly customised warehouse.

The pursuit of truly digital SCs and smart manufacturing systems exerts considerable pressure on the frontiers of automations by emphasising the adoption of IAVs to promote workable relationships among environmental performance, economic growth and social benefits (Bechtsis et al., 2017). The transition from traditional SCs to digital networks in a viable manner that promotes sustainability compels the utilisation, integration and coordination

**Table 2**
Simulation reporting tool: Indicative environmental results for a simulation cycle.

| Emissions Category | Emissions Type | Vehicle Type | | |
|---|---|---|---|---|
| | | LPG | DSL | ELE |
| Direct Emissions | $CO_2$ (g) | 2.592.382,46 | 1.921.775,68 | 0,00 |
| | CO (g) | 21.637,28 | 5.940,64 | 0,00 |
| | $NO_X$ (g) | 17.699,18 | 18.202,98 | 0,00 |
| | THC (g) | 2.447,70 | 1.513,74 | 0,00 |
| Indirect Emissions | Global Warming (kg) $CO_2$ eq | 3.130,70 | 1.978,14 | 682,58 |

Symbols: LPG for Liquefied Petrol Gas, DSL for Diesel, ELE for Electric.
Note: Results are calculated taken into consideration both loaded and unloaded travel time. The calculations assume that each vehicle carries 1t of load for each loaded km (Fuc et al., 2016).

of IAVs across different levels of operations (Bechtsis et al., 2017). Taking into consideration this perspective, the present study initially provides a critical categorisation of software tools and platforms used for simulating IAV systems in SC ecosystems. The findings of the review indicate that the use of simulation methods in industrial manufacturing and SC management sectors is continuously growing while the incipient need for highly efficient and customisable simulation techniques encourages the elaboration of hybrid simulation methods combining agent-based simulation with artificial intelligence (Negahban and Smith, 2014).

In this context, this paper contributes to sustainable SC research by identifying a framework for the systematic development of simulation software tools that combine environmental sustainability performance with operational elements. In particular, the presented software framework supports the process of simulating and evaluating global supply networks through allowing for the development of customised simulation tools dedicated to sustainable SCs defined by IAV platform technologies, while contemporarily providing expanded applicability to all the abstraction layers (bottom-up approach) for generating meaningful insights to real-world scenarios. Furthermore, we test the proposed framework by programming a corresponding simulation software tool, that is highly customisable, and we further recommend a five-stage stepwise process for developing software tools that support the effective integration of IAVs in sustainable supply networks. We finally test the developed software tool to the case of a customisable industrial warehouse while we monitor the resulting eco-indicators of the utilised IAV system.

In conducting this study, some limitations are evident which, however, provide stimulating grounds for expanding our research horizons. Firstly, the provided analysis framework was developed using an extensive literature review and our narrow knowledge over real-word working environments, while testing and refinement was restricted to the application of the conceptual warehouse's intra-logistics operations. In this sense, input from academic experts and practitioners may provide greater insights into the framework of integrating IAVs in digital SCs for promoting sustainability, and would further facilitate generalisability of the provided findings. Secondly, the bespoke software tool presented in this study captures environmental sustainability performance metrics, but does not quantify economic and/or social considerations. On-going research programming work aims to extend the tool's capabilities and provide greater flexibility and customisability.

With respect to future scientific directions, we aim to demonstrate the applicability of the proposed framework on real-world settings, initially through the case of last-mile logistics operations and specifically through the case of urban consolidation centres in clinical trial and pharmaceutical supply networks. To date, the extant literature on intelligent systems and simulation appears to have a myopic focus on warehouse management operations,

meaning that the existing studies have largely not considered diversified, yet coordinated, operations across a supply network. This research could promote the development of a novel framework that integrates IAVs in end-to-end operations so as to foster sustainability performance and to ensure network competitiveness (Ngai et al., 2014).

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