Integrating Resilience and Sustainability Paradigms in Vaccine Supply Chain Management: A Multi-Objective Simulation/Optimization Approach

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Abstract Vaccination is crucial for human health, and the success of vaccination programs depends not only on the vaccines themselves but also on the strength of the supporting supply chain and logistical systems. The World Health Organization emphasizes the importance of sustainability and resilience in vaccine supply chains, as outlined in the Immunization Agenda 2030. This paper aims to illustrate how multi-objective simulation/optimization can assist decision-makers in integrating sustainability and resilience concepts in vaccine supply chain management, based on the Paradox Theory. The technique was applied to the operational management of a vaccination point in the Central Alentejo region, resulting in nine non-dominated solutions. This approach enables decision-makers to make data-based decisions and gain insights into the potential outcomes before finalizing their choices. Our findings demonstrate that multi-objective simulation/optimization provides valuable insights, allowing decision-makers to consider a more comprehensive "both-and" approach instead of singular choices.

Keywords Vaccine supply chain management · Resilience · Triple bottom line · Simulation · Multi-objective optimization

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1 Introduction

Through the Immunization Agenda 2030 (IA2030), the World Health Organization (WHO) argues that immunization is crucial to people's health, constituting a fundamental right to enjoy the highest physical and mental well-being and investment in the future [1]. The IA2030 aims to ensure that the health gains achieved through immunization are sustained and expanded, so that no one is left behind at any stage of life or in any situation. To achieve this goal, IA2030 emphasizes the optimization of existing resources as a critical factor for long-term progress and sustainability, aiming to achieve efficient, effective, and resilient immunization programs [1].

The WHO, a staunch advocate for evidence-based decision-making, also underscores the crucial role of reliable data in shaping effective immunization strategies. Among its strategic priorities, vaccine supply sustainability stands out, also emphasizing the need for evidence-based decision-making at all levels [1].

Sustainability has been identified as one of the significant competitive success factors in supply chains in recent years [2]. However, they are under increasing pressure to be environmentally and socially sustainable while delivering substantial economic performance [3, 4]. Even if the sustainability and resilience of Cold Chains, such as the vaccine supply chains, have become even more crucial, there is an urgent need for research, innovation, and strategic planning in this domain [5].

A successful vaccination program is not just about the vaccines but also about the robustness of the supply chain and logistics systems that support it. These systems enable the adequate storage, distribution, handling, and management of vaccines, ensuring strict temperature control in the cold chain, leveraging logistics, and managing information systems to promote a resilient and efficient system [6]. The ultimate goal is to ensure the uninterrupted availability of quality vaccines, from the manufacturer to the service delivery levels, avoiding stock-outs and the consequent loss of vaccination opportunities [7]. Although vaccination is a medical intervention, it is impossible to succeed without good logistics [8].

We aim to show how multi-objective simulation/optimization can help decision-makers integrate sustainability and resilience paradigms in the vaccine supply chain management, drawing from the perspective of the Paradox Theory proposed by Smith and Lewis [9].

The remainder of this paper is structured as follows: Sect. 2 presents the theoretical background, Sect. 3 outlines the methodology, Sect. 4 presents the results, and Sect. 5 presents and discusses the main findings, identifying future research lines as well.

2 Theoretical Background

2.1 Resilient and Sustainable Vaccine Supply Chains

Health sector organizations must incorporate sustainability and resilience into their supply chain management models [10], as a sustainable healthcare supply chain is crucial for effective operations [11]. To prepare for unforeseen events in the future, it is crucial to thoroughly understand sustainable healthcare supply chains. Additionally, the healthcare supply chain should possess the tools to effectively manage any negative impacts and recover from both short- and long-term disruptions, including those arising from global events that may drastically alter society and the economy [11].

It is crucial to emphasize the importance of conducting research that examines the combined impact of management practices on the economic, social, and environmental dimensions of sustainability [12, 13]. Furthermore, a gap exists in understanding how disruptions or shortages can impact the sustainability of healthcare supply chains [14]. The COVID-19 pandemic, for instance, tested the supply chain's flexibility, resilience, and robustness, impacting its performance [10, 15].

There is also a need to manage the risk in supply chains due to the uncertainty in the results. These risks have not been adequately studied, and there is a requirement to evaluate the correct risk and resilience metrics that should be incorporated into a sustainable supply chain model to make appropriate management decisions [13]. The literature highlights the pressing need for studies that investigate the impact of risk management practices on supply chain sustainability, considering the economic, social, and environmental dimensions simultaneously within a single model [2, 11–13]. Additionally, the extent to which supply chain sustainability and resilience practices are synergistic or conflicting remains a complex and multifaceted research question [16].

A literature review conducted by Wang et al. [17] on risk management in sustainable supply chains identified 16 types of risks associated with such chains. However, their findings indicate that most articles focused on environmental issues. Consequently, Wang et al. [17] suggests that further research is needed, particularly on risks associated with the social pillar. The study by Wang et al. [17] highlights the potential of supply chain disruptions on social sustainability, which may outweigh the effects of environmental risks. Moreover, empirical evidence suggests that the social dimension plays a crucial role in the sustainability of health systems, surpassing the influence of the other two dimensions [18]. Furthermore, Jahani et al. [2] argues that a significant gap exists in research that incorporates the financial dimension into the design of sustainable supply chains.

It is also crucial to recognize the importance of measuring supply chain performance. This includes identifying environmental impacts, achieving cost savings, ensuring regulatory compliance, and enhancing supply chain resilience. Such measurements directly impact sustainable performance in various areas, including supplier selection and development, mode and operator selection, vehicle routing, location decisions, and packaging options [19].

2.2 Paradox Theory and Its Application to Supply Chain Management

Good theories address "why" and "how" questions by exploring underlying processes, often presenting cohesive and logically connected arguments [20]. Historically, theorization in supply chain management, as in other management areas, has taken a trade-off perspective, forcing decision-makers to make choices [3, 4]. However, according to the same authors, this perspective has evolved over time to a contingency perspective, for example, to evaluate the context in which one option is positioned as superior to an alternative option.

Proposed by Smith and Lewis [9], paradox theory has its roots in organizational studies and explores how organizations can simultaneously address contradictory demands. It suggests that while focusing on one conflicting priority may improve short-term performance, long-term sustainability requires ongoing efforts to address numerous and divergent choices [9]. Despite its potential benefits, the application of paradox theory in supply chain management remains limited [3, 4].

Paradoxes are not problems that require solutions. Treating them this way causes paradoxes to lose their processual edge and dynamic, time-sensitive, and path-dependent properties [21]. As noted by Cunha and Putnam [21], treating paradoxes as problems can lead to potentially harmful contradictions or negative organizational outcomes.

Sustainability in supply chain management involves effectively managing materials, information, and funds to achieve simultaneous economic, environmental, and social goals [16]. However, there is evidence of conflicts between the various dimensions of sustainability, particularly regarding economic performance and environmental sustainability in supply chains [22–24]. Managing supply chains for sustainability often results in conflicting demands, which can be conceptualized as sustainability tensions [23, 24].

Framing social-ecological objectives with their conflicting elements as paradoxical tensions enables organizations and supply chains to develop better strategies for responding to complex sustainability issues in the supply chain context [24]. Proponents of a paradox perspective suggest that managers and organizations can be more effective in sustainable supply chain management if they accept contradictory elements as both valid [23]. Rather than quickly settling on "both-and" approaches, decision-makers should consider the responses to conflicting demands as repertoires that organizations and their members can use to address various types of contradictions that arise over time [21]. According to these authors, effective responses to conflicting demands in some cases involve a combination of either-or, both-and, and more-than approaches.

Decision-makers should recognize the interdependence and persistent nature of these contradictory elements [21]. This means that they should apply paradoxical thinking, a cognitive framework that accepts contradictions, leading to the recognition of a dilemma in which no single choice can resolve the tension because opposing solutions are needed and are interwoven [23]. Nevertheless, how to define and measure proficiency in responding to contradictory, interrelated, and persistent paradoxes remains unanswered [21].

3 Methodology

This section details the case study used to apply our approach (first subsection) and the methodology employed in this research (second subsection). It also explains the modeling of each decision-making level.

3.1 Case Study: Tetanus and Diphtheria Vaccination in a Vaccination Point of Central Alentejo

In Portugal, the Tetanus and Diphtheria (Td) vaccine is essential to the National Vaccination Program for adults and children over 10 years old (Direção-Geral [25]). For adults who have not previously received the Td vaccination, have an unknown vaccination status, or possess an incomplete primary vaccination record, it is recommended that they receive three doses of the Td vaccine. Additionally, Td vaccine boosters should be administered, as per the updated vaccination schedule for individuals over 18, with the next dose to be given at intervals of 20 years. Once individuals reach the age of 65, it is recommended that those who had their last Td vaccine dose more than 10 years ago receive subsequent doses every 10 years (Direção-Geral [25]). Furthermore, vaccination is recommended in cases of wounds. When there are wounds with a risk of tetanus, a booster vaccination is recommended if the last dose was received more than five years ago. A booster should be given without tetanus-prone wounds if the last dose was administered more than 10 years ago (Direção-Geral [25]).

The vaccination point integrates a personalized healthcare unit in the Central Alentejo region in Portugal, serving approximately 6500 users spread through 370 Km^2. Its vaccination point is open 12 h a day year-round, supporting open consultation. In 2022, 364 Td vaccines were administered, and in 2023, 347 Td vaccines were administered [corresponding to a triangular distribution with the following parameters (0.322, 0.677; 2.133), respectively (minimum; mode; maximum) per day].

Regarding supply chain management, the Td vaccine is supplied monthly [corresponding to the uniform distribution, with the parameters (4;5) weeks] from a central warehouse 35.3 km away. The replenishment model adopted is the up-to-level replenishment. As a matter of resilience, the current level of Td vaccine stock in the Personalized Healthcare Unit (UCSP) is twice the average monthly consumption of last year. The vehicle used for transporting the vaccines has a mixed consumption of 5.1 liters per hundred kilometers and CO_2 emissions of 131 grams per kilometer [26].

In this case, the decision maker faces the problem of considering several conflicting objectives regarding sustainability and resilience, or paradoxes: (i) minimize average stock (as a proxy for governance sustainability). An inventory hedging strategy is defined as extra inventory carried by the nodes to hedge against disruption risk [15]. It is usually not considered appropriate for perishable products, such as vaccines, as its implementation under a no-disruption scenario might result in massive wastage due to perishables [27]; (ii) maximize service level (a proxy for resilience and social sustainability). Given the ultimate goal of ensuring the uninterrupted availability of quality vaccines and avoiding stock-outs and consequent loss of vaccination opportunities [7]; (iii) minimize CO_2 emissions (a proxy for environmental sustainability). Regarding environmental concerns, green supply chain management aims to reduce CO_2 emissions, waste, and harmful emissions and preserve biodiversity throughout the supply chain [28].

The best supply chain policies for different decision profiles will be determined by considering the following parameters: reorder period and maximum stock of Td in the vaccination point.

3.2 Multi-Objective Simulation and Optimization Approach

3.2.1 First Step: Modeling and Simulation

Simulation is a well-established method for studying complex transportation and logistics systems [29]. It enables quantitative assessment of problems in supply chains, including those originating upstream and downstream [30]. Simulation allows the representation of business processes of production systems, such as demand forecasts and inventory purchase orders [31, 32]. By simulating a system, managers can test different configurations and identify the most efficient way to operate it. This process facilitates the acquisition of valuable insights, encompassing those arising from previously unconsidered events and those resulting from the cascading effects of specific events over time. These insights have the potential to unveil overlooked events that substantially influence the system's overall performance [33].

We began by identifying the problem and the components that will be modeled and analyzed. In this specific case, two processes were identified. The first process is the vaccination point process, as depicted in Fig. 1. During this process, patients arrive at the vaccination point at random intervals. If Td vaccine stock is available, they receive their vaccination. If not, and no special request for the vaccine has been

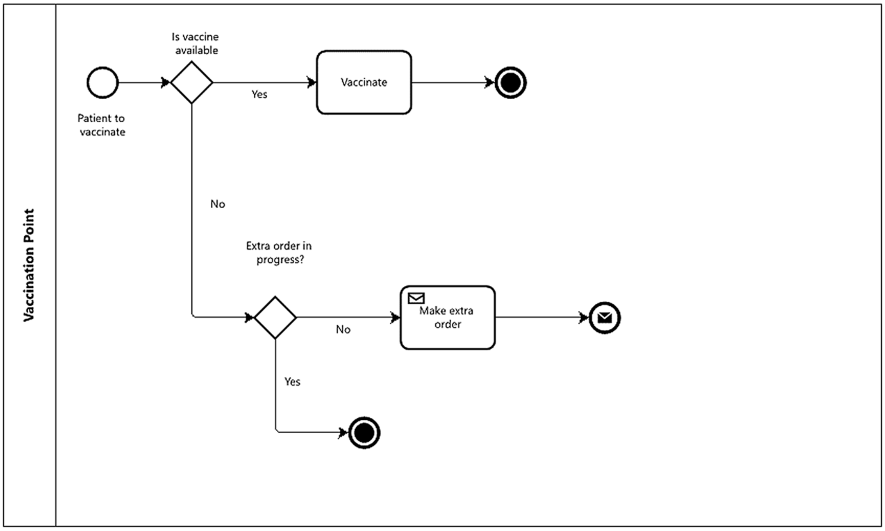

Fig. 1 Vaccination point process

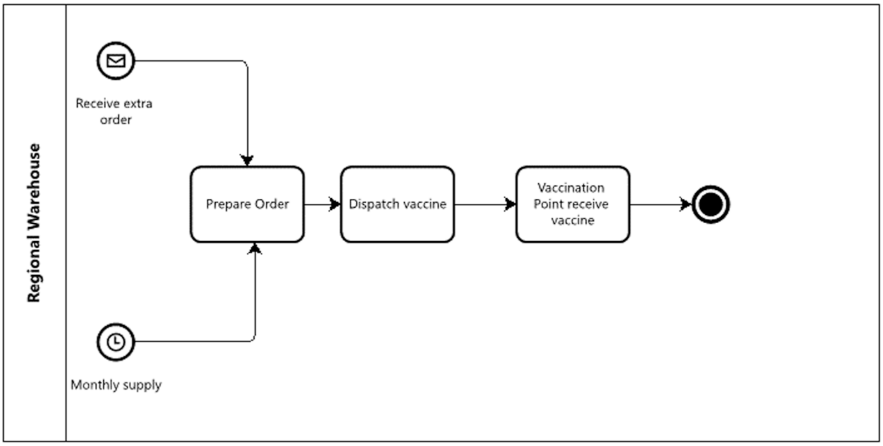

Fig. 2 Regional warehouse process

previously placed, a special request for half of the defined maximum stock will be made.

The following process pertains to the regional warehouse and is depicted in Fig. 2. This process involves the vaccination point receiving orders (both extra and periodic) for Td, preparing them (with random preparation times for extra orders), and dispatching them. As there were no supply shortages in 2022 and 2023, these were not taken into account in the model.

Different approaches, such as process or agent modeling, can be used to simulate the problem. In this case, SIMIO software (Version 16) was used, which allows the user to integrate concepts from both approaches [34]. After developing the model, the next step is validation. We used operational validation, which involves determining that the model's output behavior is satisfactory for its intended purpose and applicability [35].

3.2.2 Second Step: Multi-Objective Simulation Optimization

To use the simulation-optimization approach outlined in the second step, the user must first define the objectives to be maximized or minimized and the range of values for the parameters. This allows each decision-maker profile to establish its preferences. Finally, the maximum number of scenarios to be created is also defined. Once this setup is complete, the simulation optimization engine establishes a set of initial scenarios and runs them for the defined simulation length. The obtained objectives are recorded, and a heuristic is used to determine the following parameter values based on the recorded objectives for the new scenarios, which are created automatically. This process is repeated until the previously defined maximum number of scenarios has been reached.

At this stage, it is crucial to identify the best scenarios, along with the proper parameters and objectives, for the decision-maker. These scenarios can be analyzed using Pareto front analysis to identify a set of non-dominated scenarios. This analysis requires the use of multi-objective simulation optimization. In real-world optimization problems, for example, multiple conflicting objectives often exist to achieve the lean logistics goal of minimizing inventory while maximizing service level [36]. According to Deb [36], this results in a range of optimal compromise solutions rather than a single one. So, finding multiple optimal solutions is crucial. Access to various compromise solutions allows the decision-maker to make better choices.

In the first phase, we define the objectives to be maximized and minimized. In this case, we aim to maintain a high service level while simultaneously minimizing CO_2 emissions and the average quantity of Td vaccine in stock at the vaccination point. The primary objective considered in this case is the service level, representing the proportion of patients vaccinated. Additionally, it is essential to establish the range of values that can be used for the parameters. These parameters include the lead time (ranging from one to five weeks) and the order point (ranging from 10 to 60 units). Finally, we have set a maximum of 100 scenarios to be created.

Subsequently, the OptQuest® for SIMIO® software is utilized, wherein the simulation-optimization engine establishes a set of initial scenarios and runs them for the defined simulation duration. The resulting objectives are recorded, and based on the recorded objectives, a heuristic approach is employed to determine the parameter values for the new scenarios. This iterative process continues until the maximum number of scenarios is reached. Subsequently, the collected scenarios are

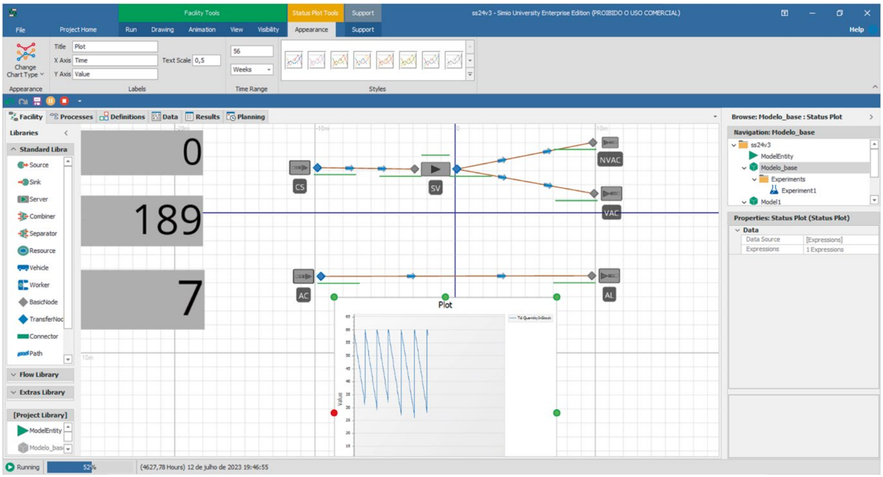

Fig. 3 Run of a simulation experience

subjected to a Pareto front analysis [33]. Figure 3 illustrates the execution of a simulation experiment.

The service level was identified as the primary response, incorporating a minimum of five and a maximum of 30 replications (due to computation constraints), a confidence level of 95%, and a relative error of 0.1.

4 Results

Through the first step, which consists of modeling and simulation, we can analyze the progress of the specified objectives and performance indicators throughout the simulation. This feature benefits users who are familiar with the parameters they wish to test, as well as those seeking a more detailed understanding of a specific scenario [33]. The average results of simulation experiences presented in Table 1 allowed the successful validation of the model.

From the results of the second step, we obtained 52 solutions, nine of which were non-dominated. Table 2 shows the results obtained in non-dominated solutions. These nine non-dominated solutions allow decision-makers to integrate resilience and economic, environmental, and social sustainability into managing the Td vaccine logistics chain according to their preferences.

The data presented in Table 2 reveals that four non-dominated solutions achieved a service level of 100 percent, indicating that there were no instances of non-vaccination. The lowest service level among non-dominated solutions was approximately 88 percent. Regarding the average Td vaccine stock at the vaccination point, the minimum value among the non-dominated solutions was one vaccine in stock,

Table 1 Average results of simulation experiences

Max Td stock level	Replenishment period (weeks)	Service level	Average stock	CO_2 (kg)
60.00	Uniform (4,5)	1	44.5	116.9

Table 2 Average results obtained from non-dominated solutions

DMU	Max Td stock level	Replenishment period (weeks)	Service level	Average stock	CO_2 (kg)
002	10.00	1.00	1	9	516.4
009	10.00	5.00	0.879	1	526.1
021	25.00	5.00	0.971	10.4	204.6
022	15.00	3.00	0.952	7.2	341.0
027	15.00	2.00	1	14	263.1
044	20.00	5.00	0.943	5.33	302.0
046	35.00	5.00	1	20.2	107.2
047	25.00	3.00	1	17	175.4
055	10.00	3.00	0.904	2	506.6

Note: DMU means Decision Making Unit

with a maximum of 20.2 vaccines. Lastly, the solution's values for CO_2 emissions ranged from [107.2-526.1] kg of CO_2 for the non-dominated solutions.

5 Concluding Remarks and Future Research Lines

Our research employed paradox theory to analyze the challenges of resilience and sustainability in the environment, society, and governance within vaccine supply chains. Additionally, we applied a multi-objective optimization simulation, enabling decision-makers to generate diverse scenarios and solutions based on their preferences. This tool also facilitates the acquisition of valuable insights, encompassing those arising from previously unconsidered events and those resulting from the cascading effects of specific events over time. This enables decision-makers to move beyond single choices to consider combinations of options, such as either-or, both-and, and more-than approaches, aligning with the proposed by Cunha and Putnam [21].

While our analysis offers valuable insights, it is essential to acknowledge its limitations. Due to its simplified nature and considering the gaps identified in Sect. 2, our study focuses solely on the operational aspects of vaccine supply chain management, specifically on demand fulfillment and inventory management. We did not consider other important factors, such as vaccine wastage or reverse logistics, which could be considered in future research. It is worth noting that factors like the potential use of electric vehicles for transportation could significantly impact the conclusions drawn from our study.

In future studies, it is advisable to consider analyzing more complex cases to gain a deeper understanding of existing paradoxes. Additionally, incorporating the preferences of decision-makers and other stakeholders through interviews could provide valuable insights. Furthermore, we recommend analyzing the solutions obtained (both dominated and non-dominated) using advanced techniques such as Data Envelopment Analysis, a nonparametric method commonly used in operations research and economics to estimate production frontiers.

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