Conceptual framework for a stochastic (r,Q) inventory policy with storage-related environmental metrics

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Abstract: Many steps have been taken to estimate greenhouse gas emissions related to transport and operations of inventories, with a particular effort to adapt them to reordering policy models. When talking about inventory management, the construction of a warehouse is also a main driver of greenhouse gas emissions. This driver can be measured through the embodied carbon of the storage building, which quantifies the equivalent carbon dioxide emissions related to its construction process. Following a literature landscape characterization regarding different reordering policies and inventory-related environmental aspects, an original framework for sustainable inventory control is developed with the aim of finding the reorder level and quantity (r, Q) considering warehouse embodied carbon. One of the main parameters for a reordering policy is product demand and, especially for retailers which are in the downstream end of the supply chain, the inventory needs to be modeled considering some variability to cope with unpredictable customer orders. To deal with this variability, which has been a big focus in the inventory control literature, demand can be considered as stochastic. Depending on the type of a product and its consumption rate, the demand's stochastic representation needs to change for more realistic modeling of such a scenario. The proposed framework considers the relevant stochastic aspects related to product demand during supply lead-time and it focuses on the main embodied carbon drivers to allow the modeling of a bi-objective reordering policy for the continuous-review inventory of a single product. The bi-objective nature of this problem is given by the economic and environmental perspectives, and it can be tackled using multicriteria decision-making methods.

Keywords: reordering policies; green supply chain; stochastic demand; embodied carbon; inventory management

I. INTRODUCTION AND LITERATURE REVIEW

Inventory control is the part of supply chain management that focuses on storing and moving of stock to meet customer demand. A supply chain (SC) is constituted by a set of subsequent levels, often called echelons, that span from upstream, where production happens, to the final customers downstream [1]. Due to differences between production and demand rates of the different entities in the SC, inventory needs to be held at warehouse locations in order to fulfil customer orders in a timely manner. In other words, inventory acts as a buffer between each echelon of a SC [2]. To correctly size and control such a buffer, inventory management deals with balancing the availability of stock with the related costs of ordering, holding, and handling operations. Effectively governing inventory is one of the main challenges for efficient SC management. Historically, the problem has been to define reordering policies that minimize inventory-related costs to enable businesses to be economically sustainable.

Wild [3] highlights the main factors that determine the choice of maintaining a certain level of product stock, namely supply lead time, amount of customer demand and its variability, and supply frequency. Starting from the economic order quantity of Harris [4], the literature has expanded with a particular increase in inventory control publications starting from the second half of the 1990s [2]. The original economic order quantity approach offers a deterministic formulation for finding the optimal order size that minimizes the order and holding costs of inventory for a single product. This formulation, often also called the square-root formula, has served as a basis for more detailed models aimed at address real-world challenges.

Governing the behaviour of the inventory can be performed using a reorder policy that defines when to place a new order of fixed size. This results in the square-root formula extension of (r, Q) policies, where a fixed quantity Q is reordered if the stock goes under the reorder level r. For this reason, these approaches are often also called reorder-level policies. Several literature reviews and surveys have been published on this topic. For example, Andriolo et al. [5] reformulated the square-root formula and gave a classification based on deterministic, stochastic, and fuzzy models. Williams and Tokar [2] focused on demand uncertainty, stockout response, and collaborative methods. Ma et al. [6] analysed different policies under stochastic representation of demand. Bushuev et al. [7] summarized other lot-sizing review papers. Of particular interest is also the literature review of Ansari and Kant [8] that tackles sustainable development by analysing trends and findings for green supply chain management.

One of the most developed extensions to reordering-level policies regards demand uncertainty. Especially in the downstream part of the supply chain, retailers often face variable customer demand. Uncertainty in demand becomes particularly relevant during supply lead time, where it may lead to stockouts or excessive remaining stock. This can be referred as demand during lead time [9] or lead-time demand [1]. Such uncertainty comes from the demand itself and from the lead time and their estimation [10]. In this regard, Wild [3] describes the normal distribution as the most common representation of demand variability while emphasizing the need to shift to a Poisson distribution for low usage rates.

Due to the established concerns related to the environmental impact of human activities, often measured as greenhouse gas emissions, green SC management has become another important focus in the inventory management literature. Contrasting such emissions means engaging in supply chain decarbonization with upstream and downstream efforts [11]. Among the total life cycle of a product, logistics and transport account for 5-15% of emissions, which can be countered by optimizing logistics networks [12]. As businesses start to consider environmental issues due to the external pressures of regulations and customers, reordering policies become a helpful tool to reduce emissions. Both warehousing and shipping activities are a vital part of the green supply chain, as it is defined by Bonney and Jaber [13]. The authors stress the importance of optimally managing inventory by implementing environmental aspects in inventory control. Similarly, Andriolo et al. [5] suggest that the environmental impact of storing and moving products, which has not been largely studied by the main literature, should be included in an integral part of an inventory management model.

The environmental sustainability of maintaining inventory is not purely affected by the energy used for running a warehouse, such as electricity and heating, but also by how the building was built. Like holding costs depend both on operational activities and depreciation of the building and its machinery, a green lot-sizing model should include indicators that quantify the effect of the greenhouse gas emissions related to both energy usage and warehouse manufacturing on the storage of an item over time. For any material or product, this means measuring the embodied carbon that quantifies the greenhouse gasses emitted due to the direct and indirect energy usage of construction [14]. Lot-sizing policies should include environmental indices for embodied carbon, thus creating a more realistic and complete model for inventory control. Since operational efficiency will continue to increase in the future years, embodied carbon will become even more important in the life cycle emissions of a building [15]. This is especially true for warehouses, where the energy used for operations is lower than in other buildings such as offices or manufacturing plans [16].

In order to tackle both demand variability and sustainable operations, this paper presents an original framework that focuses firstly on stochastic lead-time demand, and secondly on environmental sustainability. Greenhouse gas emissions are an established method to estimate environmental impact [15], and they are often converted in the measure of equivalent carbon dioxide (CO_2e), which considers both toxicity and global warming potential of such gasses. Considerations are made on how storing activities and warehousing affect CO_2e emissions. The framework is centred on the main emission drivers for embodied energy, which need to be used to characterize a warehouse with its main attributes to allow the definition of the environmental metrics in terms of $kgCO_2e$. These aspects are aimed at improving tactical decision making in supply chain management [1] by providing the groundwork for the mathematical formulation of a (r, Q) policy that combines both stochasticity of demand and environmental sustainability. In this regard, multi-criteria decision making is considered as a better alternative with respect to translating emissions into monetary costs.

The remaining sections of this paper are organized as follows. Section II describes a detailed landscape analysis about reordering policy papers with stochastic and environmental considerations, how they integrate the sustainability duality, and warehouse energy estimation to identify the main drivers for embodied carbon. Section III is devoted to presenting the developed original framework for stochastic inventory control with environmental metrics aimed at measuring CO_2e in terms of embodied carbon, warehouse operations, and supply transport. Finally, Section IV presents conclusions and directions for future work.

II. LANDSCAPE ANALYSIS OF INVENTORY CONTROL

In a fixed quantity approach the inventory is replenished of a certain predetermined amount when the reorder level is reached. The reorder level allows for covering the demand during supply lead time. In this paper, the focus is put on fixed quantity systems, referred here as reorder-level (r, Q) policies. Wemmerlov [17] highlights how order-quantity approaches are among the most robust when demand variability is considered.

This section identifies how the literature extends reorder-level approaches to include different aspects. The first part of the analysis regards representation demand variability, followed by how scholars integrate these representations in reorder-level policies. Similarly, there are a lot of papers about integrating environmental measures in inventory control. A landscape analysis of the main types of approaches adopted in the literature is presented. Finally, a specific investigation is carried out to identify how researchers measure embodied carbon of buildings, focusing particularly on warehouses. This aspect is especially useful to understand why and how these often-neglected measures are included in the proposed framework.

A. Demand variability

In the case of inventory control, the most important and volatile aspects to consider are likely to be customer demand and its variability. Due to both changes in demand and the uncertainties in its estimation, researchers are challenged to represent such variability. Probabilistic representation of demand is often used in reordering policies and can be approached in many ways. Ma et al. [6] make an important distinction for stochastic inventory control between stationary and non-stationary problems. When considering probabilistic demand as stationary, the type of the probability density function (PDF) is fixed. Although a non-stationary representation of demand may better represent a real-world scenario, the authors highlight the complexity of such an approach for reorder-level policies. For this reason, the focus of this part of the landscape analysis is on the stationary problem and how the literature tackles it by using different PDFs.

One of the most common distributions to stochastically represent demand is the normal distribution. Although the normal PDF may represent actual demand in some cases, other distributions have been used in the literature to better approximate other real-life scenarios. For example, Silver et al. [18] state the importance of shifting from normal to gamma distribution for large-enough variance and of considering the Laplace or Poisson distributions for slow-moving items. In similar regard, Vernimmen et al. [9] highlight the significance of demand during supply lead time and how it can be represented as normal for fast-moving items or as Poisson for slow-moving ones, while other items might be better represented by a gamma distribution. The fact that a skewed distribution better approximates lead-time demand [19] might be one of the reasons why the gamma PDF is of particular research interest. Table I summarizes how the analyzed papers model the stationary demand problem for the lot-sizing problem.

TABLE I
LEAD-TIME DEMAND REPRESENTATION FOR THE STATIONARY PROBLEM IN THE ANALYZED LITERATURE

Demand representation	References
Normal	Alstrøm [20], Digiesi et al. [21], Shin et al. [22], Silver et al. [18], Snyder and Shen [1]
Gamma	Namit and Chen [19], Tyworth and Ganeshan [23], Vernimmen et al. [9]
Laplace	Ng and Lam [24]

Regardless of the selected distribution for representing demand during supply lead time, in a reorder policy the stochastic demand can be implemented in two different ways. The first approach adds a safety stock (SS) to the optimal order quantity computed in the deterministic case to counter the variability of demand. For example, Ivanov et al. [25] compute SS as a function of the probability of stocking out and demand variance and use it to define the reorder level r. In this case, the stockout probability represents the so-called service level. Similarly, Silver et al. [18] compute SS as a buffer proportional to the demand variance and a safety factor selected depending on different service level definitions.

The second methodology for integrating demand variability via a static PDF is based on including shortage costs in the total cost function. In this regard, Namit and Chen [19] and Snyder and Shen [1] present a similar formulation, where stockouts are backordered, meaning that the customer order is fulfilled in the next reorder cycle. In such a formulation, the total cost of the (r, Q) policy has a third term for expected backorder cost. With this approach, the SS is computed as part of the reorder quantity Q, instead of being added to the deterministic economic order quantity.

B. Environmental measures in reordering policies

To promote green operations in inventory control it is necessary to assess the effect of decision variables on environmental measures. By implementing sustainability into reordering policies, the goal shifts from solely minimizing costs to a multi-objective problem. Wu and Dunn [26] explain how this integration of the environmental perspective affects decisions in terms of shipment frequency and distance, routing, and space utilization.

The main literature regarding reorder-level policies focuses mainly on the emissions drivers of holding operations and transport. An approach for tackling the holding emissions is to relate operational energy usage to the volume occupied by the average inventory of a product in the warehouse (e.g., [27]; [28]). This energy is required for lighting, heating, and possibly for refrigeration. A larger order quantity Q leads to more average inventory that translates to higher storing emissions. On the other hand, as Q grows, the shipment frequency lowers, and transport emissions become less relevant. Moreover, the environmental impact of transport depends mainly on travel distance and fuel consumption, for example, Tiwari et al. [29] integrate indices for such aspects and for carbon emissions due to item holding for imperfect quality products.

In the case of perishable or obsolete products, another emission driver is the disposal of items that have reached their end-of-life before being delivered to the customer. This waste disposal process requires energy [27] and can have a negative impact on the environment. Table II shows which drivers are considered in the analyzed papers that tackle environmental sustainability, including the perishability aspect.

C. Multi-objective reordering policies

Moving from a single to several objectives is one of the main challenges tackled by decision sciences. The multi-objective problem of integrating both economic and environmental sustainability in reordering policies has been mainly tackled in the research by translating emissions into costs so that a single objective function can be found (e.g., [13]; [21]). This cost approach simplifies the resolution since there is a single total cost

TABLE II
EMISSION DRIVERS CONSIDERED IN THE LITERATURE FOR SUSTAINABLE REORDER-LEVEL INVENTORY CONTROL

Reference	**Emission drivers**		
	Holding	*Transport*	*Perishability*
Bonney and Jaber [13]		×	
Bouchery et al. [30]	×	×	
Digiesi et al. [21]		×	
Battini et al. [27]	×		×
Arikan et al. [10]	×	×	
Kazemi et al. [28]	×		
Tiwari et al. [29]	×	×	×

function to be minimized with respect to the order quantity Q.

Another way of approaching the bi-objective inventory control problem is to use a multi-criteria approach like the one presented by Bouchery et al. [30]. These kinds of methods are rarely proposed in the reordering policy literature, but they allow to consider separately the two objective functions of monetary costs and CO_2e emissions. Similarly, van der Veen and Venugopal [31] consider a cost and an environmental objective, both depending on average inventory level and order frequency.

D. *Embodied carbon of warehouses*

The environmental impact of buildings can be characterized by the energy used in the different steps of their life cycle. Adalberth [32] defines a building life cycle as ‘all temporal phases or stages, from the point where the construction materials are produced until the building is to be demolished’. This includes not only energy used for operational activities, but also the energy needed for construction and end-of-life disposal. The impact of the initial phase before operations is referred as embodied energy (EE). Like operational energy, EE is strictly related to greenhouse gas emissions. For this reason, another measure for the environmental effect of the first part of a building life cycle is embodied carbon (EC). The most important greenhouse gas is carbon dioxide [33] and other harmful gasses are often expressed in terms of equivalent carbon dioxide (CO_2e) by considering both their global warming potential and toxicity. EC quantifies the CO_2e emitted due to activities from construction material manufacturing to building completion. For the scope of this analysis, the energy and carbon approaches are considered equivalent.

Due to the long lifespan of warehouses, research has put a great focus on EE or EC. Even though operational energy plays a bigger factor in the total life cycle emissions, embodied emissions remain an important factor [14] and are bound to become even more impactful as the energy efficiency in-use increases [15]. Accorsi et al. [34] consider emissions coming from building and installation in addition to operational and management energy for the multi-objective design of a warehouse. In their case study, they found that warehouse manufacturing is the second driver of carbon footprint after heating.

Even though materials are not the only factor when it comes to EC, they have been found to be responsible for the great majority of emissions. In the case study of Davies et al. [14], materials result in more than 97% of the total EC. This environmental impact is caused mainly by materials of floors, external slab, and frame of the warehouse, measured in $kgCO_2e$. The importance of concrete and steel for EC is stressed by the case study of Rai et al. [15], where these materials account for more than 80% of CO_2 emissions.

III. FRAMEWORK FOR STOCHASTIC AND SUSTAINABLE INVENTORY CONTROL

Focusing on continuous review inventory systems, the proposed framework outlines the key aspects to be considered when managing robustly a green inventory. Continuous review models allow for tight control of the inventory, which is especially important for high value or

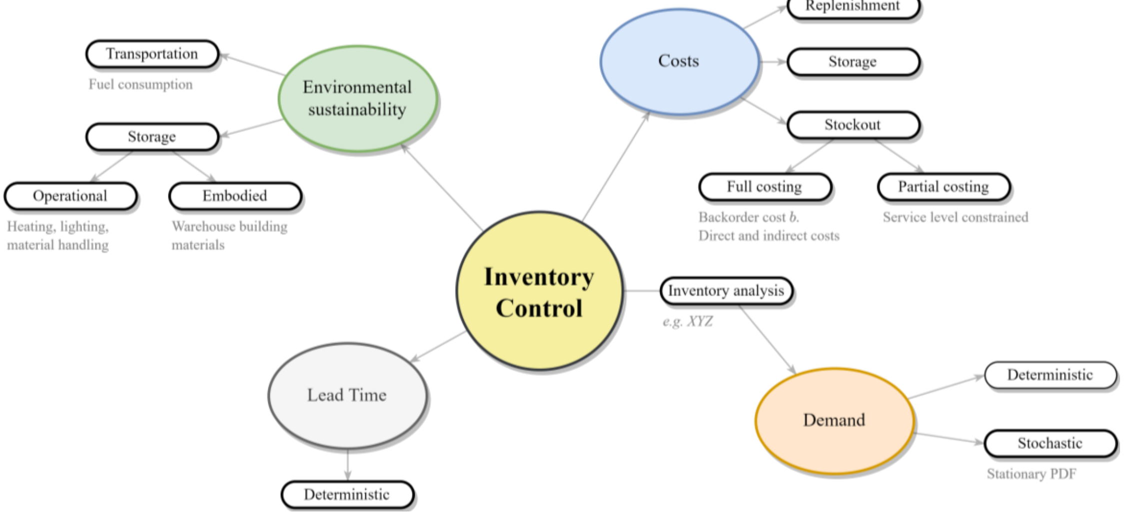

Fig. 1. Main and detailed features of inventory control that are tackled in the proposed conceptual framework.

fast-moving items. Furthermore, modern information systems are able to record the inward and outward flow of items in a warehouse in real-time. Consequently, this section presents an original framework to tackle the variability of product demand as well as the environmental aspects of maintaining and reordering stock, with a particular focus on and how these two aspects can be combined. These aspects are to be considered along with the economical perspective to perform complete and robust inventory control, as depicted in Figure 1. Demand is represented stochastically through a probability density function (PDF), which can be selected after an appropriate inventory analysis.

A. *Modeling stochastic demand*

Considering inventory management strategies, review level systems are usually robust to variability in product demand before the new order quantity is issued to the supplier. Indeed, in this fraction of the reorder interval, demand fluctuations affect only the order frequency since this is directly related to how fast the inventory reaches the reorder level. The other portion of the reorder interval is the supply lead time, which is defined as the time between the emission of the order and its receival. During the lead time, variations of demand are the most impactful since the risk of completely depleting the inventory is present. In this scenario, customer orders cannot be fulfilled, and the inventory is distinguished by a stockout state. The literature typically suggests managing out-of-stocks considering the unmet demand as backlogged. Backlogging refers to stalling the demand that cannot be met directly from on-hand stock in order to fulfil it when the reorder quantity is received. Although this assumption may be realistic in some scenarios, in a retail environment demand is often lost when a stockout occurs. To develop a robust and realistic inventory control system, both demand variability and stockout response need to be correctly modelled mathematically.

Stochastic representation of demand is one method to model its variability through a probability density function (PDF). Both the amount of demand and its pattern typically change from product to product. For this reason, a single PDF is not representative of all items in an inventory system. This framework proposes to classify items based on demand characteristics so that specific stochastic modelling can be performed for each class. Ivanov et al. [25] present an XYZ classification based on demand patterns where class X is identified by constant demand, Y with fluctuating demand, and Z with sporadic demand. For example, constant-demand products can be well represented by a normal distribution, while for other patterns a skewed distribution such as gamma might be preferable.

A further relevant aspect to be considered for a realistic inventory management regards the response of customers to stockouts, which can be modelled as an additional cost to the holding and ordering costs of a review level policy. Integrating backlogging and/or lost sales costs results in a more complete inventory control model. The problem of this formulation, often called full costing, is the quantification of the parameters for backorders or lost sales costs that are usually hard to assess accurately. For instance, Liberopolous et al. [35] describe how backorder costs have both a direct and indirect component. Direct backorder costs are determined by the loss of immediate profit and additional administrative costs, while indirect costs are related to loss of goodwill and are much harder to estimate. For the scenarios where backlogging is not representative, such as in retailing, it might be difficult to measure the quantity of unsatisfied demand and the related costs. For this reason, a service level approach might be preferable in these scenarios. Chen and Krass [36] define the service level constrained problem as a partial costing model. Even if not every cost component is considered in such models, their interpretation is generally more immediate, and they do not require the estimation of cost indices that are typically challenging to measure. In this regard, Escalona et al. [37] formulate the partial costing problem by considering different service level measures. The selection of the most appropriate approach depends on the scenario and the availability of information about stockout response. Moreover, in some circumstances maintaining a high service level might be a primary objective if brand reputation is particularly important.

B. *Modeling environmental impact of inventory*

Inventory control has been historically implemented with an economic objective. The order and holding costs are the main types of costs considered when defining optimal reordering policies. However, there exists a duality between such inventory costs and the environmental impact of maintaining stock. Firstly, one relevant component of order costs is transport, which also yields environmental emissions. Secondly, holding inventory causes greenhouse gas emissions driven both by operational energy and embodied carbon components. Operational energy comes from energy usage, like electricity for lighting or refrigeration, or gas fuel for heating. On the other hand, embodied carbon is related to the phase of the warehouse life cycle prior to operations. Since buildings are responsible for 40% of total energy consumption in the EU [38], it is especially important to include both the aforementioned holding emission drivers when developing environmentally responsible reordering policies. Thus, there will be three main emission components for managing inventory, namely, transport, operational energy, and embodied carbon.

Due to the presence of multiple emission drivers, an aggregation of the different environmental impacts is needed. Like embodied carbon measures the mass of equivalent carbon dioxide ($kgCO_2e$) caused by material production and construction activities, operational energy can be translated to $kgCO_2e$ based on the electricity source. The same can be done with transport fuel usage.

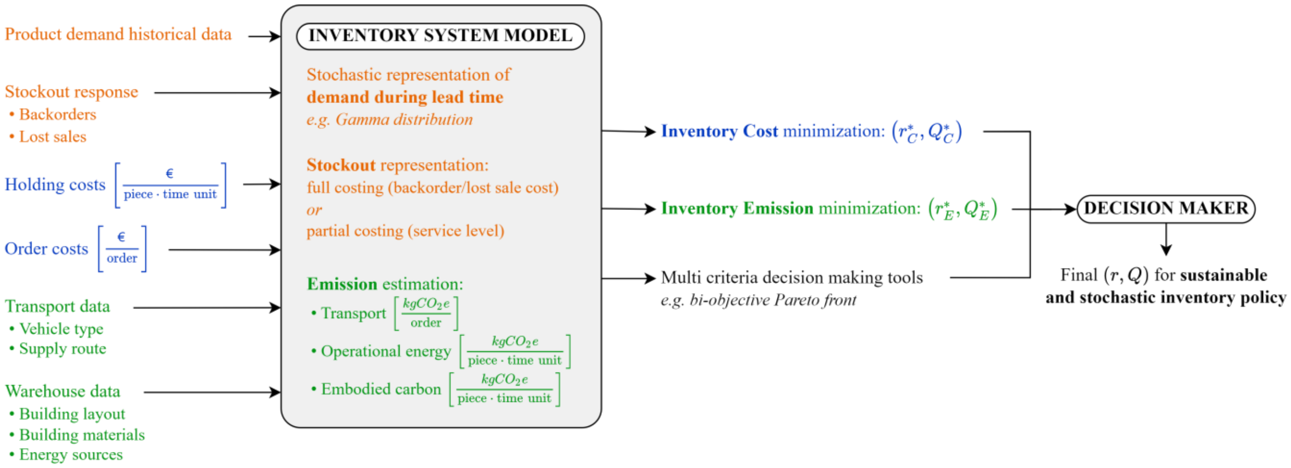

Fig. 2. Input/Output diagram of the original framework for managing an inventory system.

Unlike the other emission drivers of inventory systems, estimating the embodied carbon for an existing warehouse is a challenging task. This means acting with partial information about how the warehouse was built. However, since the most important component of embodied carbon is by far due to construction materials, embodied carbon can be quantified by estimating the amount of the most impactful materials in terms of emissions. The most important ones in construction are concrete and steel [15]. The amount of these materials needs to be identified based on warehouse shape and main features. The characterizing dimensions for each main warehouse element, like flooring, walls, pillars, and roof, allow for estimating their material content. Such preliminary estimation needs then to be adjusted based on the warehouse specific characteristics, like the window to wall ratio or insulation material and thickness.

Established the significance of the embodied carbon component as an emission driver, it is crucial to determine how this and the other environmental measures are effected by the decision variables of an inventory system. The two storage-related emissions depend, like holding costs, on average inventory. On the other hand, ordering emissions depend on order frequency and they are directly related to transport activities. In this case, the relation between cost and emission is more direct since fuel consumption yields both costs and emissions. For example, between a producer and a distribution centre, the transport routes are fixed, this results in an easier identification of transport emissions that depends not only on distance but also on vehicle velocity and altimetry profile. Due to this constant nature of the routes, it becomes feasible also to identify these latter parameters to obtain a more complete estimation of the environmental impact of inventory.

C. Tackling the bi-objective optimization problem

According to the previously-described twofold nature of the problem, adequate approaches need to be adopted to define a final management strategy for the inventory control problem. Indeed, traditional reordering policies focus on the sole economic objective, thus trying to minimize costs or maximise profits. The controllable costs related to the inventory management of a product are ordering and holding costs. When the environmental perspective is included in an inventory control system, the complexity of the problem increases since two objective functions have to be considered. Moreover, these functions are influenced by the same decision variables. For a continuous review inventory system, these variables are reorder quantity and reorder level.

The literature has mostly tackled the bi-objective problem by translating emissions into costs. This approach may be advantageous when companies are subject to carbon taxes, but it reduces transparency since emissions are not directly relatable to monetary costs. It is thus important to develop multi-objective solutions that decision makers can use to balance the tradeoffs between the aforementioned two objectives. Maintaining the two objective functions as separate, with their own units of measure, allows a greater degree of clarity on the effect of the decision variables on the economic and environmental performances of inventory control systems. Such transparency can be enhanced by visual tools, like the graphical representation of the Pareto front, that contains all the non-dominated solutions, allowing decision makers to clearly see how the choice of decision variables affects the two objective functions. Figure 2 represents the three main themes highlighted in the framework, namely, product demand, relevant costs, and emissions.

IV. CONCLUSIONS

This paper has presented a conceptual framework for stochastic inventory control with usually-neglected environmental measures. The preceding analysis of inventory management literature allowed the identification of the relevant aspects needed for developing a robust inventory control system, as well as innovative areas to be further investigated. A natural evolution of this research is the mathematical modeling of the tackled aspects of inventory management, followed by a formal validation of the developed model. Thanks to the connection of this preliminary study with a real-world application in the Trentino province of Italy regarding sustainable e-commerce logistics, this validation can realistically occur in the short future.

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