



Rethinking regionality: how spatial definitions shape efficiency in perishable food supply chains

RESEARCH ARTICLE

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Abstract

Public discourse and policymakers increasingly promote regional food supply chains as sustainable and resilient alternatives to global networks. Yet the meaning of regionality remains opaque: political boundaries, radial measures and time-based definitions are used in parallel within food value chains. This study investigates how alternative definitions of regionality affect logistics efficiency in perishable agri-food supply chains, using a model-based scenario analysis with two case studies of fresh-cut fruit and vegetable distribution in Germany. Employing spatial analysis, vehicle routing models and Monte Carlo simulations, we compare the effect of alternative definitions of regionality on fleet size, delivery times, and customer coverage. Findings reveal that distance-based definitions of regionality improve efficiency, while political borders often impose arbitrary constraints, particularly for firms located at the periphery of administrative units. This suggests that regionality concepts should be developed further towards more transparent and flexible definitions that reconcile consumer trust with logistical realities and producer viability.

Keywords: fresh-cut products, logistics efficiency, perishable goods, regionality, vehicle routing problem

JEL codes: Q13, Q18, R4

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1. Introduction

In recent years, global disruptions such as the COVID-19 pandemic, energy crises, and geopolitical instability have exposed the vulnerabilities of globally integrated supply chains. As a result, regional value chains are gaining increasing attention as potentially more resilient and sustainable alternatives (Amador *et al.*, 2015; Aday and Aday, 2020; Chowdhury *et al.*, 2021; Clancy and Ruhf, 2018; Cui *et al.*, 2023; Davis *et al.*, 2021; Marusak *et al.*, 2021). Particularly in the food and agricultural sector, regional systems are promoted for their ability to enhance food security, support local economies, and reduce environmental impact (Clancy and Ruhf, 2018). At the same time, consumer preferences in developed countries have shifted toward products that reflect ethical, social, and environmental values (aligned with the principles of SDG 12 on responsible production and consumption; Kour, 2024). This is also consistent with a broader trend towards post-materialist and identity-driven consumption (Rossi *et al.*, 2024; Witt, 2017). Among the attributes perceived as desirable in this context; Sama *et al.*, 2018t, regional origin stands out as a key purchase criterion, often associated with quality, freshness, and trustworthiness (Bannor and Abele, 2021; Zander and Hamm, 2010).

However, the meaning of regionality is far from uniform. Across countries, labeling schemes, and marketing campaigns, regional may refer to administrative boundaries, proximity-based zones, cultural regions, or travel-time isochrones (Heinze *et al.*, 2014; Herz *et al.*, 2023). Even within comparatively affluent and developed countries such as Germany, where rising incomes typically lead to more diverse and value-driven food choices in line with Bennett's Law, the concept of regionality remains fluid and inconsistently defined (Märtlbauer and Meyer, 2014). Some schemes define regions politically (e.g., federal states or districts), others spatially (e.g., within 50–70 km), while some emphasize processing location or regional cooperation (Heinze *et al.*, 2014). This definitional ambiguity can lead to confusion among consumers, strategic interpretation by firms, and most importantly to practical challenges during actual implementation in real world logistics.

So far, research on regional food systems has focused largely on consumer perception, willingness to pay, and labeling schemes (Feldmann and Hamm, 2015; Pícha *et al.*, 2018). In contrast, the operational consequences of these varying definitions for producers and supply chain actors have received scant attention.

Our study addresses this gap by investigating how alternative definitions of regionality affect the operational/logistical efficiency of food supply chains. Compared to other sectors, agri-food logistics must deal with a high degree of seasonality, perishability, biological variability, and narrow time windows for harvesting, processing and delivery (Banomyong *et al.*, 2008; Wajszczuk, 2016). Especially for firms distributing perishable goods such as pre-processed (so called fresh-cut) fruit and vegetables, the definition of regional can decisively shape operational requirements. Fresh-cut fruit and vegetables are minimally processed, ready-to-eat products that remain in a fresh state despite being peeled, cut, or trimmed (Garrett, 2002).

We develop a model-based scenario analysis, in which two contrasting case studies serve as application contexts to implement and evaluate a routing problem model under different regionality constraints. In doing so, we focus on the distribution of fresh-cut products, which require precise routing and tight delivery schedules due to their short shelf life (Bublik *et al.*, 2025a,b). Using two case studies in Germany, we compare three commonly used definitions of regionality: (1) political boundaries, as frequently applied in certification and labeling schemes; (2) radial distance zones, where consumers tend to perceive a product as regional if it is produced or processed within a radius; and (3) travel-time isochrones, where regionality is associated with a production or processing site reachable within a time constraint. The two case studies represent contrasting spatial scenarios: in one, the producer is located centrally within the politically defined region; in the other, the producer is situated at the periphery, near the administrative border. This design allows us to examine how definitional choices interact with geographical context and shape logistical outcomes alongside the following research question:

How do different definitions of regionality affect the logistical structure and efficiency of regional food distribution systems, particularly for perishable goods such as fresh-cuts?

To evaluate the logistical implications of each definition, we apply a Vehicle Routing Problem (VRP) model as a simulation framework. This model serves as a decision-support tool for quantifying how different regional definitions shape key performance indicators such as total route duration, number of vehicles needed, and average customers served per truck. Through a combination of heuristic optimization such as Nearest Neighbor- (Fix and Hodges, 1952) and Simulated Annealing algorithms (Kirkpatrick *et al.*, 1983; Metropolis *et al.*, 1953) as well as Monte Carlo simulations, we capture both deterministic and uncertain operating conditions. This approach allows us to explore the interaction between spatial definitions and logistical performance, particularly in scenarios where producers operate near regional borders or under tight delivery constraints.

Our contribution is twofold: First, we offer a systematic, model-based comparison of regionality definitions from a logistics and operational perspective - an aspect previously underrepresented in the literature. Second, we derive practical implications for certification bodies, regional policy makers, and logistics managers, showing how definitional choices can either support or hinder efficient and sustainable regional food systems.

The structure of the paper is as follows: Section 2 presents background on regionality in agri-food supply chains. Section 3 describes the methodological framework, including the VRP model, and the corresponding solving algorithms. Scenario design and case study setup are described in section 4. Section 5 reports the simulation results. Section 6 discusses the implications of the findings and concludes with recommendations for policy and practice delivering novel approaches for defining regionality.

2. Regionality in the agri- and food sector

The concept of regionality in the agri-food sector is diverse and highly context dependent. A distinction can be made between products marketed within the same region, in neighboring regions, or even internationally. Definitions of what constitutes regional often depend both on geographic scope and on the origin of raw materials. A product may, for example, be considered regional if it is produced within a 50–70 km radius of the consumer's home or business (Heinze *et al.*, 2014). Stricter approaches, however, require that production, processing, and marketing all occur within the same region, thereby ensuring value creation remains in the region and transport distances are minimized (Sauter and Meyer, 2003).

For modern, highly processed food products, such exclusivity is rarely feasible due to the complexity of value chains. Composite products composed of multiple raw materials often fail to meet strict regionality criteria, as more than half of the inputs would need to originate from the defined region (Heinze *et al.*, 2014). In practice, agricultural production also relies on external resources such as fertilizers, seeds, energy, and machinery, which makes fully closed regional economic cycles (from production through consumption and waste disposal) difficult to achieve. Nevertheless, specialties tied to cultural traditions or regional identities continue to form the backbone of regional food marketing (Gerschau and Berger, 2002).

Sustainability is another key driver of consumer preferences for regional food, with shorter transport distances often perceived as reducing the climate footprint. Yet this expectation does not always correspond to reality: factors such as production practices, transport mode, and seasonality can outweigh the benefits of reduced distances (Märtlbauer and Meyer, 2014). These contradictions highlight both the desirability of regionality and the practical constraints of its implementation.

Beyond definitions, regional food systems also face significant logistical challenges, particularly within short food supply chains (SFSCs). Research shows that fragmented distribution networks, high transportation costs, and inadequate infrastructure frequently undermine their efficiency and sustainability (Canfora, 2016; Paciarotti and Torregiani, 2021). Social and economic barriers further complicate these systems: González-Azcárate, Cruz Maceín and Bardají (2021) identify limited consumer access and inconsistent

supply as major obstacles, while Blanquart *et al.* (2010) emphasize that small-scale producers often lack the logistical capacity to reach markets effectively.

To overcome such hurdles, Day-Farnsworth and Miller (2014) highlight the need for innovative infrastructure and expertise and propose coordinated distribution models that reduce environmental impacts, expand producer opportunities, and improve traceability (Bosona and Gebresenbet, 2011). Regional food hubs, established to aggregate and distribute local products, illustrate both potential and difficulty: inbound logistics from farms, which simultaneously constitute the farms' outbound logistics, frequently represent a bottleneck. As Mittal and Krejci (2019) and Mittal and Krejci (2015) demonstrate, improving these flows is critical for hub performance. Insights from conventional supply chains can also provide guidance, with best practices such as route optimization and network consolidation offering ways to enhance regional food supply chains (Mittal *et al.*, 2018).

3. Material and methods

This article integrates two core approaches from logistics research. First, it aims to identify optimal delivery routes for a set of customers within a given regional framework, considering specific operational constraints. This objective is addressed through a Vehicle Routing Problem (VRP) model that incorporates multiple parameters. Second, the study conceptualizes the issue as an inverted Location Selection Problem (LSP), examining how different definitions of regional boundaries affect the performance of an existing logistics location.

Using QGIS (Quantum GIS) software (QGIS.org, 2024), Open Street Maps and openrouteservice, we developed spatial scenarios for two case studies, each involving a fresh-cut depot and multiple restaurant customers. The VRP is solved using the Nearest Neighbor (NN) heuristic combined with a Simulated Annealing (SA) algorithm, subject to constraints on delivery time windows and unloading durations. To account for uncertainty, Monte Carlo simulations are applied, with the objective of minimizing the number of vehicles and total driving time.

3.1 The Vehicle Routing Problem (VRP)

The VRP is a generalization of the Traveling Salesman Problem (TSP). While in the latter one person visits all customers, in the VRP several vehicles are available for this purpose. (Dantzig and Ramser, 1959). VRP belongs to the group of combinatorial optimization problems (Dorigo and Gambardella, 1997). In this problem, customers and depots are located on the vertices of a graph. The edges show the path between the vertices and their associated costs (Khajepour, Sheikhmohammady and Nikbakhsh, 2020). The objective of the VRP is to determine a cost-minimizing fleet configuration and corresponding set of routes, such that each customer (vertex) is visited exactly once, all routes start and end at the depot, and total transportation costs are minimized. There are basic constraints:

- (1) Each route starts and ends at the depot.
- (2) Each customer is visited by exactly one vehicle.
- (3) The total demand of customers visited on a route does not exceed the vehicle capacity.

Depending on the specific application, the Vehicle Routing Problem can incorporate a variety of additional constraints (Laporte and Osman, 1995). The VRP has been extensively studied and widely applied to optimization problems in the logistics of the agricultural and food sectors. In this study, we extend the classical VRP by introducing two additional constraints: each customer must be visited within a predefined time window, and a fixed unloading or service time is allocated at each delivery point.

The following paragraphs present the parameters, decision variables, objective function, and constraints used in our implementation of the VRP.

The parameters are: N , number of customers; K , number of vehicles available; $D=\{0,1,\dots,N\}$, set of places, where 0 represents the deposit; c_{ij} , travel time between place i and place j ; Q , maximum number of customers a vehicle can serve; T , maximum time (in min) that a vehicle can be on the road; L , service time per customer.

The decision variables are: x_{ij}^k , binary variable which is 1 if vehicle k travels directly from place i to place j , otherwise 0; t_{ik}^k , arrival time of vehicle k at location i .

Objective function:

Minimize total travel time:

$$\text{Minimize } \sum_{k=1}^K \sum_{i \in D} \sum_{j \in D} c_{ij} x_{ij}^k \quad (1)$$

Constraints:

- (1) Every vehicle starts at the depot but does not have to end there. The reason for this is that although the delivery to the customers must take place within the limited time windows, there is then enough time to return to the depot. Therefore, the return from the last customer to the depot does not necessarily have to take place.

$$(a) \sum_{j \in D} x_{0j}^k = 1 \quad \forall k \quad (2)$$

$$(b) \sum_{i \in D} x_{0i}^k \leq 1 \quad \forall k \quad (3)$$

- (2) Each vehicle visits each customer exactly once:

$$(a) \sum_{k=1}^K \sum_{i \in D} x_{ij}^k \quad \forall j \in D \setminus \{0\} \quad (4)$$

- (3) When a vehicle arrives at a customer's door, it must also depart:

$$(a) \sum_{j \in D} x_{ij}^k = \sum_{i \in D} x_{ij}^k \quad \forall k, \forall i \in D \quad (5)$$

- (4) Time restrictions and maximum number of customers per vehicle:

$$t_j^k \geq t_i^k + c_{ij} + L - T(1 - x_{ij}^k) \quad \forall k, \forall i, j \in D, i \neq j \quad (6)$$

$$\sum_{j \in D \setminus \{0\}} x_{ij}^k \leq Q \quad \forall k, \forall i \in D \quad (7)$$

In summary, the version of the VRP applied in this study can be characterized as a Vehicle Routing Problem with Service Time and Capacity Constraints (VRPSTCC). Figure 1 summarizes the research design in a conceptual flowchart.

3.2 Solving the VRP

VRPs are NP-hard (Dorigo and Gambardella, 1997), making exact methods like Linear Programming (LP) and Branch-and-Bound (B&B) increasingly impractical for complex problems with numerous variables (Laporte, 1992). Instead, heuristics and meta-heuristics are commonly used. Heuristics employ tailored functions to efficiently navigate solution spaces, while meta-heuristics, such as Simulated Annealing or Genetic Algorithms, iteratively guide the search to balance exploration and exploitation (Blum and Roli, 2003; Desale *et al.*, 2015). In our case, a two-stage metaheuristic approach was employed to solve the VRP.

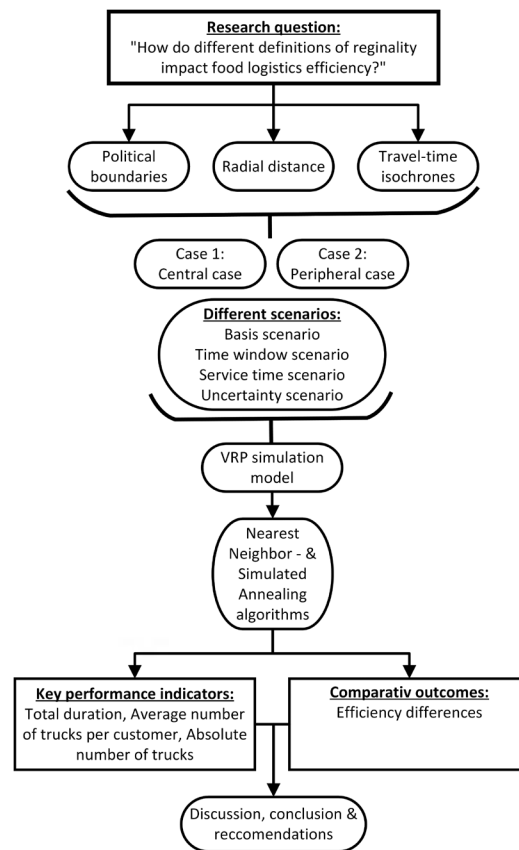


Figure 1. Conceptual flowchart of the research design. Source: own representation.

Nearest Neighbor algorithm

The Nearest Neighbor algorithm (Fix and Hodges, 1952) constructs delivery routes by starting at the depot and iteratively adding the nearest unvisited customer (Ferdiani Harahap and Sawaluddin, 2023). In this study, the process continues until either the time window constraints or the maximum number of customers per vehicle is reached.

Numerous studies have demonstrated that the Nearest Neighbor algorithm can be effectively applied to solve variants of the VRP: Ferdiani Harahap and Sawaluddin (2023) show that the Near Neighbor Algorithms can reduce distances by up to 13.14% and costs by 13.17%. Even for more complex routing problems, such as the capacitated vehicle routing problem, this algorithm can be applied successfully. Although the algorithm leads to a quick solution, it is often not optimal (Bhatia and Vandana, 2010). Compared to the Tabu Search (TS) metaheuristic, the latter finds shorter driving tracks than the Nearest Neighbor algorithms (Masudin *et al.*, 2019), in combination with Nearest Neighbor and Tabu Search, a hybrid meta heuristic approach creates a competitive solution that combines the two strengths of the respective approaches and can successfully solve the VRP on a larger scale (Du and He, 2012). Thus, the Nearest Neighbor algorithms is an effective way to generate an initial route, which is then refined by another (meta) heuristic.

Simulated Annealing algorithm

This method is used to further optimize the initial routes generated by the Nearest Neighbor algorithm. The method is inspired by annealing techniques in metallurgy, where a material is heated and then gradually cooled to achieve a more stable structural configuration. In combinatorial optimization, this process, known as Simulated Annealing, aims to improve an initial solution through iterative modifications. To avoid being

trapped in local minima, the algorithm occasionally accepts suboptimal solutions, thereby increasing the chance of approaching a global optimum. Simulated Annealing has been successfully applied to various optimization problems, including the VRP (Kirkpatrick *et al.*, 1983; Metropolis *et al.*, 1953). The Simulated Annealing algorithm proves to be an efficient and fast solution of the VRP and can be compared with other meta heuristics (van Breedam, 1995). For VRPs with time constraints, high-quality results are achieved, and at the same time, SA can also be applied to bi-criteria optimization problems (Woch and Łebkowski, 2013). The combination of Simulated Annealing and the Nearest Neighbor algorithm has also been described in the literature as an efficient and practical approach (Guo and Huang, 2007). In the case of route planning, this combination can significantly reduce computation time and improve route efficiency (Sriwana *et al.*, 2022).

3.3 Monte Carlo simulation

The Monte Carlo simulation uses random numbers to model statistical fluctuations, generating probability distributions and providing precise numerical insights into complex systems characterized by uncertainties (Binder and Heermann, 1992). This technique is particularly valuable for combinatorial optimization problems, including VRPs, where it is often combined with heuristics (Alemany *et al.*, 2016; Juan *et al.*, 2009). Monte Carlo simulation has been applied to VRPs with constraints such as capacity, route length, and service times (Juan *et al.*, 2012), but its integration with a hybrid optimization approach combining the Nearest Neighbor algorithm and Simulated Annealing has not been explored in this form so far.

4. Case studies

In our analysis, we conduct a model-based scenario analysis, in which the case studies serve as application contexts for implementing and validating the VRP model under different regionality constraints. The following section provides a more detailed description of these case studies, which are situated in the German fresh-cut produce market.

4.1 The German fresh-cut market

The out-of-home catering sector in Germany is increasingly adopting fresh-cut products due to labor shortages, rising costs, and growing demand for convenience and health-focused options (Behr and Effertz, 2018). While household use of fresh-cuts in Germany lags behind countries like the Netherlands and the UK, demand is rising in system catering, communal catering, and food service sectors, driven by standardized processes, tight budgets, and the need for labor-saving solutions (Behr and Effertz, 2018; Behr *et al.*, 2022). Fresh-cut products are highly perishable, requiring fast logistics to maintain freshness within a six-day window (Menn, 2020). The fresh-cut market can be described as a niche market (Bublik *et al.*, 2025b). Orders are often prepared immediately after placement and delivered in narrow morning time slots, creating logistical challenges such as underutilized truck capacity and precise routing needs. In this analysis, we focus on a B2B (business-to-business) context, as the buyers of fresh-cut products are typically canteens and restaurants. However, these businesses also have a clear incentive to pay attention to regionality: if they prioritize regional sourcing in their procurement, they can market their dishes as regional specialties, which in turn may lead to a higher willingness to pay (WTP) among their end consumers. This brings us back to the recurring and fundamental question: What is regionality and how should it be defined?

4.2 Framework of the case studies

Two case studies were conducted, focusing on a fresh-cut producing company aiming to sell its products regionally to various restaurants. The case studies differ in area size and depot location. In the first case (Central case; Figure 2), the depot is centrally located within the German district of Ostalbkreis, defined politically as a regional boundary. In the second case (Peripheral case; Figure 3), the depot is positioned on the edge of the Bio-Musteregion Heidenheim+ project area, creating a peripheral location. These distinctions enable the examination of how depot positioning within regional boundaries impacts logistics.

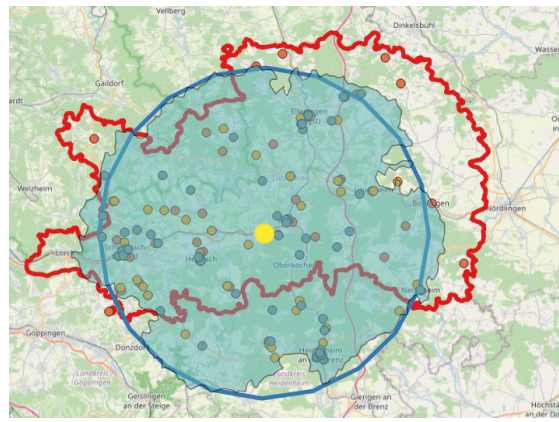


Figure 2. Central case. Yellow point, company/starting point; red line, political borders of district; blue circle, radius; blue area, isochrones; other points, restaurant location within the different areas. Source: own representation.

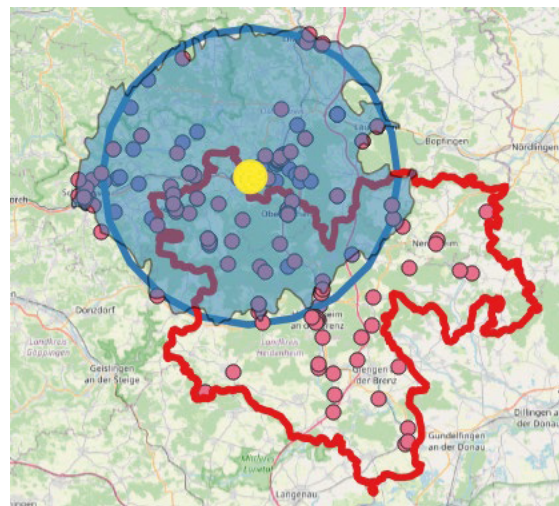


Figure 3. Peripheral case. Yellow point, company/starting point; red line, political borders of organic project region; blue circle, radius; blue filled area, isochrones; other points, restaurant location within the different areas. Source: own representation.

Three definitions of regionality, namely political borders, radii, and isochrones, were analyzed for each case and are detailed in Table 1.

- (1) **Political borders:** In this definition, regionality is determined by administrative or jurisdictional boundaries. All customers located within the same officially defined region as the production company are considered part of the regional market. In the first case study, this corresponds to the Baden-Württemberg district of Ostalbkreis, while in the second it refers to the organic model region Heidenheim+. In practical terms, this definition reflects how regional food systems are often institutionalized through certification schemes, development programs, or administrative governance structures. For the routing model, this definition restricts the set of eligible customers to those located within the administrative boundary.

Table 1. Comparison of both case studies

		Area (km ²)	Number of restaurants in area	Number of restaurants randomly taken
Central case	Ostalbkreis	1510.4	448	55
	Radius	1487.1	489	55
	Isochrones	1481.0	515	55
Peripheral case	Bio Musterregion	874.0	244	55
	Radius	862.4	272	55
	Isochrones	872.0	355	55

Source: own representation.

- (2) **Radii:** In this definition, regionality is defined by a fixed geographic radius around the production company. All customers located within this circular distance are considered regional. The radii in both case studies were selected to generate areas approximately equivalent in size to the respective political regions, thereby enabling a comparable spatial scale across definitions.
- (3) **Isochrones (as reference for the radial definition):** This definition uses travel time rather than geographic distance to define regionality. Customers are considered regional if they can be reached within a specified travel time from the production company based on the road network. Isochrones were generated using the ORS tool *openrouteservice* and were calibrated to produce areas similar in size to the political regions in the respective case studies.

Restaurant locations were identified using data from Open Street Maps for six distinct areas (three definitions of regionality for each of two case studies). Within each simulation, 55 restaurants were randomly selected from each area. The number of customers per scenario was set at 55, which reflects a realistic delivery workload for regional fresh-cut suppliers operating in medium-density service areas. This number balances computational feasibility with empirical realism, approximating the upper bound of daily delivery capacity for a single depot serving B2B clients within tight morning delivery windows. Transport times between the depot (fresh-cut producer) and these restaurants were calculated using the ORS tool in QGIS, generating $100n \times m$ (56×56) time matrices. Random target coordinates were selected in each iteration, and logistics optimization was performed using a combination of the Near Neighbor method and the Simulated Annealing algorithm. These methods addressed the Vehicle Routing Problem under constraints of delivery time windows and unloading service times, aiming to minimize the number of required trucks and total route duration while maximizing the average number of customers served per truck.

Four scenarios were analyzed to evaluate the impact of different logistical constraints on efficiency, as summarized in Table 2. This approach enabled a comparative assessment of regionality definitions and their implications for logistics optimization.

- (1) **Basis scenario:** First, the routes of the two case studies were optimized based on the above criteria. The time window for delivery was 180 min, and the service time was 15 min/customer (this capacity limitation is maintained for all other scenarios). At the same time, a capacity limit of 15 customers/vehicle applies. The delivery window of 180 min and the service time of 15 min/customer are based on expert knowledge from the fresh-cut sector in Germany and reflect typical practice in B2B logistics, particularly in out-of-home catering. These values were derived from consultations with practitioners and reflect the operational constraints of narrow morning delivery windows and on-site unloading processes under real-world settings. Accordingly, the simulation of this time window is intended to simulate the fact that the fresh-cut products are desired by all customers at the same time in the morning within a narrow time window. Service time covers the unloading of the products at the customer's site.
- (2) **Time Window scenario:** In a next step, this route optimization was carried out for different time windows, which varied from 90–260 min in 15-min steps. The service time remained constant at 15 min/customer.

Table 2. Comparison of the different scenarios

	Basis scenario	Time Window scenario	Service Time scenario	Uncertainty scenario
Time window (min)	180	Range: 120–360 Steps: 15	180	Mean: 180 SD: 15
Service time (min)	15	15	Range: 5–20 Steps: 1	Mean: 15 SD: 2
Max. customers/truck	15	15	15	Mean: 15 SD: 3

Source: own representation.

- (3) Service Time scenario: Compared to (2), the delivery window remained constant at 180 min, but the service time per customer varied from 5–20 min in 1-min increments.
- (4) Uncertainty scenario: Finally, a Monte Carlo simulation was performed in combination with route optimization to subject both the time window (mean=180 min; SD=15 min) and the service time (mean=15 min; SD=3 min) to fluctuations. In all previous scenarios the capacity constraint was constant at 15 customers, here it was assumed to be a mean value of 15 with a standard deviation of 3 customers. 100 runs of the Monte Carlo Simulation were carried out in each case.

Subsequently, the economic implications were considered. To ensure consistency, travel times were rounded to the nearest full min. The number of trucks required was rounded up, since partial vehicles are not operationally feasible (e.g., a calculated value of 6.4 necessitates 7 trucks to serve all customers). Conversely, the number of customers served per vehicle was rounded down, as the next customer beyond the threshold could not be reached (e.g., 8.8 results in 8 customers). While precise operating costs per hour are difficult to quantify, due to factors such as vehicle size, weight, type of refrigeration and toll charges, economic advantages associated with optimized routing can still be observed in various forms.

- (1) Number of trucks required: A smaller number of trucks required is associated with cost savings for operation.
- (2) Capacity utilization: Serving more customers per truck improves resource efficiency and lowers per-customer costs.
- (3) Total duration of routes: A shorter route total duration is associated with lower costs. However, this represents the least effect, as only the period of delivery in a limited time window is considered. Further use for the further utilization of the trucks is not considered here. Furthermore, certain costs, such as depreciation, insurance or personnel costs, are incurred regardless of the respective route duration.

5. Results

5.1 Results of the Basis scenario

The results (relative values in Table A1 in the Appendix) presented in Table 3 indicate that in the Central case, defining regionality based on radial distance yields the most efficient outcomes: total route duration is minimized, fewer trucks are required, and more customers are served per vehicle. The Peripheral case confirms this trend, with *t*-tests revealing statistically significant differences between the definitions (Table A1 in the Appendix), particularly between political boundaries and radial definitions.

However, statistical significance does not always translate into practical relevance. In Ostalbkreis, for instance, total route duration decreases only marginally, from 1406 min under the political definition to 1387 min using isochrones (–1.4%) and 1371 min with radii (–2.4%), equivalent to savings of 19 and 35

Table 3. Basis scenario results: comparison between the central and peripheral case

		Central case			Peripheral case		
		Ostalbkreis	Isochrone	Radius	Bio Musterregion	Isochrone	Radius
Total duration (min)	Mean	1405.68	1386.60	1370.59	1347.79	1289.79	1272.31
	SD	49.73	35.34	42.80	35.57	32.00	35.27
Average number of customers/ truck	Mean	6.14	6.23	6.34	6.65	6.82	6.88
	Mean, rounded	6	6	6	6	6	6
Number of trucks	SD	0.19	0.27	0.36	0.35	0.20	0.10
	Mean	8.97	8.85	8.70	8.30	8.07	7.99
	Mean, rounded	9	9	9	9	9	8
	SD	0.26	0.36	0.48	0.46	0.26	0.1

Relative values in Table A1 in the Appendix. Source: own representation.

min per delivery round. These minor differences are unlikely to impact daily operations. By contrast, in the Bio-Musterregion, total route time drops from 1348 min (political) to 1290 min (isochrones, -4.3%) and 1272 min (radii, -5.6%), yielding savings of up to 76 min per round, an improvement that may meaningfully reduce overtime or enable service to additional customers.

A comparable contrast is observed in fleet size. In Ostalbkreis, the requirement decreases only marginally, from 8.97 trucks under the political definition to 8.85 with isochrones and 8.70 with radii. All values round to nine vehicles, indicating minimal practical impact. In contrast, the Bio-Musterregion exhibits a more substantial reduction, with the fleet size dropping from 8.30 (political) to 8.07 (isochrones) and 7.99 (radii). Here, the radius-based definition reduces the rounded requirement from nine to eight trucks, representing a change with clear cost implications. As for the average number of customers per truck, the variation remains slight. In Ostalbkreis, the average increases from 6.14 (political) to 6.23 (isochrones) and 6.34 (radii); in the Bio-Musterregion, from 6.65 to 6.82 and 6.88, respectively. Although these differences are statistically significant, the rounded average consistently remains six, indicating no meaningful operational difference.

5.2 Results of the Time Window scenario

These results (absolute values in Table A2 in the Appendix, relative values in Figure A1 in the Appendix) were analyzed to assess how varying delivery time windows (ranging from 120 to 360 min) affect logistical performance in the two case studies. All other parameters from the baseline scenario were held constant. For each of the three regional definitions in both case studies, route optimization was performed across 17 time window configurations, using 100 randomly generated travel time matrices per configuration (2 case studies \times 3 regions \times 17 time windows \times 100 matrices = 10 200 optimizations in total).

For each time window, key indicators were computed: total route duration, number of trucks required, and average number of customers served per truck. Summary statistics include the mean, standard deviation, median, minimum, and maximum. The detailed results are presented in in Table A2 and Figure A1 in the Appendix, while Figure 4 provides a visual summary of the most relevant outcomes for ease of interpretation.

The analysis shows that longer delivery time windows reduce the total duration of all routes, although the marginal gains diminish as the time window increases. In general, the political definition of regionality yields the longest route durations. In the Central case, the isochrone-based definition occasionally underperforms

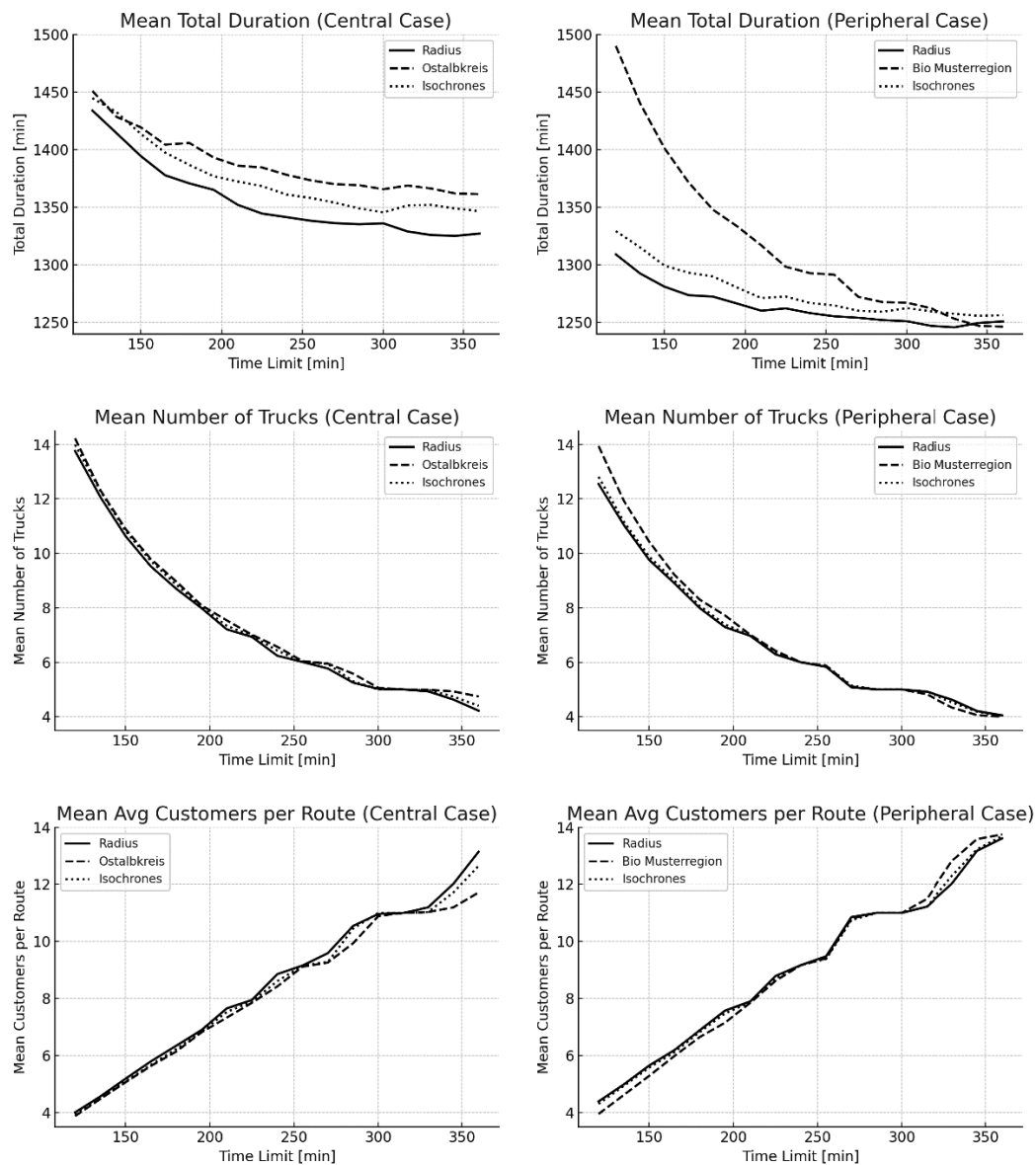


Figure 4. Results of the time window scenario. Source: own representation.

for narrow time windows, whereas in the Peripheral case, this trend reverses at broader time windows. Similar patterns are observed in terms of fleet size and average number of customers served per truck. In the Peripheral case, all three regional definitions begin to converge around a 300-min window, with the political definition unexpectedly producing slightly better results than isochrones or radii. Conversely, in the Central case, the differences between definitions become more pronounced as time windows expand, with radius and isochrone definitions consistently outperforming the political boundary approach.

From an economic perspective, the number of trucks required is a key factor. When the depot is located at the edge of a political region, more trucks are needed compared to definitions based on isochrones or radii (Table 4), with these differences being statistically significant (Figure A1 in the Appendix). This is especially pronounced in smaller time windows. In the second, peripheral scenario, political boundaries show an advantage over isochrones for larger time windows (starting from 315 min), while radii and isochrones outperform in terms of average customers served per truck. Additionally, a time advantage over isochrones is observed with a 360-min time window.

Table 4. Trucks needed in the time window scenario

Time limit (min)	Central Case			Peripheral Case		
	Radius	Ostalbkreis	Isochrone	Radius	Bio Musterregion	Isochrone
120	14	<i>15</i>	14	13	<i>14</i>	13
135	13	13	13	12	12	12
150	11	11	11	10	<i>11</i>	10
165	10	10	10	9	<i>10</i>	9
180	9	9	9	8	<i>9</i>	9
195	8	<i>9</i>	9	8	8	8
210	8	8	8	7	<i>8</i>	7
225	7	8	7	7	7	7
240	7	7	7	6	6	6
255	7	7	7	6	6	6
270	6	6	6	6	6	6
285	6	6	6	5	5	5
300	6	6	5	5	5	5
315	5	5	5	5	5	5
330	5	5	5	5	5	5
345	5	5	5	5	5	5
360	5	5	5	5	4	5

Differences highlighted in italics. Source: own representation.

5.3 Results of the Service Time scenario

The analysis (Table A3 in the Appendix, relative values in Figure A2 in the Appendix) investigates how varying service times, ranging from 5 to 20 min, affect logistics performance in the two case studies, with all other parameters held constant as in the baseline scenario. For each of the three regional definitions in both case studies, route optimization was performed across 16 service time settings, each evaluated using 100 randomly generated travel time matrices (2 case studies×3 areas×16 service times×100 matrices = 9600 optimizations in total).

For each service time, the following key indicators were calculated: total route duration, number of trucks required, and average number of customers served per truck, including mean, standard deviation, median, minimum, and maximum. Detailed results are provided in Table A3 in the Appendix, while Figure 5 offers a visual summary of the most relevant metrics. In the Central case, the political definition leads to the longest route durations at short and medium service times. However, as service time increases, its performance converges with the other two definitions and even outperforms isochrones beyond approximately 18 min. Across all parameters and service intervals, the radius-based definition consistently delivers the best results in the Central case.

In the Peripheral Case, differences between definitions are minimal at short service times, but these diverge significantly as service time increases. The political definition results in longer route durations than both isochrones and radius when service times exceed 10 min. Regarding fleet size, the political definition initially requires fewer trucks at short service times, aligns with the other definitions at medium durations, and is outperformed by isochrones and radius at higher service times. The isochrone and radius definitions follow similar trends throughout. As shown in Figure 5, increasing service time consistently leads to longer total route durations, a higher number of trucks required, and a decline in average customers served per vehicle across both case studies and all regionality definitions.

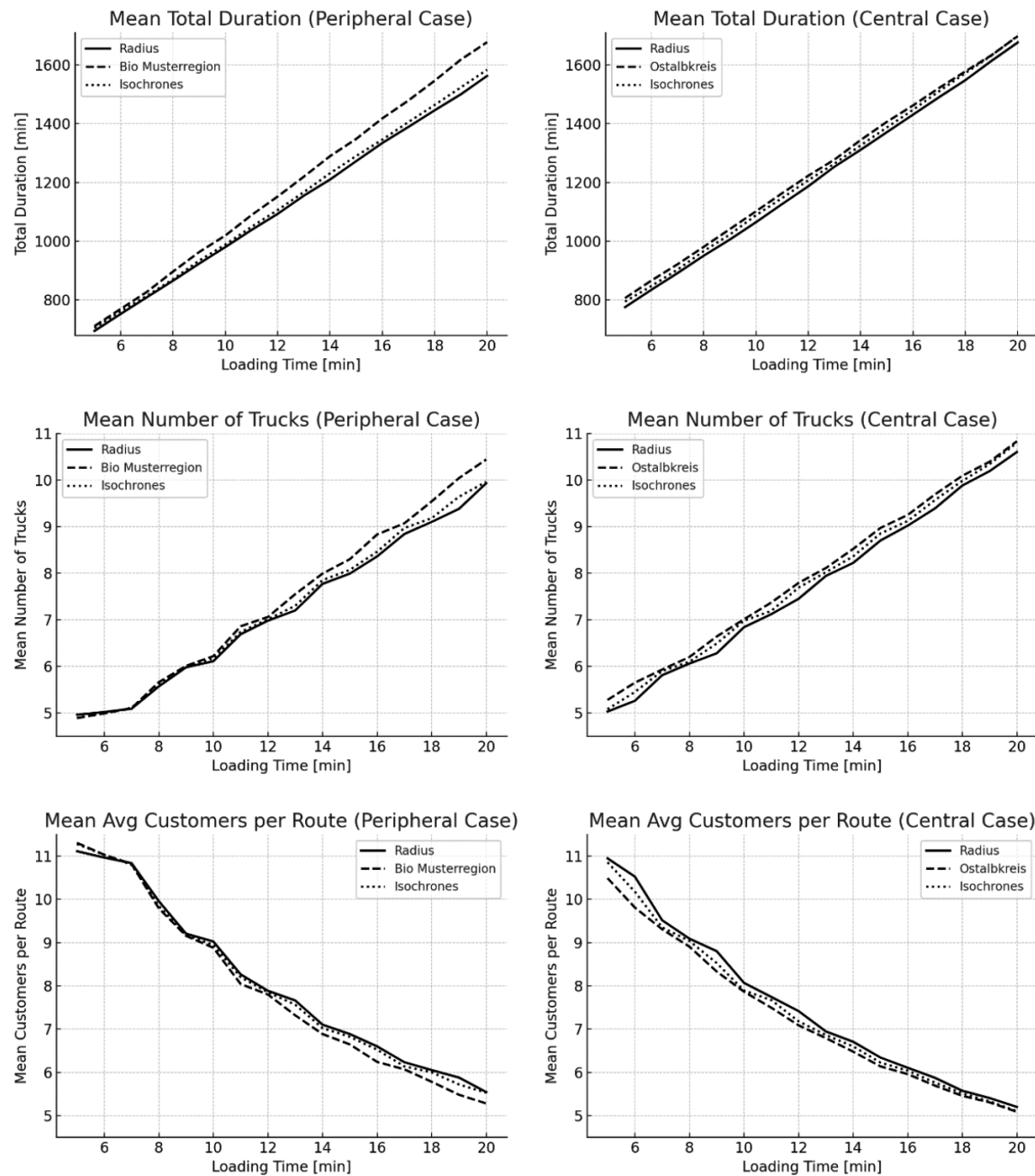


Figure 5. Results of the service time scenario. Source: own representation.

As shown in Table 5, the second scenario, in which the depot is peripherally located, requires a larger number of trucks compared to the scenario with a centrally located depot within politically defined boundaries. In Case Study II (Peripheral case), these differences become increasingly pronounced as service times increase.

In Case Study I (Central case), the most striking difference appears between the political definition (Ostalbkreis) and the radius-based definition. Longer service times further amplify the inefficiencies associated with a peripheral depot when regionality is defined politically, compared to radius or isochrone-based approaches.

Table 5. Trucks needed in the service time scenario

Loading time (min)	Central case			Peripheral case		
	Radius	Ostalbkreis	Isochrones	Radius	Bio Musterregion	Isochrones
5	6	6	6	5	5	5
6	6	6	6	6	5	5
7	6	6	6	6	6	6
8	7	7	7	6	6	6
9	7	7	7	6	7	6
10	7	8	7	7	7	7
11	8	8	8	7	7	7
12	8	8	8	7	8	8
13	8	9	9	8	8	8
14	9	9	9	8	8	8
15	9	9	9	8	9	9
16	10	10	10	9	9	9
17	10	10	10	9	<i>10</i>	9
18	10	<i>11</i>	10	10	10	10
19	11	11	11	10	<i>11</i>	10
20	11	11	11	10	<i>11</i>	10

Differences highlighted in italics. Source: own representation.

5.4 Results of the Uncertainty scenario

As shown in Table 6, in both case studies, the radius-based definition again produces the shortest total route durations, followed by isochrones, while the political definition consistently yields the longest durations. In Ostalbkreis, however, the absolute reductions remain modest: moving from the political to the radius definition reduces mean total duration from 1402 min to 1373 min (−2.1%), a saving of about 29 min per round. In the Bio-Musterregion, the effect is more pronounced, with durations dropping from 1350 min (political) to 1272 min (radius, −5.8%), corresponding to a time saving of 78 min. These reductions could make a practical difference in highly time-sensitive operations.

For the number of customers per truck, the pattern is reversed. Political boundaries yield higher averages: in Ostalbkreis, 9.0 customers per truck under the political definition versus 8.8 with isochrones and 8.8 with radii; in the Bio-Musterregion, 8.5 versus 8.2 (isochrones) and 8.1 (radius). Although differences are statistically significant, they translate into less than one additional customer per vehicle and thus have limited operational relevance.

The same holds for fleet size. In Ostalbkreis, truck requirements increase slightly when moving from the political definition (6.23) to isochrones (6.31) or radii (6.39). In the Bio-Musterregion, the requirement rises from 6.66 (political) to 6.84 (isochrones) and 6.89 (radii). After rounding, however, all cases require seven trucks, indicating no meaningful difference in practice. Taken together, the uncertainty scenario confirms the overall pattern: radial and isochrone definitions tend to reduce travel times, but political definitions may enable higher vehicle utilization. Yet, as in the deterministic scenarios, only the larger effects, such as the one-hour saving in the Bio-Musterregion, appear operationally relevant, while smaller percentage differences do not alter fleet requirements or daily planning. This highlights again the location situation within the peripheral case.

Table 6. Uncertainty scenario results: comparison between the central and peripheral case

		Central case			Peripheral case		
		Ostalbkreis	Isochrone	Radius	Bio Musterregion	Isochrone	Radius
Total duration (min)	Mean	1402.42	1387.78	1373.09	1350.25	1287.18	1271.57
	SD	129.58	129.93	129.58	140.31	125.05	123.37
Average number of customers/ truck	Mean	9	8.88	8.77	8.45	8.20	8.13
	Mean, rounded	9	8	8	8	8	8
	SD	1.22	1.25	1.24	1.27	1.15	1.11
Number of trucks	Mean	6.23	6.31	6.39	6.66	6.84	6.89
	Mean, rounded	7	7	7	7	7	7
	SD	0.84	0.87	0.89	1.00	0.96	0.94

Relative values in Table A4 in the Appendix. Source: own representation.

6. Discussion and conclusion

Regionality is an increasingly important quality attribute for many agri-food supply chains. However, definitions of regionality vary widely. This study examined how different definitions of regionality such as political boundaries, radial distance, and travel-time isochrones, shape the logistical organization and efficiency of perishable agri-food supply chains. Using a simulation-based VRP model applied to two case studies of fresh-cut fruit and vegetable distribution in Germany, the analysis demonstrates that the way regionality is defined has measurable operational consequences for supply chain design and logistics performance.

Across the different scenarios analyzed in this study, distance-based definitions of regionality produced more efficient logistical outcomes than politically defined regional boundaries. Both radial distance and travel-time isochrone approaches were associated with shorter total route durations and lower fleet requirements. In contrast, politically defined regional boundaries often imposed additional logistical constraints, particularly when producers were located near administrative borders or at the periphery of the defined region.

However, the results also demonstrate that the effects of political regional definitions are not uniformly negative. In some scenarios, political boundaries allowed higher vehicle utilization, resulting in slightly more customers being served per vehicle. This indicates that each regionality definition entails specific trade-offs between logistical efficiency, operational constraints, and institutional considerations. The most relevant differences emerged in the Peripheral Case, where adopting radial or isochrone-based definitions reduced delivery times by up to six percent and lowered fleet requirements from nine to eight vehicles. In contrast, the differences in the Central Case were smaller and often operationally negligible, suggesting that the spatial position of a production facility within a region strongly influences how regional definitions translate into logistical outcomes.

These findings underline that regionality should not be understood solely as a marketing claim or policy narrative but also as an operational parameter shaping logistics decisions. In practice, regional food labeling schemes and regional development programs frequently rely on administratively defined territories, while logistical operations follow spatial proximity and transport network structures. As a result, administrative boundaries may exclude geographically closer customers while including more distant ones simply because they fall within the political/jurisdictive region. Unless related to product quality in one way or the other, such distinctions are arbitrary from a spatial and logistical perspective. In the context of highly perishable products such as fresh-cut fruit and vegetables, where delivery speed and tight time-windows are critical, these institutional constraints may translate directly into inefficiencies in routing and fleet allocation.

Our findings therefore suggest that regionality should be conceptualized as a multidimensional construct combining institutional legitimacy with spatial and logistical functionality. Political or administrative boundaries provide governance structures, certification frameworks, and policy legitimacy. Distance- or time-based definitions, by contrast, reflect the physical realities of transportation networks and supply chain operations.

In contrast to the literature which examines how consumers perceive regional food products (Bannor and Abele, 2021; Feldmann and Hamm, 2015; Pícha *et al.*, 2018; Zander and Hamm, 2010), the present study approaches regionality from the perspective of producers and supply chain operations. By focusing on the logistical implications of alternative regional definitions, this study therefore addresses an important gap in the literature: It has so far been largely overlooked how regionality concepts shape operational constraints and routing decisions within agri-food supply chains. Previous research has emphasized that logistics represents a major bottleneck for regional food systems due to fragmented distribution networks, high transportation costs, and limited infrastructure (Canfora, 2016; Paciarotti and Torregiani, 2021). In addition, small-scale producers frequently face challenges in accessing markets efficiently (Blanquart *et al.*, 2010; González-Azcárate *et al.*, 2021). While this literature has primarily focused on infrastructural, organizational, or economic barriers, the present study shows that the definition of “region” itself can also affect logistical performance. In other words, not only physical distance and transport infrastructure but also the institutional framing of regionality can shape the efficiency of food supply chains.

Beyond the firm-level perspective analyzed in this study, these findings also point toward potential implications at the network level. Regional food systems increasingly rely on collaborative structures such as food hubs, producer cooperatives, or inter-regional distribution networks. In such multi-depot environments, heterogeneous definitions of regionality across adjacent regions may generate coordination problems. If neighboring regions apply different political or spatial criteria, supply chains may become fragmented, leading to duplicated transport routes, reduced consolidation potential, and inefficiencies at the system level. What appears to be a manageable constraint for a single firm may therefore translate into more substantial inefficiencies within the entire network.

From a policy and certification perspective, the findings also reveal an important strategic trade-off: Administratively defined regional boundaries may provide institutional benefits, such as eligibility for subsidies, regional development programs, or public procurement contracts. Firms that operate beyond these boundaries, even if geographically closer to certain customers, may lose access to such policy instruments. Conversely, firms located just outside administrative borders may face structural disadvantages despite their geographical proximity and logistical efficiency. Producers therefore face a strategic choice between adhering to politically defined regional markets to maintain institutional eligibility and adopting more spatially efficient distribution strategies.

These insights highlight the need for more flexible approaches to defining regionality in agri-food policy and certification frameworks. Rigid administrative definitions may unintentionally undermine the operational viability of regional food systems by excluding geographically proximate actors. Such inconsistencies can increase transaction costs, reduce logistical flexibility, and potentially weaken the credibility of regional labeling systems from both producer and consumer perspectives.

One feasible way to address this challenge is to develop hybrid definitions of regionality that combine political legitimacy with spatial functionality. Rather than replacing administrative boundaries entirely, certification schemes could integrate proximity-based criteria such as radial distance or travel time. For example, a politically defined core region could be complemented by a spatially defined buffer zone that allows geographically close firms outside administrative borders to participate under clearly defined thresholds. Such a dual-layer approach would preserve institutional legitimacy while better aligning regional definitions with the logistical realities of perishable food distribution.

Despite these insights, the limitations of the study should be acknowledged. First, the analysis is based on two case studies located in Germany and should therefore not be generalized without caution to other regions or supply chain contexts. Second, the routing simulations rely on assumptions regarding vehicle capacities, demand distribution, and service times that may not fully reflect real-world variability. While the Monte Carlo simulations introduced stochastic variation into key parameters, they cannot fully substitute for empirical transport data. In addition, the analysis focuses primarily on logistical performance indicators such as route duration, fleet size, and vehicle utilization, without incorporating broader economic, environmental, or social sustainability indicators. Future research could extend our analysis by incorporating additional product categories, empirical logistics data, and alternative regionality definitions.

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Appendix

Table A1. Results of the Basis Scenario (Relative Differences)

	Isochrones	Radius
Total duration		
Ostalbkreis	−1.4% **	−2.4% ***
Isochrones		1.2% **
Bio-Musterregion	−4.3% ***	−5.6% ***
Isochrones		1.4% **
Avg. number of customers/truck		
Ostalbkreis	−1.3% **	−3.0% ***
Isochrones		1.7% *
Bio-Musterregion	−2.8% ***	−3.7% ***
Isochrones		1.0% **
Number of trucks		
Ostalbkreis	1.4% **	3.3% ***
Isochrones		−1.9% *
Bio-Musterregion	2.6% ***	3.6% ***
Isochrones		−0.9% **

Differences between means (%): * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Source: own representation.

Table A2. Absolute results of the Time Window scenario

Time_limit (min)	Mean_total_duration (min)			Mean_number_of_trucks			Mean_average_customers_ per_route		
	Radius	Ostalbkreis	Isochrone	Radius	Ostalbkreis	Isochrone	Radius	Ostalbkreis	Isochrone
Central case									
120	1433.83	1450.79	1444.61	13.76	14.22	13.99	4.01	3.88	3.94
135	1414.12	1428.30	1432.41	12.07	12.32	12.29	4.57	4.48	4.48
150	1394.29	1419.27	1413.53	10.63	10.89	10.82	5.19	5.06	5.09
165	1377.66	1404.27	1397.36	9.52	9.79	9.72	5.79	5.63	5.67
180	1370.59	1405.68	1386.60	8.70	8.97	8.85	6.34	6.14	6.23
195	1365.02	1393.09	1376.84	7.99	8.09	8.05	6.89	6.81	6.84
210	1351.94	1385.96	1372.18	7.21	7.54	7.34	7.65	7.33	7.52
225	1344.37	1384.43	1368.24	6.93	7.01	6.97	7.95	7.85	7.90
240	1341.31	1378.09	1360.93	6.24	6.57	6.43	8.85	8.42	8.60
255	1338.16	1373.30	1358.00	6.01	6.04	6.01	9.15	9.11	9.15
270	1336.08	1369.89	1353.84	5.77	5.95	5.94	9.59	9.26	9.28
285	1335.14	1369.02	1348.88	5.25	5.58	5.30	10.54	9.94	10.45
300	1335.92	1365.54	1345.40	5.02	5.06	5.00	10.96	10.89	11.00
315	1328.85	1368.72	1351.48	5.00	5.00	5.00	11.00	11.00	11.00
330	1325.78	1366.18	1351.90	4.93	4.99	4.99	11.19	11.03	11.03
345	1325.02	1361.87	1348.84	4.63	4.93	4.74	12.02	11.19	11.72
360	1327.01	1361.25	1346.51	4.22	4.74	4.40	13.15	11.72	12.65
Peripheral case									
120	1308.97	1489.82	1329.18	12.55	13.94	12.81	4.39	3.95	4.30
135	1292.38	1440.00	1315.02	11.04	11.93	11.16	4.99	4.62	4.94
150	1280.93	1401.25	1299.23	9.76	10.43	9.88	5.65	5.29	5.58
165	1273.52	1371.39	1293.05	8.90	9.21	9.00	6.19	5.98	6.11
180	1272.31	1347.79	1289.79	7.99	8.30	8.07	6.88	6.65	6.82
195	1266.26	1333.34	1280.12	7.29	7.72	7.39	7.57	7.15	7.47
210	1260.04	1316.73	1271.02	6.97	7.01	6.99	7.90	7.85	7.87
225	1262.12	1298.27	1272.36	6.29	6.42	6.35	8.79	8.62	8.71
240	1258.03	1292.69	1266.80	6.00	6.00	6.00	9.17	9.17	9.17
255	1255.24	1291.36	1264.66	5.83	5.87	5.88	9.48	9.41	9.39
270	1253.96	1272.08	1260.05	5.08	5.11	5.14	10.85	10.80	10.74
285	1251.96	1267.51	1259.14	5.00	5.00	5.00	11.00	11.00	11.00
300	1250.97	1267.02	1262.37	5.00	5.00	5.00	11.00	11.00	11.00
315	1246.95	1262.19	1259.49	4.92	4.82	4.92	11.22	11.50	11.22
330	1245.69	1253.06	1257.39	4.63	4.34	4.53	12.02	12.82	12.29
345	1249.46	1246.96	1255.62	4.21	4.06	4.19	13.17	13.59	13.23
360	1250.78467	1246.25714	1256.23029	4.05	4	4.02	13.6125	13.75	13.695

Source: own representation.

Central case		Total duration			Number of trucks			Mean customers per route		
Time window	Isochrone/ Ostalbkreis	Isochrone/ Radius	Ostalbkreis/ Radius	Isochrone/ Ostalbkreis	Isochrone/ Radius	Ostalbkreis/ Radius	Isochrone/ Ostalbkreis	Isochrone/ Radius	Ostalbkreis/ Radius	
	120		0,75%	1,18%	-1,62%		3,34%		-1,69%	-3,19%
135		1,29%	1,00%			2,07%		-1,83%	-1,95%	
150		1,38%	1,79%		1,79%	2,45%				
165		1,43%	1,93%			2,84%	0,68%	-2,13%	-2,79%	
180	-1,36%	1,17%	2,56%	-1,34%	1,72%	3,10%	1,44%	-1,83%	-3,23%	
195	-1,17%		2,06%					-0,79%	-1,17%	
210	-0,99%	1,50%	2,52%	-2,65%		4,58%	2,68%		-4,24%	
225	-1,17%	1,78%	2,98%	-0,57%			0,58%			
240	-1,25%	1,46%	2,74%	-2,13%	3,04%	5,29%		-2,81%	-4,88%	
255	-1,11%		2,63%							
270	-1,17%	1,33%	2,53%		2,95%	3,12%		-3,25%	-3,44%	
285	-1,47%		2,54%	-5,02%		6,29%	5,17%		-5,74%	
300	-1,47%		2,22%		-0,40%		1,01%		-0,67%	
315	-1,26%	1,70%	3,00%							
330	-1,05%	1,97%	3,05%		1,22%			-1,47%	-1,47%	
345	-0,96%	1,80%	2,78%	-3,85%	2,38%	6,48%	4,67%		-6,86%	
360	-1,08%		2,58%	-7,17%	4,27%	12,32%	7,98%	-3,77%	-10,88%	

Peripheral case		Total duration			Number of trucks			Mean customers per route		
Time window	Isochrone/ Bio Musterregion	Isochrone/ Radius	Bio Musterregion/ Radius	Isochrone/ Bio Musterregion	Isochrone/ Radius	Bio Musterregion/ Radius	Isochrone/ Bio Musterregion	Isochrone/ Radius	Bio Musterregion/ Radius	
	120	-10,78%	1,54%	13,82%	-8,11%	2,07%	11,08%	8,89%	-1,99%	-10,00%
135	-8,68%	1,75%	11,42%	-6,45%		8,06%	6,87%		-7,40%	
150	-7,28%	1,43%	9,39%	-5,27%	1,23%	6,86%	5,50%	-1,28%	-6,42%	
165	-5,71%	1,53%	7,68%	-2,28%		3,48%	2,20%	-1,21%	-3,33%	
180	-4,30%	1,37%	5,93%	-2,77%	1,00%	3,88%	2,64%	-0,92%	-3,47%	
195	-3,99%	1,09%	5,30%	-4,27%		5,90%	4,53%	-1,30%	-5,58%	
210	-3,47%	0,87%	4,50%	-0,29%		0,57%		-0,33%	-0,62%	
225	-2,00%		2,86%					-0,89%	-1,94%	
240	-2,00%		2,76%							
255	-2,07%		2,88%							
270			1,44%		1,18%					
285			1,24%							
300			1,28%							
315		1,01%	1,22%	2,07%			-2,39%			
330		0,94%	0,59%	4,38%		-6,26%		2,29%	6,64%	
345		0,49%					-2,63%		3,13%	
360	0,80%	0,44%					-0,40%		1,01%	

Source: own representation.

Figure A1. Absolute results of the Time Window scenario. Green, significant deviation on with $p \leq 0.05$; red, no significant deviation; X/Y , value means X divided by Y .

Table A3. Absolute results of the Service Time scenario

Loading_time (min)	Mean_total_duration (min)			Mean_number_of_trucks			Mean_averaga_customers_ per_route		
	Radius	Ostalbkreis	Isochrone	Radius	Ostalbkreis	Isochrone	Radius	Ostalbkreis	Isochrone
Central case									
5	775.70	806.52	794.51	5.03	5.28	5.08	10.95	10.49	10.85
6	834.55	865.85	847.52	5.26	5.65	5.45	10.52	9.81	10.18
7	891.29	921.23	903.15	5.81	5.93	5.90	9.52	9.31	9.35
8	950.33	980.50	966.09	6.06	6.20	6.10	9.09	8.90	9.04
9	1005.52	1040.79	1022.50	6.28	6.64	6.49	8.80	8.33	8.53
10	1064.47	1101.41	1088.08	6.84	7.01	6.98	8.07	7.86	7.89
11	1126.32	1163.11	1146.67	7.12	7.37	7.19	7.74	7.49	7.67
12	1186.83	1222.51	1207.30	7.45	7.79	7.69	7.42	7.09	7.18
13	1253.33	1277.38	1263.80	7.94	8.11	8.02	6.94	6.79	6.86
14	1310.84	1343.98	1325.87	8.22	8.52	8.36	6.71	6.48	6.60
15	1370.59	1405.68	1386.60	8.70	8.97	8.85	6.34	6.14	6.23
16	1430.34	1461.65	1446.92	9.02	9.25	9.12	6.11	5.96	6.04
17	1489.89	1521.07	1509.92	9.39	9.69	9.57	5.87	5.69	5.76
18	1547.55	1577.57	1571.60	9.88	10.09	9.98	5.57	5.46	5.52
19	1613.33	1632.45	1631.49	10.19	10.39	10.34	5.41	5.31	5.33
20	1675.56	1697.13	1698.27	10.60	10.83	10.80	5.20	5.09	5.10
Peripheral case									
5	694.79	711.10	705.08	4.96	4.89	4.90	11.11	11.30	11.28
6	752.51	769.72	761.93	5.02	4.99	4.99	10.96	11.03	11.03
7	809.17	827.37	814.42	5.09	5.10	5.11	10.84	10.82	10.80
8	865.66	896.58	870.56	5.57	5.66	5.63	9.96	9.79	9.85
9	923.81	963.08	934.19	5.98	6.01	6.00	9.20	9.15	9.17
10	980.00	1019.28	988.45	6.11	6.22	6.17	9.02	8.88	8.94
11	1038.18	1088.66	1048.64	6.69	6.86	6.74	8.26	8.04	8.20
12	1092.88	1152.00	1105.88	6.98	7.06	7.01	7.88	7.80	7.85
13	1154.88	1219.31	1167.00	7.20	7.55	7.30	7.66	7.32	7.56
14	1209.59	1289.19	1230.90	7.77	7.99	7.85	7.10	6.88	7.02
15	1272.31	1347.79	1289.79	7.99	8.30	8.07	6.88	6.65	6.82
16	1334.07	1417.70	1345.39	8.36	8.83	8.46	6.60	6.24	6.52
17	1388.81	1478.73	1405.30	8.84	9.07	8.97	6.23	6.07	6.14
18	1445.24	1545.92	1463.34	9.10	9.54	9.18	6.05	5.78	6.00
19	1499.54	1617.56	1523.02	9.38	10.04	9.64	5.88	5.48	5.72
20	1562.00	1676.63	1582.89	9.93	10.44	9.96	5.54	5.28	5.53

Source: own representation.

Central case		Total duration			Number of trucks			Mean customers per route		
Loading time:	Isochrone/ Ostalbkreis	Isochrone/ Radius	Ostalbkreis/ Radius	Isochrone/ Ostalbkreis	Isochrone/ Radius	Ostalbkreis/ Radius	Isochrone/ Ostalbkreis	Isochrone/ Radius	Ostalbkreis/ Radius	
	5		2,43%	3,97%	-3,79%		4,97%	3,50%	-0,84%	-4,19%
6	-2,12%	1,55%	3,75%	-3,54%	3,61%	7,41%	3,74%	-3,31%	-6,79%	
7	-1,96%	1,33%	3,36%			2,07%			-2,20%	
8	-1,47%	1,66%	3,18%			2,31%	1,47%		-2,02%	
9	-1,76%		3,51%			5,73%	2,36%	-3,13%	-5,36%	
10	-1,21%	2,22%	3,47%		2,05%			-2,19%	-2,52%	
11	-1,41%	1,81%	3,27%	-2,44%		3,51%	2,36%		-3,21%	
12		1,73%	3,01%		3,22%	4,56%	1,32%		-4,44%	
13			1,92%	-1,11%	1,01%	2,14%			-2,22%	
14		1,15%	2,53%	-1,88%	1,70%	3,65%		-1,59%	-3,42%	
15	-1,36%		2,56%	-1,34%	1,72%	3,10%	1,44%		-3,23%	
16		1,16%	2,19%	-1,41%		2,55%	1,33%		-2,40%	
17	-0,73%	1,34%	2,09%	-1,24%		3,19%	1,23%	-1,87%	-3,06%	
18		1,55%	1,94%			2,13%			-2,10%	
19			1,19%		1,47%	1,96%			-1,87%	
20		1,36%	1,29%		1,89%	2,17%			-2,18%	
Peripheral case		Total duration			Number of trucks			Mean customers per route		
Loading time:	Isochrone/ Bio Musterregion	Isochrone/ Radius	Bio Musterregion/ Radius	Isochrone/ Bio Musterregion	Isochrone/ Radius	Bio Musterregion/ Radius	Isochrone/ Bio Musterregion	Isochrone/ Radius	Bio Musterregion/ Radius	
	5		1,48%			-1,21%			1,73%	
6	-1,01%		2,29%			-0,60%			0,59%	
7	-1,56%	0,65%	2,25%							
8	-2,90%		3,57%	-0,53%					-1,66%	
9	-3,00%		4,25%						-0,54%	
10	-3,02%		4,01%						-1,60%	
11	-3,68%	1,01%	4,86%			2,54%			-2,69%	
12	-4,00%	1,19%	5,41%						-1,08%	
13	-4,29%	1,05%	5,58%	-3,31%	1,39%	4,86%			-4,49%	
14	-4,52%	1,76%	6,58%	-1,75%	1,03%	2,83%	2,00%	-1,11%	-3,04%	
15	-4,30%	1,37%	5,93%	-2,77%	1,00%	3,88%	2,64%		-3,47%	
16	-5,10%		6,27%	-4,19%		5,62%	4,53%	-1,16%	-5,44%	
17	-4,97%	1,19%	6,47%	-1,10%	1,47%	2,60%	1,13%	-1,54%	-2,65%	
18	-5,34%	1,25%	6,97%	-3,77%		4,84%	3,81%		-4,47%	
19	-5,84%	1,57%	7,87%	-3,98%	2,77%	7,04%	4,34%	-2,70%	-6,75%	
20	-5,59%	1,34%	7,34%	-4,60%		5,14%	4,73%		-4,74%	

Source: own representation.

Figure A2. Absolute results of the Service Time scenario. Green, significant deviation on with $p \leq 0.05$; red, no significant deviation; X/Y , value means X divided by Y .

Table A4. Results of the Uncertainty scenario (relative differences)

	Isochrones	Radius
Total duration		
Ostalbkreis	-1.0% *	-2.1% ***
Isochrones		1.1% *
Bio-Musterregion	-4.7% ***	-5.8% ***
Isochrones		1.2% **
Avg. number of customers/truck		
Ostalbkreis	1.3% *	2.6% ***
Isochrones		-1.3% *
Bio-Musterregion	2.7% ***	3.5% ***
Isochrones		-0.7%
Number of trucks		
Ostalbkreis	-1.3% *	-2.6% ***
Isochrones		1.2% *
Bio-Musterregion	-3.0% ***	-3.8% ***
Isochrones		0.9%

Differences between means (%): * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Source: own representation.