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Holonic optimization system for sustainable agriculture planning in Algeria

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Thanks

All praise and thanks are due to Allah Almighty, whose guidance, wisdom, and blessings have accompanied me throughout this journey. Without His mercy and strength, none of this would have been possible.

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Dedication

First and foremost,
All praise is due to Allah, the Most Gracious, the Most Merciful,
Who granted me strength when I was weak,
Light when all seemed dim,
And hope when the path was unclear.

To the dearest soul I own,
My beloved mother,
The warmest heart, the safest place,
Whose silent prayers shaped every step I took.

To my sister, my partner in all storms,
To my small and big family each one of you a part of this journey.
To the love of my heart and the ache of my soul,
My brother…
Who left me halfway
Took a part of me with him,
But still walks beside me in unseen ways.
You were my shield, my pride, my forever hero.

To my grandmother,
Whose prayers wrapped me like a gentle cloak,
And to my father may Allah have mercy on his soul
Who remains etched in every breath of ambition I take.

To my beautiful friends,
Each by name,
Your laughter and presence colored this path with joy and courage.

And to all who stood by me,
Whose support whispered,
"Keep going, you're not alone."

This is not just the end of the way
It is the birth of every dream that dared to begin in silence.

Aicha

Abstract

Agricultural planning in Algeria remains largely centralized, facing limitations in adaptability, responsiveness, and sustainability. With rising environmental challenges and the need for local-level customization, traditional systems struggle to efficiently manage complex agricultural data and decision-making processes. This thesis proposes a novel holonic optimization system for sustainable agricultural planning, designed to bridge the gap between local needs and national strategies. Inspired by holonic and multi-agent system principles, the solution introduces a hierarchical model composed of four interdependent levels: local, district, regional, and national. Each level functions as an autonomous agent (holon) capable of making partial decisions that contribute to a global agricultural plan.

To operationalize this model, real data was collected from the Wilaya of Tébessa, structured into regional catalogs and parcel-level datasets. These were then used to simulate and evaluate different optimization techniques, namely the Genetic Algorithm (GA), Weighted Sum Method (WSM), and the BKPACS algorithm, which is the proposed approach in this work. Comparative results demonstrated that the holonic system using BKPACS outperforms traditional methods in terms of execution time, sustainability, and solution quality. The integration of AUML diagrams and a structured database further enhanced system clarity and applicability. Ultimately, this research offers a scalable, intelligent, and practical solution for transforming agricultural planning in Algeria, paving the way for digital, data-driven decision support in the agricultural sector.

Keywords:

Holonic system, sustainable agriculture, optimization, multi-agent system, BKPACS, genetic algorithm, AUML, Algerian agriculture, decision support, decentralized planning.

Résumé

La planification agricole en Algérie reste largement centralisée, ce qui limite son adaptabilité, sa réactivité et sa durabilité. Face aux défis environnementaux croissants et à la nécessité d'une prise en compte des spécificités locales, les systèmes traditionnels peinent à gérer efficacement la complexité des données agricoles et des processus décisionnels. Ce mémoire propose un **système** d'optimisation holonique innovant pour la planification agricole durable, visant à combler le fossé entre les besoins locaux et les stratégies nationales. Inspiré des principes des systèmes multi-agents et des structures holoniques, le modèle introduit une hiérarchie composée de quatre niveaux interdépendants : local, district, régional et national. Chaque niveau fonctionne comme un agent autonome (holon), capable de prendre des décisions partielles qui s'intègrent dans une vision globale.

Pour valider ce modèle, des données réelles ont été collectées auprès de la Direction des services agricoles de la wilaya de Tébessa, puis structurées sous forme de catalogues régionaux et de tableaux de parcelles agricoles. Ces données ont permis de simuler et d'évaluer plusieurs méthodes d'optimisation, notamment l'algorithme génétique (GA**)**, la méthode des pondérations (WSM) et l'algorithme BKPACS, proposé dans ce travail. Les résultats comparatifs ont montré que le système holonique basé sur BKPACS surpasse les méthodes classiques en termes de rapidité, de durabilité et de qualité des solutions générées. L'intégration des diagrammes AUML et d'une base de données bien structurée a renforcé la clarté et l'applicabilité du système. Ce travail offre ainsi une solution intelligente, évolutive et pragmatique pour transformer la planification agricole en Algérie, en ouvrant la voie à une gestion numérique et durable du secteur.

Mots-clés :

Système holonique, agriculture durable, optimisation, système multi-agent, BKPACS, algorithme génétique, AUML, planification décentralisée, soutien à la décision, Algérie.

ملخص

تعاني عملية التخطيط الفلاحي في الجزائر من مركزية مفرطة تحدّ من قدرتها على التكيّف والاستجابة السريعة، كما تُضعف من استدامتها على المدى الطويل. ومع تفاقم التحديات البيئية والحاجة إلى حلول مرنة تُراعي الخصوصيات المحلية، لم تعد الأنظمة التقليدية قادرة على إدارة البيانات الزراعية واتخاذ القرارات المعقدة بفعالية. في هذا السياق، يقترح هذا البحث نظامًا ذكيًا ومبتكرًا يُعرف بـ نظام التخطيط الهولوني الأمثل، يهدف إلى الربط بين احتياجات المستويات المحلية والأهداف الوطنية في إطار هيكلي مرن ولامركزي.

يعتمد هذا النظام على مفاهيم الأنظمة متعددة الوكلاء (MAS) والهياكل الهولونية، حيث يتم تنظيم النظام في أربعة مستويات مترابطة: المحلي، الدائرة، الجهوي، والوطني. يعمل كل مستوى كـ"هولون" مستقل، قادر على اتخاذ قرارات جزئية تُدمج لاحقًا في خطة زراعية شاملة. تم تطبيق هذا النموذج باستخدام بيانات حقيقية من ولاية تبسة، تم تنظيمها في كتالوجات جهوية وجداول للقطع الزراعية. ثم تم اختبار النظام من خلال مقارنة ثلاثة خوارزميات تحسين :الخوارزمية الجينية(GA) ، طريقة المجموع المرجّح(WSM) ، وخوارزمية BKPACS المقترحة في هذا العمل.

أظهرت النتائج تفوقBKPACS من حيث سرعة التنفيذ، جودة الحلول، ومدى توافقها مع معايير الاستدامة. كما تم استخدام مخططات AUML وقاعدة بيانات منظمة لدعم وضوح النموذج وتطبيقه العملي. في الختام، يُقدم هذا البحث نظامًا قابلاً للتوسع، ذكياً وواقعياً من شأنه أن يُحدث نقلة نوعية في التخطيط الزراعي في الجزائر نحو التحول الرقمي المستدام.

الكلمات المفتاحية

النظام الهولوني، الزراعة المستدامة، التحسين، الأنظمة متعددة الوكلاء، BKPACS، الخوارزمية الجينية، AUML، التخطيط اللامركزي، دعم القرار، الجزائر.

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Acronyms

AI	Artificial Intelligence
AUML	Agent Unified Modeling Language
BKPACS	Bounded Knapsack Problem And Colony System
BADR	Banque de l'Agriculture et du Développement Rural
CSA	Climate-Smart Agriculture
CRMA	Caisse Régionale de Mutualité Agricole
CNMA	Caisse Nationale de Mutualité Agricole
DB	Data Base
FILAHA	Algeria's National Agricultural Plan (2014–2020)
FAO	Food and Agriculture Organization (of the UN)
GDP	Gross Domestic Product
HMAS	Holonic Multi-Agent System
MAS	Multi-Agent System
MLO	Modified Lion Optimizer
MOGA	Multi-Objective Genetic Algorithm
MENA	Middle East and North Africa
MCA	Maître de Conférences A (Academic rank in Algeria)
PNDA	Programme National de Développement Agricole
PRAR	Politique de Renouveau Agricole et Rural
PRCHAT	Programme de Renforcement des Capacités Humaines et de l'Appui Technique
WSM	Weighted Sum Method
WEF	Water-Energy-Food Nexus
UN	United Nations

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General Introduction



General Introduction

The agricultural sector is one of the most promising sectors in Algeria not only for ensuring food security and providing employment opportunities but also for its direct impact on societal stability and the achievement of sustainable development. However, this sector faces increasing challenges due to climate fluctuations, limited resources, and a reliance on traditional planning methods that lack efficiency and flexibility. Therefore, there is a pressing need to consider intelligent, dynamic planning models that are adaptable to local, regional, and national specificities. This work is part of the search for innovative solutions for sustainable agricultural planning in Algeria, by proposing a multi-Agent holonic system that integrates artificial intelligence approaches with decentralized planning. The objective is to support decision-making and ensure an equitable and efficient distribution of agricultural resources across various organizational levels.

❖ Problem Statement and General Context

Various studies and agricultural policies in Algeria point to a gap between national strategies and the ability of provinces and municipalities to implement them effectively. Decisions are often made centrally without considering the specific characteristics of each region. Furthermore, the sector suffers from the lack of accurate and structured databases on agricultural land, which hinders the implementation of effective plans or the simulation of realistic scenarios.

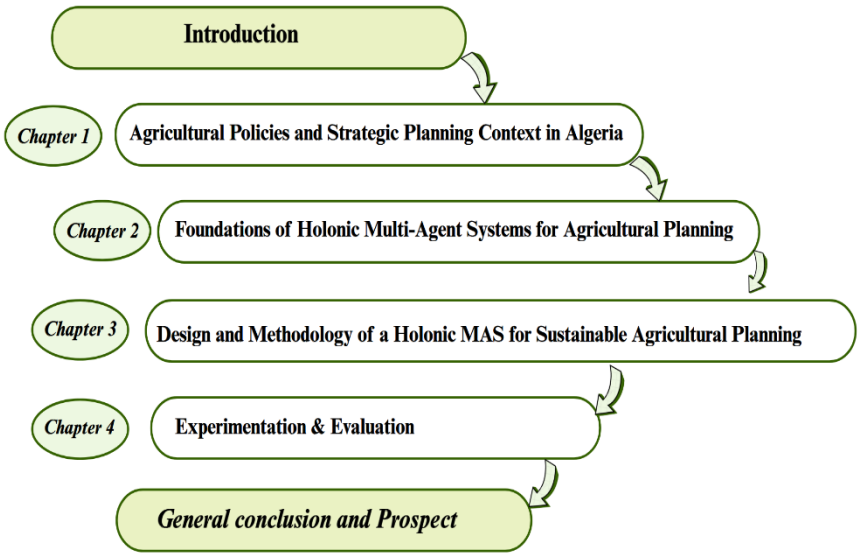
In this context, the holonic system emerges as an ideal solution for dividing the agricultural system into interconnected autonomous units (Holons), each capable of making local decisions while maintaining coordination and integration at the national level.

❖ Project Objectives

This work offers scientific and practical contributions at several levels:

- ✓ Proposing a novel holonic intelligent system in the Algerian agricultural context.
- ✓ Restructuring agricultural data in the provinces (Wilaya of Tebessa) and generating realistic data usable in simulations.
- ✓ Comparing multiple optimization algorithms to demonstrate the effectiveness of the proposed system.
- ✓ Providing a generalizable methodology applicable to other provinces, making this project a foundational step toward a national agricultural planning system.

❖ Overall Structure of the Work



The work is divided into the following integrated methodological phases:

- **Analysis of the agricultural context in Algeria**: policies, challenges, and central vs. decentralized planning approaches.
- **Literature review and analysis of existing models**: with a focus on holonic systems and optimization algorithms used in agriculture. with a particular emphasis on the foundational concepts of holonic systems and multi-agent architectures
- **Describes the proposed methodology**: This work offers scientific and practical contributions :
  - ✓ **Contribution 1:** Design and development of a holonic system architecture adapted to the Algerian agricultural planning context. This includes a full description of each level (local, regional, national), their associated holons, and the roles and interactions of their agents.
  - ✓ **Contribution 2:** Modeling the holonic system using AUML diagrams, including detailed Use Case and Sequence Diagrams to capture the logic of inter-agent communication and decision-making processes.
  - ✓ **Contribution 3:** Adoption of a global-to-local modeling strategy. While the system is designed to be applied nationally, we developed a specific case study for the Wilaya of Tebessa to demonstrate and validate the feasibility of our approach in a real-world context.

- ✓ **Contribution 4:** Collection of agricultural data from Tebessa's Directorate of Local Agricultural Interests and the development of two structured data protocols: a regional agricultural **catalog** (Protocol 1) organizing general data by municipality, and detailed parcel-level **dataset** (Protocol 2) characterizing agricultural plots based on realistic and statistically inferred data.

- ➢ **Experimentation & Evaluation:** Designing small-scale agricultural projects to be used as a baseline for testing algorithms. Application of the BKPACS (Bounded Knapsack Problem Ant Colony System) algorithm a knowledge-based heuristic optimization approach that combines pattern recognition and constraint satisfaction to generate efficient planning solutions. It is compared with other algorithms to extract optimal solutions that balance cost, profit, and distance to the desired goal. Simulating holonic solutions involves combining partial solutions at the municipal level to obtain comprehensive solutions at the national level. Evaluation was based on multiple metrics, including: total cost, total profit, solution quality, and distance to objective, execution time, sustainability score, and qualitative crop diversity.

Finally, this project is not merely a theoretical academic exercise, but rather an effort to provide a practical solution that can be expanded and adapted to the Algerian context. It combines systemic thinking and software engineering to serve a sector that is an economic and social backbone of the country. We hope this work will be a step forward in the development of decision support tools in the agricultural sector and contribute to the achievement of sustainable development goals in Algeria.

Chapter 1:

Agricultural Policies and Strategic Planning Context in Algeria



1. Introduction

Today, agriculture plays a crucial role in ensuring food security, economic stability, and sustainable development worldwide. In Algeria, this sector is particularly vital as it supports a significant portion of the population, provides employment, and contributes to the national economy. Yet it faces significant challenges such as climate change, water scarcity, and outdated practices. The country's agricultural potential is hindered by inefficient resource management and a heavy reliance on food imports, which underscores the need for modernization and investment in sustainable practices (Sabah & Rabie, 2024) (Benbekhti et al., 2024).

Over the years, Algeria has implemented various agricultural policies and development programs to address these challenges and boost agricultural production.these initiatives have shaped the country's agricultural landscape. The continuous evolution of policies reflects the government's commitment to achieving food security and improving the resilience of the sector against external pressures. Historical policies have often mirrored socialist management approaches, leading to underutilization of resources and a need for modernization through smart agriculture practices (Farid & Ali, 2024). Furthermore, the COVID-19 pandemic underscored the necessity for sustainable agricultural systems to ensure food security and improve living (Draou, 2022).

To clearly define our objectives, it is essential to examine Algeria's agricultural landscape, including its evolution, challenges, and sustainability efforts. Analyzing the strategies implemented to enhance productivity and ensure food security provides valuable insights. Additionally, understanding key development initiatives sheds light on the sector's progress. Finally, exploring the structural framework of agricultural planning offers a comprehensive view of its management and future direction.

2. Historical Development of Algerian Agriculture

Algeria's agricultural sector has undergone several phases of reform. Before 1971, the self-managed sector struggled with low productivity due to a lack of incentives and excessive bureaucracy, while the private sector, despite covering a large area, was largely ignored in agricultural policies.

Between **1971 and 1979**, the government launched the "Agrarian Revolution," expropriating large private estates and redistributing them to poor and landless farmers. However, the socialist sector suffered from low productivity due to insufficient technical support and innovation. Industrialization was prioritized, leaving agriculture with minimal investment.

From **1980 to 1986**, Algeria initiated a transition toward a market economy by promoting private land ownership and merging state-run farms into a unified socialist sector. The government also eased market regulations, provided financial support, and encouraged private sector involvement to boost productivity.

Between **1987 and 1999**, major reforms led to the restructuring of state farms into collective and individual enterprises. Some nationalized lands were returned to their original owners, while investments in irrigation projects increased. The liberalization of agricultural markets allowed private sector growth, but austerity measures, subsidy removals, and currency devaluation slowed modernization and investment in mechanization (Laoubi & Yamao 2012).

Table 1. 1 Summary of the Development of Algeria's Agricultural Sector.

Period	Key Reforms	Challenges
Before 1971	- Self-managed sector with low productivity. - Private sector ignored in policies.	- Lack of incentives. - Excessive bureaucracy.
1971-1979 (Agrarian Revolution)	- Large private estates expropriated. - Land redistributed to poor and landless farmers. - Industrialization prioritized over agriculture.	- Low productivity in socialist farms. - Lack of technical support and innovation. - Minimal agricultural investment.
1980-1986 (Market Transition)	- Encouraged private land ownership. - Merged state-run farms into a unified socialist sector. - Eased market regulations and provided financial support.	- Need for more private sector involvement. - Transitioning from a centralized to a market economy.
1987-1999 (Liberalization & Reforms)	- State farms restructured into collective and individual enterprises. - Some nationalized lands returned to original owners. - Increased investment in irrigation. - Agricultural market liberalization.	- Austerity measures and subsidy removals. - Currency devaluation. - Slow modernization and mechanization.
1999–2024 (Modernization & Sustainability)	- Focus on sustainable agriculture and food security. - Gradual adoption of modern technologies and digital tools.	- Climate challenges and water scarcity. - Limited integration of small farmers into value chains.

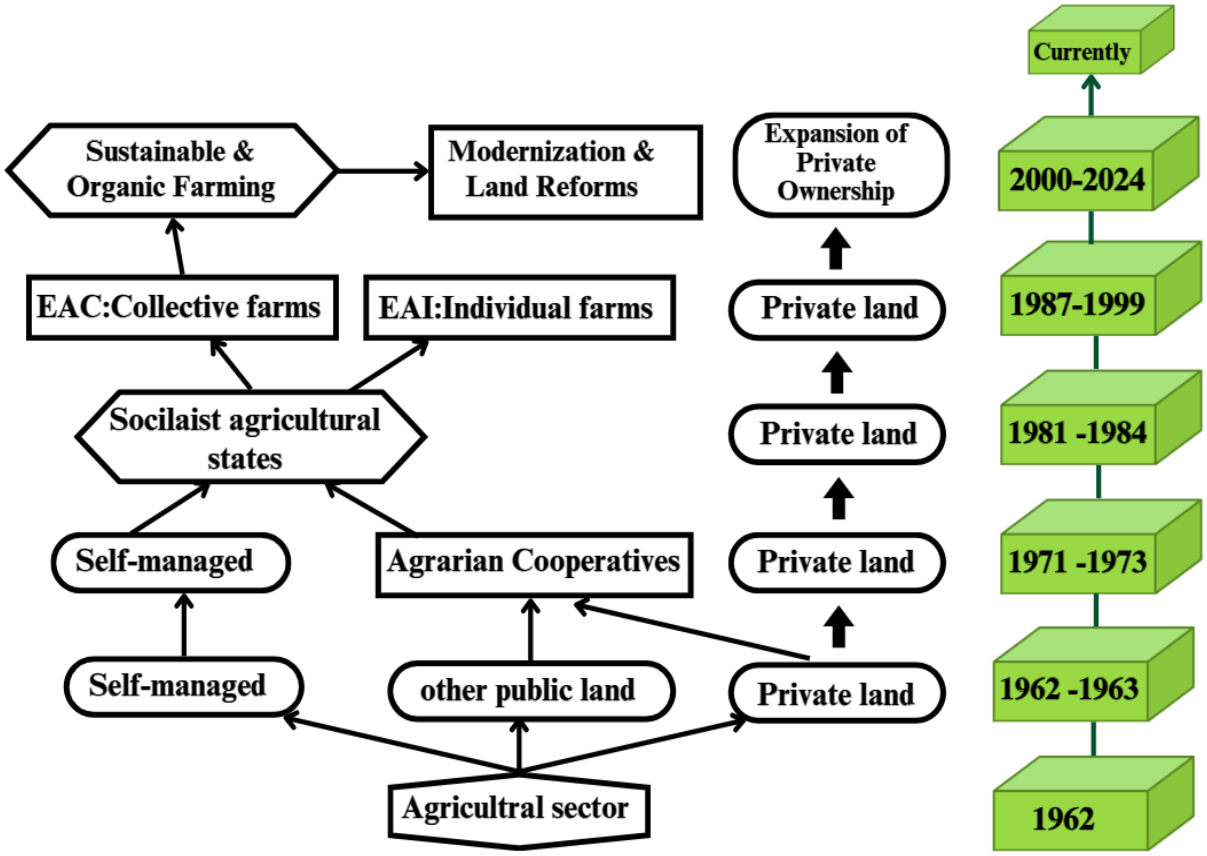


Figure 1. 1 Summary trend of land reform in Algeria
(Inspired from: (Laoubi & Yamao 2012)).

3. Contemporary Challenges Algerian Agriculture

Agriculture plays a crucial role in Algeria's economy, contributing over 12% to the GDP in 2017. The government since the 2000s to diversify the economy, which is heavily reliant on oil, has prioritized the sector. Key agricultural products include cereals, vegetables, and livestock, with exports primarily consisting of processed goods and certain crops. (Agriculture Algérienne M1 Rural, n.d.).

Historically, public institutions until the 1990s, when private sector participation began to rise, dominated the sector indicating a shift towards a more mixed agricultural economy(Mohamed & Abdelaziz, 2024). Despite Algeria's vast agricultural potential, challenges such as climate variability, inefficient resource management, and a heavy reliance on food imports persist(Gaad et al., 2024). The wheat market exemplifies this dependency, as urban encroachment and outdated practices hinder domestic production(Sabah & Rabie, 2024). Recent studies emphasize the

importance of sustainable agricultural practices and increased government investment to enhance productivity and resilience against climate change (Benbekhti et al., 2024).

Furthermore, the agricultural sector is identified as a key driver for economic growth, with potential for job creation and value addition if adequately supported(Chetouh, 2024). These challenges is essential for Algeria to achieve food security and reduce import reliance.

4. Multi-Level Agricultural Context in Algeria

4.1 Local Agricultural Context

Agriculture in Algeria is characterized by smallholder farms that primarily focus on subsistence farming. These local farms often face challenges such as limited access to modern agricultural techniques and resources, which affects productivity and sustainability.

Local projects contribute to regional and national supply, showcasing the potential for localized agricultural initiatives to drive economic development (Noui et al., 2024).

4.2 Regional Agricultural Context

Algeria's agricultural landscape is divided into four main regions: the Tell region, with fertile lands ideal for cereals and fruits; the High Plateaus, used for livestock and cereal farming; the Saharan region, where oasis farming and irrigation support agriculture; and the steppe zones, primarily for sheep grazing and dry farming. Each region's unique climate and resources necessitate specialized agricultural planning to ensure sustainability and food security.

The regional level context encompasses various dimensions, including climate information needs, governance, learning processes, and healthcare training. Climate change impacts necessitate reliable regional projections to inform adaptation strategies, highlighting the importance of localized data for effective policy-making(Giorgi et al., 2009).

4.3 National Agricultural Context

Nationally, Algeria's agricultural policies aim to enhance food security and reduce dependency on imports. The government has implemented various programs to modernize the agricultural sector, promote sustainable practices, and improve the livelihoods of farmers across the country.

Algeria's agricultural policies focus on food security and self-sufficiency but face challenges due to inefficiencies and import dependence, especially in wheat. Modernization and smart agriculture are essential for economic stability(Sabah & Rabie, 2024).

5. Principles and Practices of Sustainable Agriculture in Algeria

Sustainable agriculture in Algeria is crucial for enhancing food security and economic resilience, particularly given the country's significant agricultural potential and challenges such as climate variability and resource inefficiencies. Research indicates that increased government spending on agriculture positively impacts productivity and food security in the short term, but long-term benefits require consistent investment and adaptive measures(Benbekhti et al., 2024).The implementation of Climate-Smart Agriculture (CSA) practices, including biofertilizer application, is essential for improving resilience against climate change while promoting sustainable farming methods(Gaad et al., 2024). As, the Water-Energy-Food (WEF) nexus approach highlights the need for integrated resource management, particularly in regions like Ain Temouchent, where agricultural expansion has led to groundwater overuse. Furthermore, sustainable agricultural strategies in desert environments can enhance productivity, reduce environmental impact, and promote biodiversity(Riene & Touati, 2023). These interconnected challenges is vital for achieving long-term sustainability and food security in Algeria (Draou, 2022).

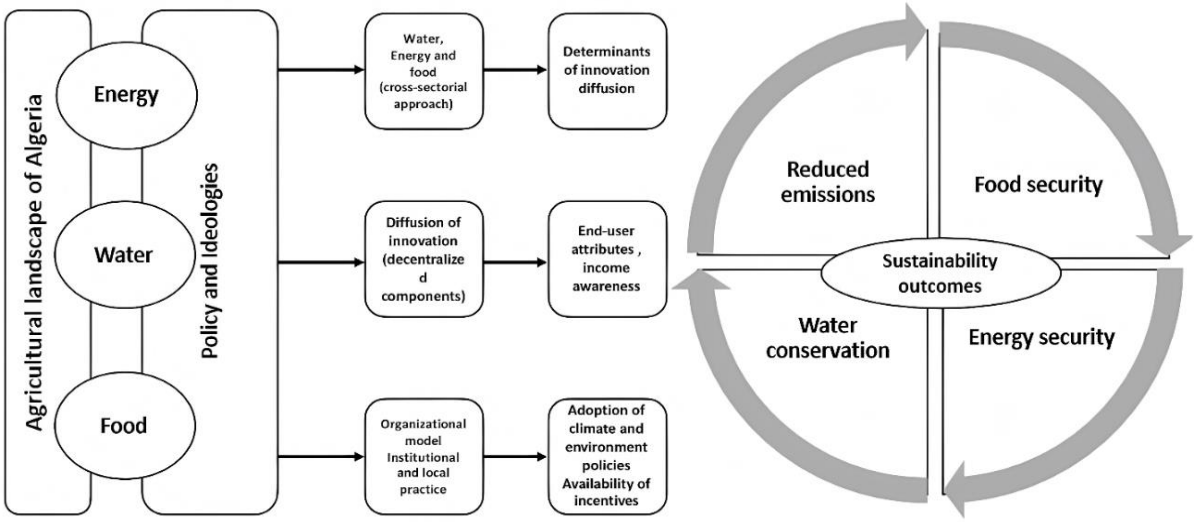


Figure 1. 2 Conceptual model of the Algerian sustainability targets.
Source: (Agadi et al., 2023).

6. Food Security and Environmental Sustainability

Algeria ranks joint 68th out 113 countries in the index and 12th out of 15 MENA countries, with an overall food security environment score of 58.9. It scores best in the Affrdability (66.8) pillar and its weakest pillar is Sustainability and Adaptation (54.2), for which it closely follows its performance in Quality and Safety (54.7). Although Algeria has succeeded in providing affrdable food to consumers, it still faces challenges in addressing climate-change risks. Gaps remain in the form of a national commitment to manage exposure, low levels of climate fiance flws and absence of environmental economic accounting systems. A lack of policy commitments in the form of a nutrition plan or dietary guidelines demonstrate that Algeria also needs stronger food quality and safety measures. (Global Food Security Index 2022). (Sabah & Rabie, 2024)

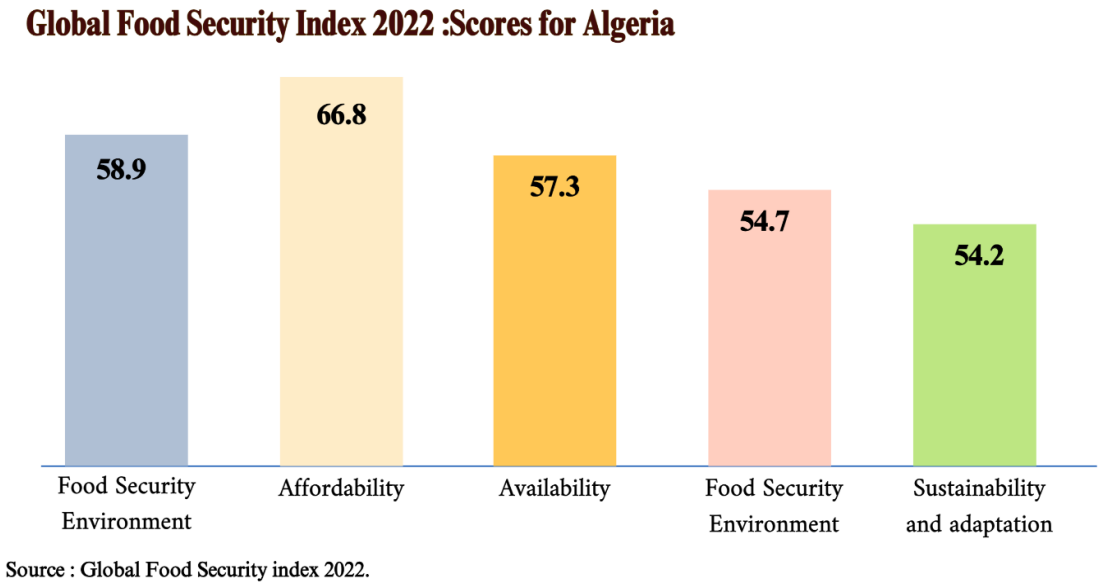


Figure 1. 3 Global Food Security: scores for Algeria
Source: Global food Security, index2022.

7. Agricultural Policy Program in Algeria

7.1 National Agricultural Development Program (PNDA 2000-2010)

The Algerian government has committed a substantial sum of €600 million to the National Program for Agricultural Development (PNDA) as part of its 2001-2004 economic recovery support plan focusing on revitalizing the agricultural sector. The program's primary goal was to ensure the country's food security and promote income and employment opportunities in rural areas while managing fragile natural resources. To achieve these objectives, the program aimed to

improve agricultural production by expanding production capabilities, increasing the availability of agricultural inputs and reproductive materials, preserving and protecting the environment, and promoting economic and functional reforestation in mountainous regions. The ultimate target of the program was to achieve an annual growth rate of 10%, a significant improvement from the previous decade's rate of 4% (Bessaoud et al., 2019).

7.2 The Agricultural and Rural Renewal Policy (PRAR 2010-2014)

The Agricultural and Rural Renewal Policy (PRAR 2010-2014) aims to enhance food security through three strategic pillars: Agricultural Renewal, Rural Renewal, and Strengthening of Human Capacities and Technical Support to producers **(PRCHAT).** Agricultural Renewal focuses on boosting productivity and sustainable practices, aligning with findings that technological integration can increase agricultural productivity by 9.8%(Yaohong et al., 2025) Rural Renewal emphasizes improving living standards through infrastructure development, which is crucial for rural revitalization and poverty alleviation(Wang, 2024). **PRCHAT** aims to enhance farmers' technical skills, reflecting the need for education and capacity building in rural areas to ensure effective management of production systems(Wang, 2024), this policy's multi-faceted approach mirrors broader trends in rural development, emphasizing the importance of state support, innovation, and infrastructure to achieve sustainable agricultural growth and food security.

7.3 FILAHA Plan (2014-2020)

The FILAHA Plan (2014-2020) aims to significantly enhance Algeria's agricultural sector by targeting a reduction in agricultural imports by $2 billion by 2019, while promoting domestic production and exports. This initiative is underpinned by a projected average agricultural growth rate of 5% and the expansion of irrigated areas to 2 million hectares, which aligns with broader agricultural strategies that emphasize productivity improvements and competitiveness in the sector(El Hassani, 2013). The plan's focus on diverse sectors, including fisheries and aquaculture, is expected to create approximately 1.5 million jobs, with a notable contribution from fishing(Koval et al., 2024). In addition, the successful export of Algerian potatoes to various Arab and European countries illustrates the potential for agricultural exports to bolster the economy, similar to trends observed in other regions like Egypt, where horticultural exports have shown significant growth (Naggar, 2024).

7.4 Economic Relations Plan 2020-2024

The Ministry of Agriculture and Rural Development has developed a sectoral program that outlines a road for implementing various actions to improve the current and future situation of agriculture and rural development. The program incorporates relevant data to assess current affairs and identify opportunities for qualitative and/or quantitative progress that can be achieved in the short term or even immediately for specific actions. The main objective of this strategy is to enhance agricultural production through the extension of irrigated areas, promote agriculture production and rural development in mountainous regions, and integrate knowledge and digitization into agriculture development programs (Ferrah 2021).This comprehensive approach helps to modernize the agriculture sector, increase productivity and efficiency, and foster sustainable development in rural areas. By leveraging digital technologies, the sector can overcome critical challenges such as climate change, water scarcity, and land degradation. The program represents a significant step towards achieving the goals of national food security, economic growth, and job creation in Algeria.(Agadi et al., 2023).

7.5 The Roadmap for Algerian Agricultural Sector to 2025

Algeria has developed a new strategy for the period 2025-2029 emphasizes a transition towards sustainable practices, mechanization, and smart agriculture to enhance food security and economic diversification. Current challenges include climatic constraints, land scarcity, and a reliance on food imports, necessitating reforms that shift from centralized control to market-responsive strategies, The government aims to transition from traditional agricultural methods to smart agriculture, which is essential for optimizing resource management and improving productivity (Farid & Ali, 2024).

The latest World Food Security Report issued by the United Nations ranked Algeria first in Africa in terms of food security, with a score of 63.9%, placing it among the countries capable of supporting the UN program's efforts to achieve "zero hunger" by 2030.

The Algerian government has pledged to double these figures by supporting smart agriculture, expanding irrigated areas and improving the rational use of agricultural land, through digitizing sector programs. Algeria is also working to further highlight agricultural innovation, with the goal of introducing new technologies, by urging researchers to connect most agricultural land to new digital technologies by 2025 (Saad, 2022).

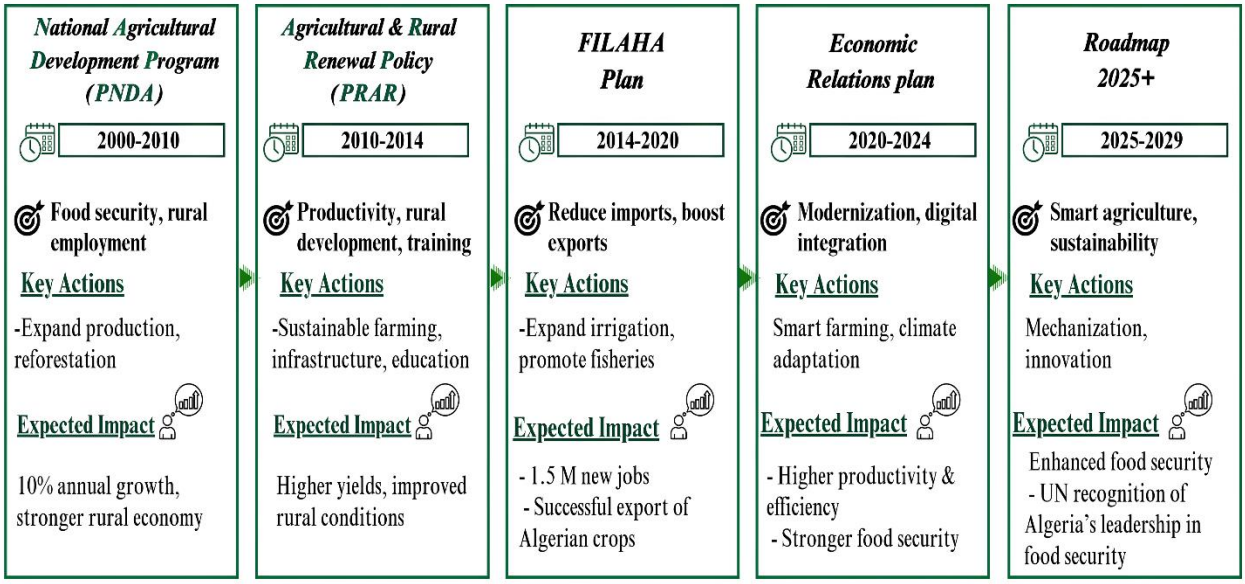


Figure 1. 4 Summary plan: Agricultural Policy in Algeria

8. Strategic Planning Approaches in Algerian Agriculture

The architectural framework of agricultural planning in Algeria can be analyzed through both centralized and decentralized approaches, reflecting a complex interplay of historical policies and current practices. **Centralized** planning has often mirrored socialist management styles, leading to inefficiencies and a lack of responsiveness to local agricultural needs, as evidenced by the challenges faced in achieving food security and self-sufficiency(Farid & Ali, 2024).

Conversely, **decentralized** approaches, which emphasize farmer participation and local conditions, have shown promise in enhancing agricultural productivity and market organization, (Öztürk, 2024).

The dairy sector in Ghardaïa exemplifies this dynamic, where collective organization and market restructuring have positively influenced production, yet challenges such as power asymmetry and inadequate financing persist(Oulmane et al., 2022).

8.1 Centralized Vs Decentralized Agricultural Planning

Centralized and **Decentralized** approaches in agricultural planning each present distinct advantages and challenges, necessitating a balanced integration for optimal effectiveness. Centralized systems offer uniformity and control, enabling large-scale coordination and technological advancements, which can enhance efficiency in resource allocation and market management (Öztürk, 2024) (Verma, 2024).

However, they often overlook the unique needs and capabilities of local farmers, potentially leading to inefficiencies and a disconnect from ground realities (Öztürk, 2024).

Conversely, decentralized systems empower local actors, fostering community involvement and tailored strategies that can address specific regional challenges, yet they may suffer from inconsistencies and lack of oversight, which can lead to corruption and inefficiencies (Febriandiela et al., 2024).

Table 1. 2 Comparison of Organizational Properties: Centralized and Decentralized Systems.

Property	Centralized	Decentralized
Geographical Distribution	Single location	Geographically distributed, relying on information systems (IS) for collaboration.
Coordination: Authority, Decision Rights, and Regulations	✓ Decision-making flows from top to bottom. ✓ Upper management has strict control and governance. ✓ Clear and rigid roles, responsibilities, and accountability. ✓ Standardized methods and procedures. ✓ Goals are uniformly set by high-level authorities.	Lateral coordination involves: ✓ Delegating authority and decision-making to business units or individuals. ✓ Allowing entities to define their own roles and responsibilities. ✓ Supporting diverse goals across units. ✓ Promoting collaboration between independent entities to achieve shared or complementary objectives.
Communication Patterns	Communication follows a strict hierarchy; direct interactions and open communication are limited.	Informal communication networks; flexible and constantly evolving communication methods; dynamic, project-based teams.

8.2 Decentralized Planning Models in Practice: Rural Development Cases

This diagram illustrates how state regulation based on decentralization supports rural development and the export of organic agricultural products. It highlights the role of regulatory tools, mechanisms, and principles in facilitating exports. Decentralization empowers local authorities to develop support programs, offer financial incentives, and provide advisory services to exporters. It also enhances infrastructure and attracts investment at the local level, ensuring better logistics and creating a favorable environment for production and quality improvement.

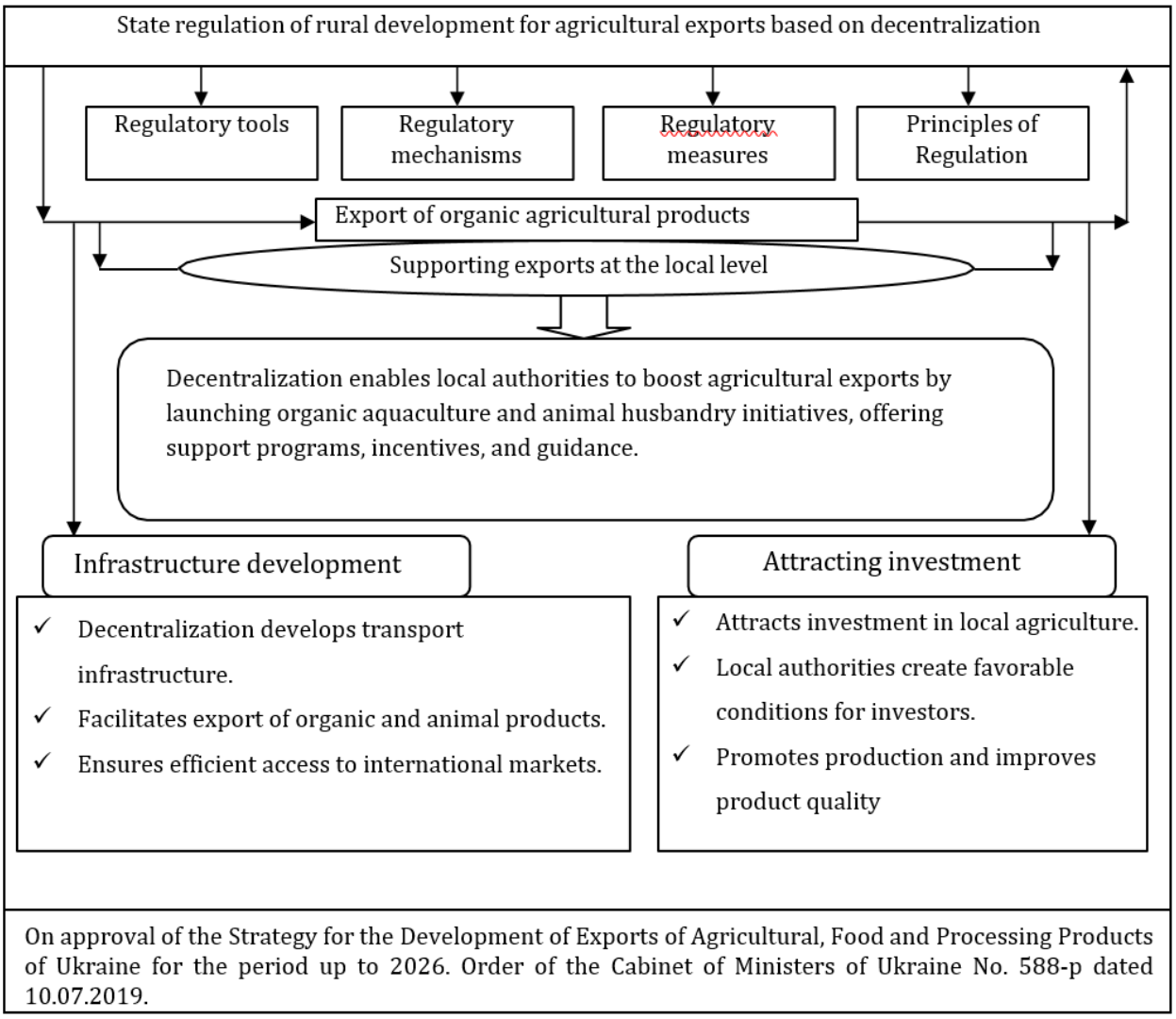


Figure 1. 5 State regulation of rural development based on decentralization for the export of organic products and animal husbandry (Inspired from (Koval et al., 2024)).

9. Legal and Institutional Framework for Agricultural Management

9.1 Agricultural Land Concession Law

Law Numb: 10-03 of August 15, 2010, is considered one of the most important laws defining the terms and conditions for exploiting agricultural land belonging to the state. This law aims to regulate the exploitation of agricultural land by granting concessions to investors, while defining their rights and obligations to ensure optimal land use (MADRP, 2021).

9.2 Public Procurement Law

On August 5, 2023, Law No. 23-12 was promulgated, establishing the general rules for public procurement, with the aim of enhancing transparency and efficiency in the management of public resources. With regard to the agricultural sector, this law seeks to improve the mechanisms for awarding contracts related to agricultural investments, including the distribution of agricultural land of an investment nature according to a concession system. It also establishes a framework for regulating tenders for agricultural equipment, irrigation, and infrastructure supporting the sector, with a focus on encouraging local producers and supporting innovation in the agricultural field.(Public Procurement Law, 2023).

10. Governance Models :Choosing Between Centralization and Decentralization

Considering the above-mentioned laws, the following can be concluded:

- **Centralization:** National laws, such as the Concession Law and the Public Procurement Law, determine the general framework for the management of the agricultural sector and land allocation, reflecting a centralized approach to policy and legislative development.
- **Decentralization**: Local authorities, such as provincial directorates, are granted executive powers to implement these laws at the local level, indicating some decentralized aspects of implementation.

- The agricultural system in Algeria faces challenges due to its reliance on both centralized and decentralized approaches. The centralized model suffers from bureaucracy and limited adaptability, while the decentralized model lacks effective coordination. Neither approach alone can achieve sustainability. Therefore, it is essential to develop a hybrid model that integrates the strengths of both, leveraging centralization for strategic direction and

decentralization for flexibility and innovation, ensuring a more efficient and sustainable agricultural planning system.

- Effective agricultural planning thus requires a hybrid model that leverages the strengths of both approaches, ensuring that local conditions and farmer capacities are integrated into broader planning frameworks, as evidenced by successful initiatives like India's e-nam system (Öztürk, 2024).

11. Conclusion

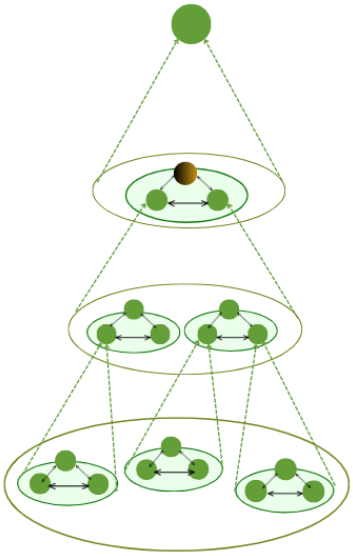
Agriculture remains a key pillar of Algeria's economy and food sovereignty, yet it continues to face deep-rooted challenges that demand modern, adaptive, and sustainable planning approaches. Despite various governmental efforts to improve productivity and ensure long-term stability, many constraints such as resource inefficiency and centralized decision-making still persist.

This chapter provided an overview of the evolution of agricultural strategies and the current landscape, offering a comprehensive understanding of the structural and policy context. These insights highlight the urgent need for innovative planning systems tailored to both national objectives and local realities.

The following chapter introduces intelligent architectures specifically Holonic Systems and Multi-Agent Models as promising solutions for enhancing the adaptability, scalability, and efficiency of agricultural planning in Algeria.

Chapter 2:

Foundations of Holonic Multi-Agent Systems for Agricultural Planning





1. Introduction

Following the analysis of the centralized and decentralized planning models in Algerian agriculture, it becomes clear that existing systems struggle to respond to local complexity while maintaining national coherence. This gap calls for a more adaptive and intelligent approach. Recent research has introduced innovative paradigms such as Multi-Agent Systems (MAS) and Holonic Architectures, which enable decentralized, autonomous decision-making while preserving hierarchical coordination. These systems are particularly suitable for agricultural environments where actors, resources, and objectives vary across levels.

In this chapter, we first explore the key theoretical foundations of holonic and multi-agent systems. Then, we present a critical review of related work and algorithms that have been applied to agricultural planning, identifying existing gaps and highlighting the originality of our proposed solution.

2. Agriculture Planning Challenges in Algeria

In Algeria, agricultural planning at the local, regional, and national levels faces complex challenges due to the pressing need to ensure food security, sustainability, and fair resource allocation. The sector is increasingly impacted by environmental degradation, climate change disruptions, and the depletion of essential resources, all of which threaten agricultural productivity and contribute to persistent food insecurity (Benbekhti et al., 2024),

The integration of land use and food system planning is often disjointed, lacking a holistic approach that considers rural development and consumer needs, and the economic barriers, such as high implementation costs and market volatility, impede the transition to sustainable practices, particularly for smallholder farmers (Kareska, 2024).

The need for participatory governance and adaptive management resources is critical, as these factors are essential for ensuring sustainable agricultural practices and food security in the face of growing population demands and environmental challenges (Benbekhti et al., 2024) (Kareska, 2024).

3. Intelligent Modeling Approaches in Agriculture

In response to the increasing complexity, scale, and multi-dimensional nature of agricultural planning, traditional centralized systems have proven insufficient to meet the evolving needs of this sector. Agriculture today involves the coordination of numerous heterogeneous actors, from

smallholder farmers to national policymakers, all operating under diverse environmental, social, and economic conditions. Furthermore, agricultural planning must now integrate multiple conflicting objectives, such as maximizing productivity, minimizing environmental impact, ensuring food security, and adapting to climate variability. Among the most promising paradigms are Multi-Agent Systems (MAS) and Holonic Architectures, both of which offer structured, flexible, and autonomous decision-making frameworks

4. The Concept of Holons and Holarchic Structures

The holonic concept was developed by the philo- sopher Koestler (1971) in order to explain the evolution of biological and social systems. On the one hand, these systems develop stable intermediate forms during evolution that are self-reliant. On the other hand, in living and organizational systems it is difficult to distinguish between ''wholes'' and ''parts'': almost everything at the same time is a part and a whole. These observations led Koestler to propose the word ''holon'' which is a combination of the Greek word ''holos'' meaning whole and the Greek suffix ''on'' meaning particle or part as in proton or neutron(Giret & Botti, 2004).

The holonic concept refers to a decentralized approach in manufacturing and system design, characterized by the integration of autonomous units called holons, which can operate independently while also collaborating within a larger system. This concept combines hierarchical and heterarchical control mechanisms, allowing for distributed decision-making and concurrent scheduling, which enhances adaptability and responsiveness to changes in manufacturing environments (McFarlane & Bussmann, 2003). Collectively, these studies underscore the relevance of holonic structures in facilitating self-organization and resilience across diverse domains.

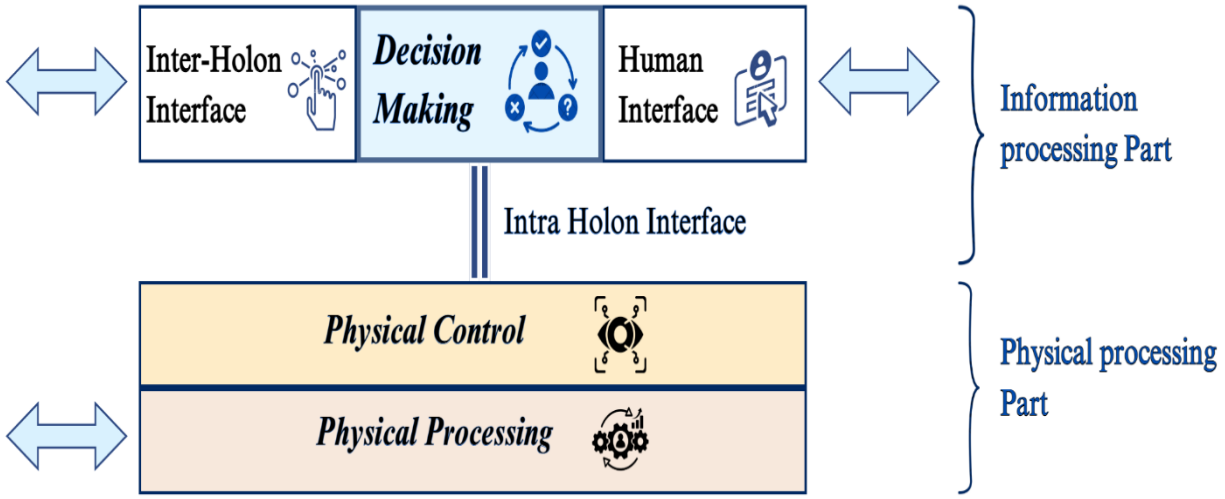


Figure 2. 1 General Architecture of a Holon.

4.1 Characteristics of Holons

- **Autonomy:** Each holon must be able to develop, control, and supervise the execution of its own plans or strategies, while being able to autonomously correct its malfunctions.
- **Cooperation:** Holons must be able to negotiate with each other, implement mutually accepted common plans, and respond together to malfunctions.
- **Openness:** The system must allow the addition of new holons, the deletion of existing ones, or the modification of their functional capabilities, all with minimal human intervention. These holons or their functions can come from varied and heterogeneous sources. (Giret & Botti, 2004).

4.2 The Concept of Holarchy

Holarchy is a concept derived from system sciences, emphasizing the organization of interacting complex systems into self-regulating, autonomous entities known as holons. These holons form a holarchy, a structure where each holon is both a part and a whole, capable of independent operation while contributing to the larger system's functionality. holarchical architectures are employed to decentralize control processes, allowing for intelligent, cooperative, and autonomous production units that enhance system stability and resilience against disturbances (Salazar et al., 2018). Each Holon can form a part of "Super-Holon" and at the same time contains "SUB-Holons", creating a flexible and multi-level structure.

Unlike the traditional "hierarchical structure "(Hierarchy), which depends on a strict sequence of orders and control from top to bottom, the Holrocyte is characterized by being a dynamic structure that allows interaction and coordination between various levels, while maintaining a certain degree of independence in making decisions within each Holon. This gives the Holonian system a great ability to adapt and self –development (Pournaras et al., 2020).

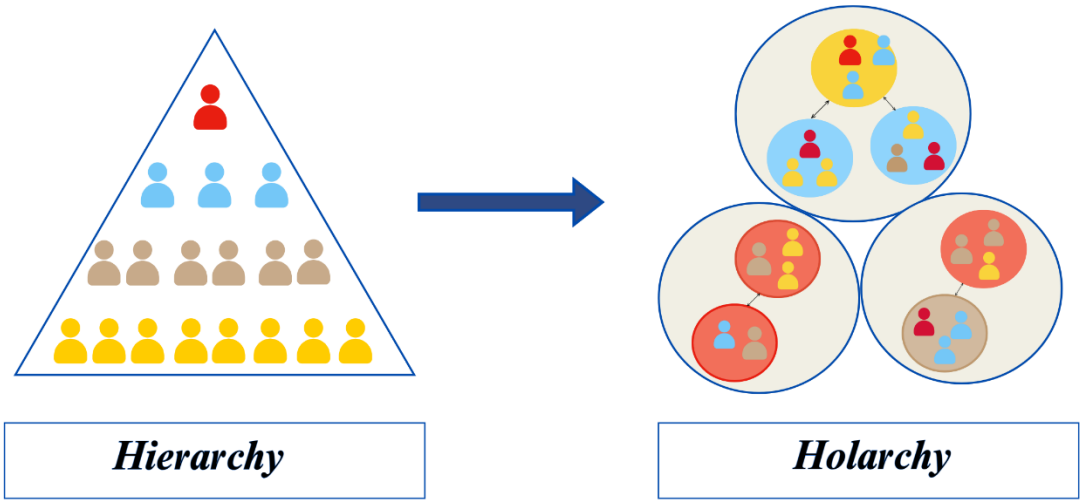


Figure 2. 2 Hierarchy vs Holarchy

❖ The difference between Holarchy and Hieraarchy can be summarized as follows:

Table 2. 1 Key Differences between Hierarchy and Holarchy.

Feature	Hierarchy	Holarchy
Nature of relationships	Vertical, centralized	Interactive, decentralized
Autonomy of units	Low	High
Adaptability	Limited	Strong
Domains	Classical management systems, military…	Biological systems, smart agriculture …

4.3 Holarchic Architecture

Holarchic architecture, as described in the provided papers, is a conceptual framework that organizes systems into hierarchical structures known as holarchies, where each unit, or holon, functions both as a whole and a part of a larger system. This dual nature allows holons to maintain autonomy while being integrated into higher-order structures, facilitating complex organizational dynamics. In management and manufacturing, holarchies enable the creation of flexible and

adaptive systems, such as holonic manufacturing systems, which enhance efficiency and responsiveness to changes in the environment (Mella, 2009). According to Koestler, a holarchy is defined as an **open, ordered hierarchy of self-regulating halons** referred to as a Self-regulating Open Hierarchic Order (SOHO). These holons are coordinated with their local environments, functioning simultaneously as superordinate systems made up of their components, and as subordinate parts under the control of higher-level holons (Boudjemaa, 2020).

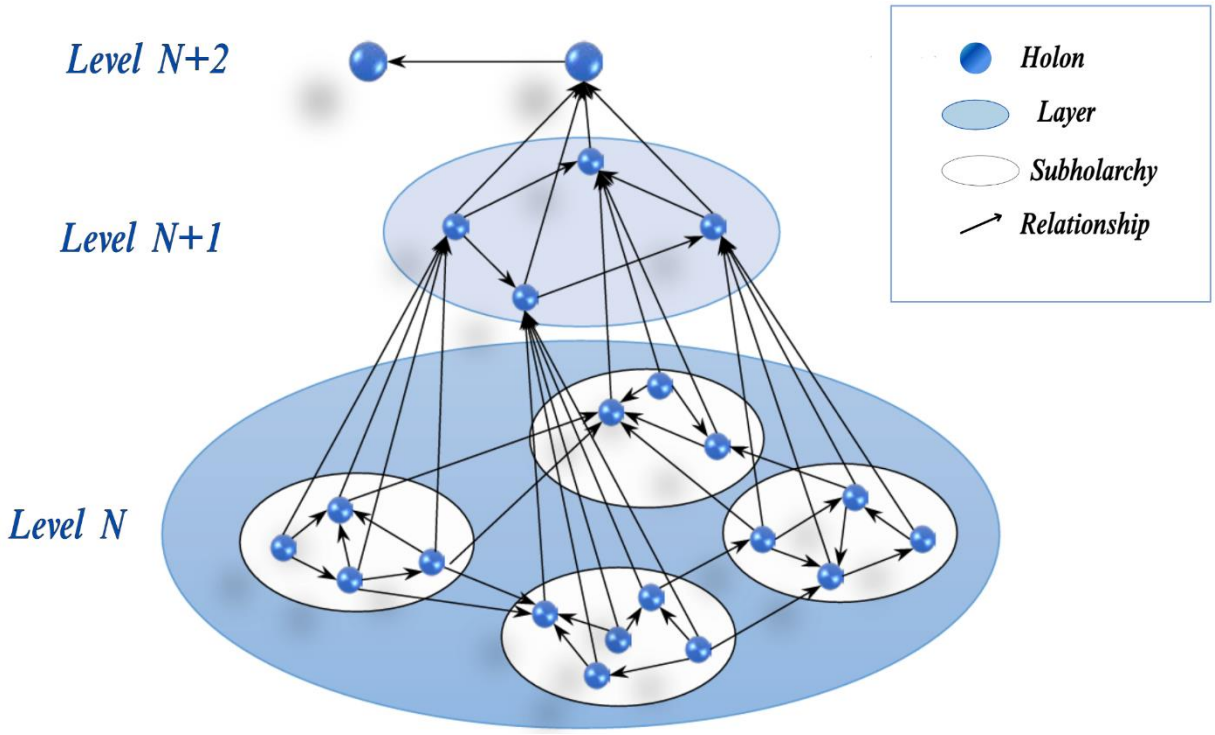


Figure 2. 3 Architecture of a multi-layered holarchy
(Inspired from ((Ferber, 1999) (Boudjemaa,2020)).

The organization of holons can be visualized as a hierarchical tree structure, where the branches widen downward. At each node of this structure is a holonic agent. A single holon plays a dual role: it is both a "head holon" (or supervisor) for the holons below it, and a "member holon" (or subordinate) for those above it. The hierarchy, or holarchy, begins with the base holons, located at the lower levels, and culminates with a final or terminal holon at the top. This structure is called open because it allows interconnection with the external environment.

Each holon is vertically connected to the levels above and below via a whole/part relationship, but does not communicate directly with the holons at its own level. Horizontal exchanges must pass through a higher level. Two types of formation are possible:

- A top-down decomposition, from an initial holon to the base holons.
- Or an ascending composition, by grouping the basic holons until obtaining a final holon.

5. Multi-Agent Systems (MAS) and the Holonic Approach

The integration of Multi-Agent Systems (MAS) with the holonic approach, known as Holonic Multi-Agent Systems (HMAS), offers a robust framework for managing complex, distributed environments across various domains (Bernhard et al., 2024).

The holonic approach in MAS provides a versatile and effective solution for complex system management, offering scalability, adaptability, and enhanced decision-making capabilities across diverse applications.

5.1 Agent and Multi-Agent Systems

- **Agent:** The concept of an agent, particularly within the realm of artificial intelligence and computer science, refers to an autonomous entity capable of perceiving its environment, reasoning, and acting towards achieving specific objectives. This concept is rooted in the idea of intelligent behavior, where agents are designed to operate independently and interact with other agents, whether artificial or human, to fulfill their goals (Pooja, 2023). The notion of agents has evolved significantly since Carl Hewitt introduced the idea of an "actor" in 1977, which laid the groundwork for computational agents that communicate and perform tasks concurrently (Marichal et al., 2009)Agents are integral to multi-agent systems (MAS).
- **Multi-agent system (MAS):** Do sophisticated frameworks comprise multiple autonomous agents that interact with each other and their environment to achieve shared or individual objectives. These systems leverage the agents' social and situated capabilities, allowing them to adapt proactively to changes and collaborate effectively in diverse applications, including industrial manufacturing, robotics, and power systems engineering (Dong, 2023) (Marichal et al., 2009).

  A MAS (Multi-Agent System) is composed of two or more related agents. An agent is an autonomous and flexible computational system capable of acting within an environment the term flexible refers to the agent’s ability to be:

- **Reactive**: it responds to changes in the environment.
- **Pro-active**: it seeks to fulfill its own plans or goals.
- **Social**: it communicates with other agents through some language (Giret & Botti, 2004).

Certain properties are typically attributed to agents, to varying degrees, depending on the specific problem to be solved:

- ✓ **Autonomy:** agents operate without direct intervention from humans or other agents.
- ✓ **Social ability:** agents interact with other agents (human or not) via an agent communication language.
- ✓ **Rationality:** an agent can reason based on perceived data to compute an optimal solution.
- ✓ **Reactivity:** Agents are able to perceive the environment's stimulus and these stimulus guide the agents' actions on their environment.
- ✓ **Pro-activeness:** Agents are not only stimulus- reacting entities, but also have an enterprising character and can act guided by their own goals.
- ✓ **Adaptability:** It is related to the learning that an agent may do and with its capabilities to change its own behavior based on this learning.
- ✓ **Mobility:** It isthe capability of an agent to move through a network.
- ✓ **Yeracity:** An agent cannot deliberately provide false information.
- ✓ **Benevolence:** An agent is willing to help other agents if this is not against its owns goals (Giret & Botti, 2004).

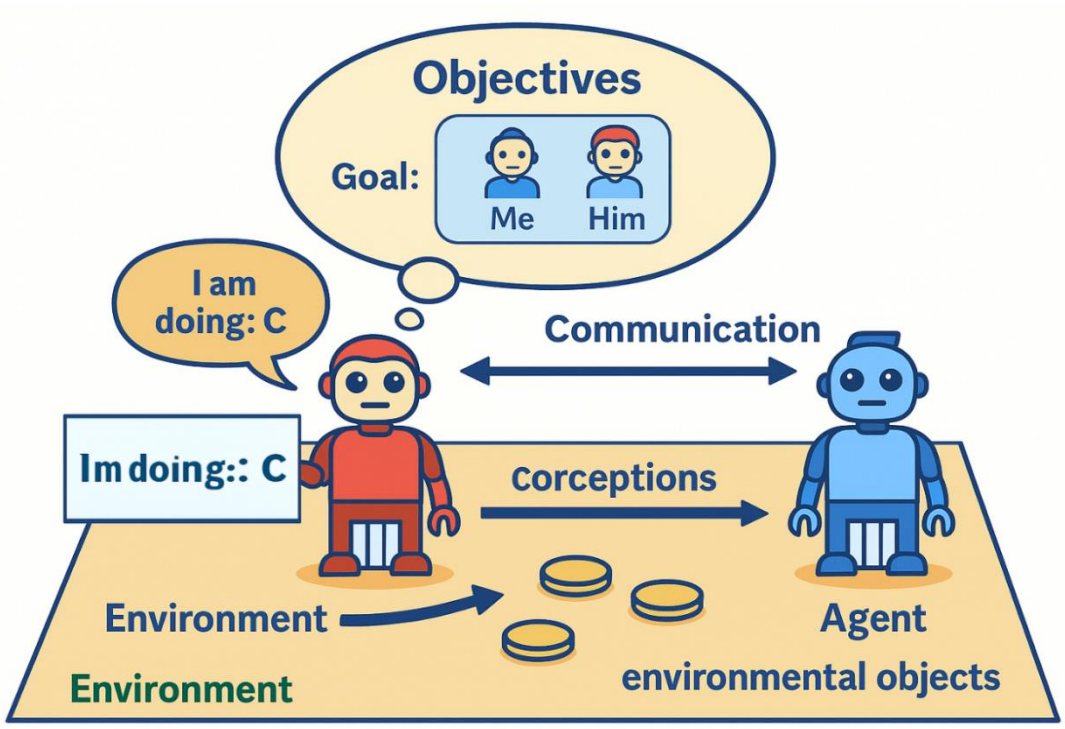


Figure 2. 4 the functioning of an agent in an environment
(Inspired from (tpesiai, 2013)).

Multi-Agent Systems (MAS) are built upon the principles of autonomous agent interaction within dynamic environments. Each agent is designed to perceive its surroundings, analyze relevant data, and make decisions based on internal goals and environmental constraints. The above illustration represents a conceptual visualization of how an agent operates within a multi-agent system (SMA). Each agent is autonomous, capable of perceiving its environment, communicating with other agents, and making decisions based on its internal state and established goals. As illustrated, the agent maintains a representation of its current state ("I am doing: C"), the goal it is pursuing ("Goal: B"), and a model of its surroundings, including other agents and environmental influences. This ability to perceive, reason, and act is a fundamental building block of multi-agent systems, where agents interact to collectively solve complex problems. Such systems are particularly important in dynamic and distributed contexts, supporting decentralized decision-making, adaptability, and structured collaboration. By enabling systematic communication and intelligent coordination, these systems form a strong foundation for deferent applications

5.2 The Holonic Agent

Holonic agents represent a sophisticated paradigm in multi-agent systems characterized by their self-similar structure, where agents (holons) can decompose into sub-agents, allowing for dynamic autonomy adjustments based on specific tasks or environments (Gerber, 2002).This hierarchical organization facilitates direct communication and negotiation among agents at the same level, enhancing efficiency and role management within the system(Adam & Mandiau, 2005). Holonic agents have been effectively applied in various domains, including manufacturing, where they operate as units of production in cooperative knowledge-based systems, ensuring robustness and fault tolerance (Deen, 2002).

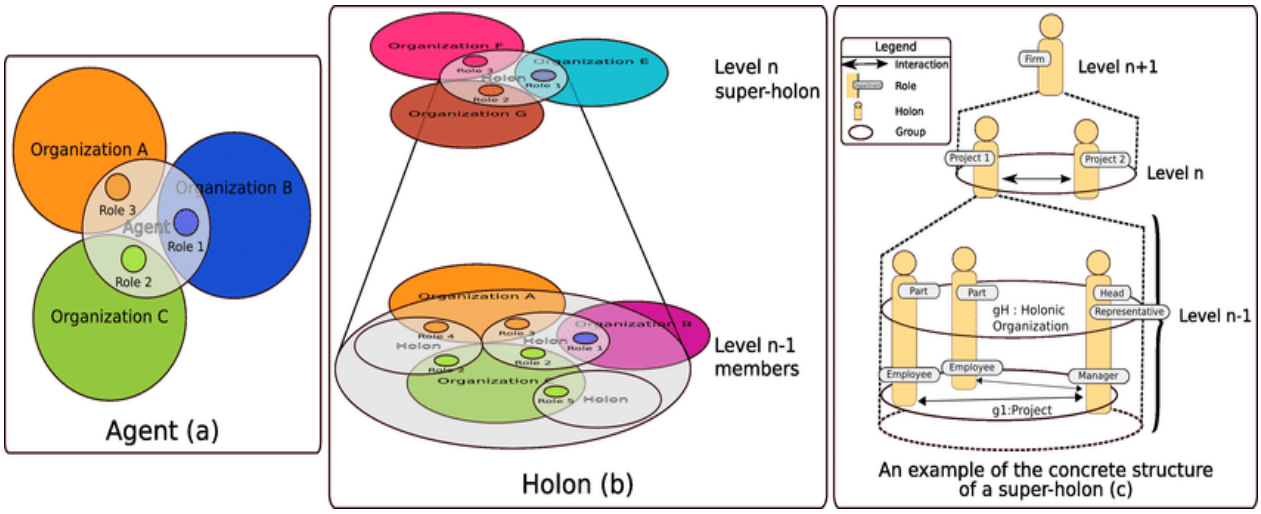


Figure 2. 5 Agent and Holon symbolic representation, and an example Of the concrete structure of a super-holon (source (Cossentino et al., 2007)).

The holonic agent extends the traditional concept of an agent by embedding it within a flexible and recursive organizational structure. Rather than being limited to a single role or context, a holonic agent is capable of dynamically participating in multiple organizations, assuming various roles depending on the context and interaction level. This dynamic nature allows the holon to function both as an independent agent and as part of a collective, adapting its behavior to internal goals and external coordination needs (Cossentino et al., 2007).

This multi-level integration is illustrated in the accompanying **(Figure 2.5).** In part (a), the agent is shown interacting with multiple organizations (A, B, C), taking on different roles simultaneously, which exemplifies its distributed responsibilities. Part (b) expands on this by presenting the holon as a composition of agents each engaged in different roles forming a cohesive

unit capable of integrating into a higher-level structure known as a super-holon. Finally, part (c) visualizes the internal structure of such a super-holon, highlighting how members coordinate through specific roles and responsibilities to ensure the system's coherence and adaptability.

5.3 Agents vs Holons

In the context of distributed intelligent systems, both agents and holons are widely used to model autonomous and cooperative entities. While they may appear similar at first glance since both exhibit autonomy, reactivity, and proactivity their underlying principles, structures, and functionalities differ in meaningful ways. The following table presents a detailed comparison between agents and holons based on various features

Table 2. 2 Comparison of features between Agent and Holon(Source((Giret & Botti, 2004)).

Features	Agent	Holon
Autonomy	Yes	Yes
Reactivity	Yes	Yes
Proactivity	Yes	Yes
Social Capability	Yes, the user interface is implemented to facilitate interactions	Yes, the user interface is specific to each holon
Cooperation	Yes, it can be both competitive and cooperative	Yes, holons do not expressly reject cooperation
Organization, openness	Yes, holarchies are implemented using open structures	Yes, holarchies
Rationality	Yes	Yes
Learning	Yes	Yes
Volunteering	Yes	Yes
Mobility	Yes	Holons rarely require mobility to perform tasks
Recursion	There is no proper recursive architecture	Yes
Information processing and physical processing	There is no explicit separation.	Information processing and physical processing There is no explicit separation. The separation is explicit, although the processing is often integrated.
Mental attitudes	Yes	They don't need to reason based on emotional intelligence.

6. Modeling Holonic Systems Using AUML

As part of our study of holonic and multi-agent systems, it is essential to rely on a modeling approach adapted to the complexity and distributed nature of these systems. To this end, we use the Agent Unified Modeling Language (AUML), a specialized extension of UML designed to model interactions in multi-agent systems (MAS).

Agent UML (AUML) is a specialized extension of the Unified Modeling Language (UML) tailored for modeling multi-agent systems (MAS). It enhances standard UML sequence diagrams to capture dynamic aspects of agent interactions, such as role assignments, nondeterministic decision-making, and concurrent communications, thereby facilitating the description of agent interaction protocols (Küster Filipe, 2004).AUML incorporates various notations and methodologies to guide the modeling process, addressing the complexities inherent in agent-based systems (Hong-han & Rui-zhong, 2011). AUML also supports automated testing sequence generation through formal specifications, enabling both unit and social testing of agent behaviors, which is crucial for verifying interactions within MAS (Mokhati et al., 2007).

We will use the Agent United Modeling Language (AUML) to model the various components and interactions of the system. The main AUML diagrams will be:

- **Use Case Diagram:** To identify the main interactions between agents and users of the system.
- **Sequence Diagram:** To describe the temporal interactions between agents.
- **Class Diagram:** To represent agents and their relationships.

7. Literature Review and Related Work

After identifying the problem and discussing the key agricultural concepts in Algeria in the previous chapters, this chapter We begin by revisiting some relevant previous works in the field, highlighting both the optimization algorithms commonly used and the approaches that have employed holonic systems and multi-agent systems. This literature review allows us to position our work within the existing research landscape. This comparison will help justify the choices made in our own approach and clarify the originality and added value of our proposed holonic optimization system.

7.1 Multi-Level Decision-Making in Agricultural Planning

Multi-level decision-making in agricultural planning involves a complex interplay between local, regional, and national strategies to enhance food security and economic stability. At the farm level, local decision-making is crucial, as farmers must adapt to market conditions and resource availability, which can be supported by advanced crop planning techniques like double deep Q-learning that optimize planting areas based on predicted prices and sustainability goals (Sisto et al., 2022a).

Regionally, coordination is essential for resource distribution and crop diversification, necessitating participatory approaches that engage stakeholders in decision-making processes, as demonstrated by integrating backcasting and multiple criteria decision analysis (MCDA) tools.(Sisto et al., 2022b).

Nationally, effective agricultural planning must encompass the entire agri-food system, addressing the inadequacies of market mechanisms and ensuring that food security strategies are comprehensive and inclusive(Öztürk, 2024). This multi-tiered approach fosters resilience and adaptability in agricultural systems, ultimately contributing to sustainable development (Zhang et al., 2015a).

➢ Case Study: Decision-Making in Rural Development Contexts

Decision-making involves selecting among competing alternatives. In rural development, policies must consider the role of local communities, their cultural beliefs, and traditions for effective implementation. Engaging rural dwellers such as elders, traditional leaders, women, and youth is essential in designing policies, particularly for food security. Their involvement in

implementation, monitoring, and evaluation ensures the success and sustainability of development programs (Nwagboso, 2012). The chat below presents how such policies and programmes should originate:

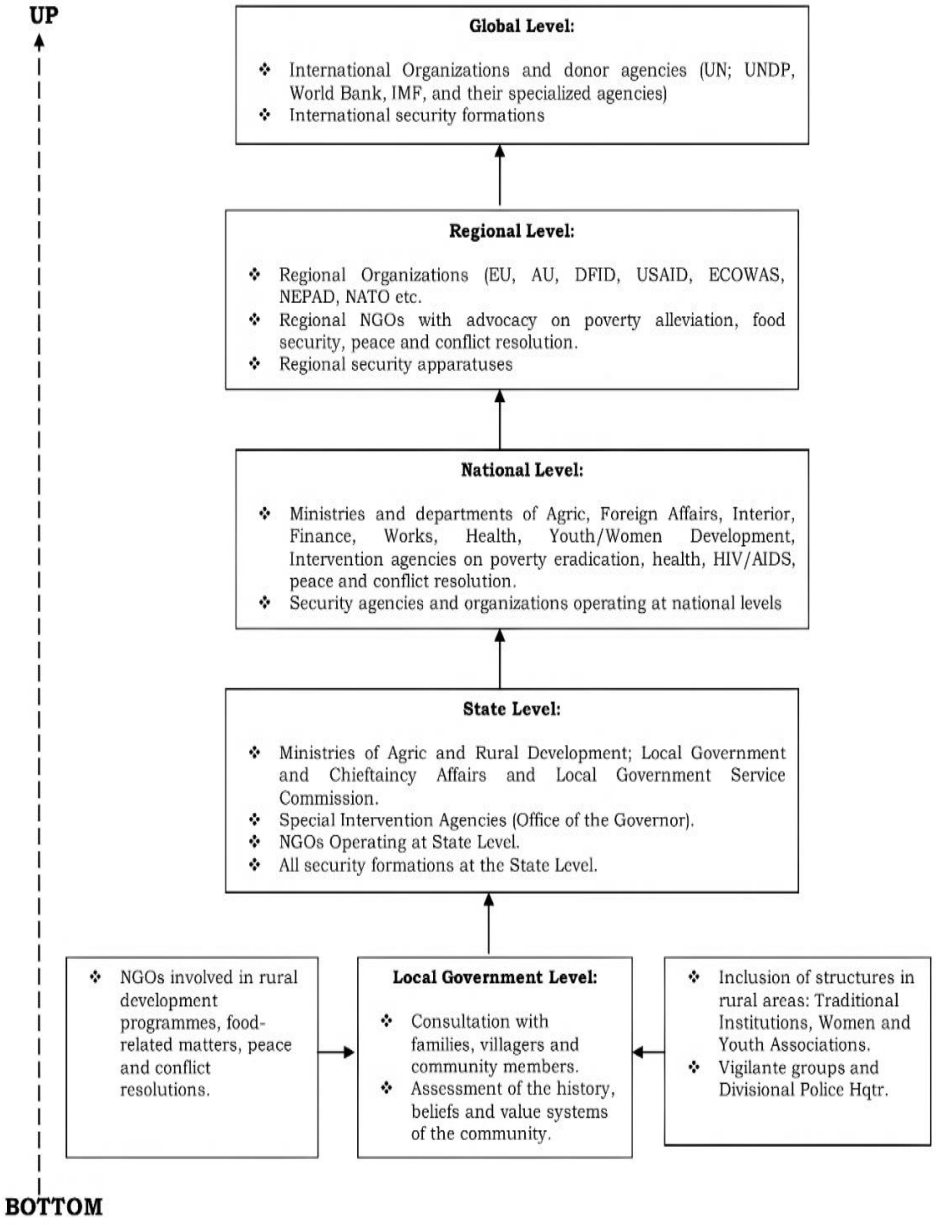


Figure 2. 6 A Sample of Proto-Type Bottom-Up Approach of Rural Development for Achievement of Food Security and Global Peace in the 21st Century (Source (Nwagboso's Field Work, 2011).

This diagram represents a hierarchical model for rural development, food security, and global peace, following a multi-level governance structure from local to global levels. While it claims to be a bottom-up approach**,** it still exhibits characteristics of a centralized system.

- **Hierarchy of Governance:** The diagram divides governance into five levels**:** Local, State, National, Regional, and Global, and It suggests that decision-making starts at the local level, but in reality, higher levels still dominate the process.
- **Local Participation:** Local governments and communities are included in the framework; however, they primarily play a consultative role rather than having actual decision-making power.
- **Role of International Organizations**: Global actors such as the UN, World Bank, and IMF are positioned at the top, indicating external influence on national policies. This suggests that food security and rural development in many countries remain highly dependent on international aid and policies.
- **Security & Conflict Resolution Focus:** The model integrates security agencies at each level, implying a strong link between food security, peace, and stability. However, economic, social, and technological aspects of development are less emphasized.

➢ **Limitations**

- **Not Truly Decentralized:** Power still flows top-down rather than bottom-up.
- **Rigid Structure:** Limited direct interaction between levels, reducing flexibility.
- **Lack of Technology & Innovation**: No mention of digital solutions or smart agriculture.
- **Weak Economic & Environmental Focus**: Prioritizes security over sustainability.
- **Dependence on External Organizations**: High reliance on international agencies, reducing national autonomy.

7.2 Application Domain: Agriculture Planning

Agricultural planning is applied across various contexts, including crop management, resource allocation, and sustainability practices, particularly in regions like Algeria where challenges such as resource depletion, climate change, and economic instability are prevalent (Potluri et al., 2024).

In Algeria, the management of water and soil resources is critical, as farmers face uncertainties related to weather patterns and market fluctuations, necessitating innovative solutions

for optimal resource utilization. Digital solutions, such as web applications and AI-driven decision support systems, can significantly enhance agricultural planning by providing real-time data analytics, crop monitoring, and tailored recommendations for resource management (Castellanos Serrano et al., 2024). These technologies facilitate better decision-making by integrating multiple criteria, thus addressing the complexities of agricultural production under uncertainty and promoting sustainable practices that can adapt to evolving environmental and economic conditions (Potluri et al., 2024).

7.3 Overview of Previous Works in the Current Context

In our project, it is helpful to examine how similar architectures have been applied in different fields. While these implementations are not directly related to agriculture, they offer valuable insights into the flexibility and adaptability of such systems when dealing with distributed decision-making and complex coordination tasks. The table below highlights key studies, their application areas, and the methodologies used.

Table 2. 3 Comparative Analysis of Existing Approaches.

Study Title	Description/Objective	Location	Domain	Used Approach	Centralized /Decentralized
Reinventing Urban Agriculture in Algerian Urban Policies. (Korchi & Bendjaballah, 2023)	It emphasizes the potential to enhance urban sustainability through better inclusion in public policies and increased stakeholder collaboration.	Algeria	Agriculture in Urban Policies	Multi-level stakeholder engagement	Centralized
Trans-Cultural Transport Simulator (A multi-agent model For the study of flexible transport systems In urban environnements) (Lammoglia, 2017)	To evaluate the effectiveness and spatial coverage of flexible and informal transport systems through multi-agent simulation in different socio-economic contexts	France & Senegal	Urban Transport Planning	Multi-Agent Simulation (MAS), Multi-Level Modeling, Behavioral Analysis using NetLogo	Decentralized, with focus on self-organized systems and agent cooperation/competition dynamics
Tri-level Multi-follower Decision Making (Zhang et al., 2015b)	Proposes a multi-agent, tri-level decision-making model to analyze hierarchical and	Not specified (Generic /	Decision analysis, Production planning	Multi-level Multi-agent Optimization	Decentralized (Hierarchical)

	decentralized decision processes in complex systems such as supply chains.	Theoretical)			
Holonic Control for Smart Farming (Clark et al., 2019).	Introduces a decentralized, intelligent control strategy for smart farming, leveraging autonomous holons to enhance flexibility, scalability, and real-time resource optimization.	India	Smart Agriculture	Holonic System	Hybrid (Holonic)
Intelligent Decision Support System for Urban Project Planning (Boudjemaa, 2020).	Proposes a holonic multi-agent system (H-MAS) using ant colony optimization to support sustainable urban planning. The system generates optimal project plans by coordinating agents at different levels based on holonic architecture .	Tébessa, Algeria	Urban Planning,	Holonic Multi-Agent System (SMAH), Optimization (H-MACO)	Holonic
Sustainable Farming through Decentralized Energy Systems (Agadi et al., 2023).	Examines the use of decentralized energy systems on Algerian farms to improve energy resilience, highlighting opportunities for renewable energy integration and offering policy guidance to promote sustainable agriculture	Algeria	Energy, Agriculture	Decentralized energy systems	Decentralized
Group Decision Support for Agriculture Planning (Zaraté et al., 2023)**.**	Enhances collaborative crop planning among farmers by fostering consensus and coordination.	Not specified	Agriculture	Centralized optimization and group decision support	Centralized

7.4 Optimization Algorithms in Sustainable Agriculture

Optimization algorithms are mathematical techniques used to find the best solution among a set of possible solutions to a specific problem. In the context of sustainable agriculture, these algorithms are employed to address multi-objective challenges such as maximizing crop yields, minimizing water and fertilizer use, reducing greenhouse gas emissions, and ensuring equitable land distribution. Below is a detailed analysis of the most relevant algorithms, their applications, and limitations.

Table 2. 4 Comparative Analysis of Optimization Algorithms for Sustainable Agricultural Planning in Algeria.

Algorithm Name & Description	Application Domains	Problem Formulation (Continuous /Discrete)	Type of System Optimization	Example in Algerian Agriculture	Quantitative Metrics	Limitations
The Weighted Sum Method (WSM): is a multi-criteria decision-making technique that assigns weights to different criteria based on their importance. It combines these weighted criteria to produce a suitability score for each alternative.	Engineering design, resource allocation, economics (trade-off analysis).	Continuous (suitability scores are calculated on a continuous scale).	Single-objective secularization (aggregates multiple objectives into a single weighted sum).	Used to identify the most suitable lands for durum wheat cultivation in the Mleta region by integrating factors such as soil type, slope, and climate(Abdelkader & Delali, 2012).	**Used 5 criteria** (soil, slope, rainfall, temperature, altitude), applied on **30 parcels** 87% accuracy	The subjectivity of weight assignment can lead to biased results if not carefully calibrated.
Multi-Objective Optimization (MOO) Algorithms: Algorithms are designed to optimize multiple conflicting objectives simultaneously.	Supply chain optimization, energy system design, and financial portfolio management.	Both continuous and discrete, depending on the problem (e.g., land allocation can be discrete, while water use can be continuous).	Multi-objective Pareto optimization (seeks trade-offs between conflicting objectives).	Used to optimize crop planning to conserve groundwater and maximize profit (Lin et al., 2021).	**4–6** objectives, **200+** solutions, **20%** improvement in water savings	Computational complexity increases with the number of objectives, and finding a Pareto-optimal solution can be challenging.

Modified Lion Optimizer (MLO): The Modified Lion Optimizer (MLO) is a nature-inspired metaheuristic algorithm that mimics the behavior of lions in searching for prey. It is used to optimize complex problems by assessing solutions based on expected, optimistic, and pessimistic values.	Renewable energy optimization, mechanical engineering design, network routing.	Continuous (optimization of crop selection based on climatic and soil conditions).	Metaheuristic global optimization (nature-inspired search for global optima in complex spaces).	Applied to predict crop yields and recommend crops based on local climatic and soil conditions (Haldorai et al., 2024).	**3** parameters, RMSE = **12%**, **150** iterations	May converge prematurely if the search space is not properly defined.
Multi-Objective Genetic Algorithm (MOGA): is a population-based evolutionary algorithm that uses genetic operators such as crossover and mutation to search for optimal solutions in multi-objective problems.	Robotics path planning, aerospace engineering, and environmental conservation planning.	Continuous (e.g., energy ratio, benefit-to-cost ratio, and greenhouse gas emissions).	Evolutionary multi-objective optimization (Uses genetic operators to explore Pareto fronts).	Used to optimize energy use, reduce production costs, and mitigate greenhouse gas emissions in edible onion production.(Elhami et al., 2022).	Optimized across **3 objectives**, tested on **population size = 100**, **50 generations**	Requires careful tuning of parameters and Can be slow with large datasets
Artificial Intelligence (AI) and Machine Learning (ML) Algorithms: AI and ML algorithms, such as convolutional neural networks (CNNs) and predictive models,	Healthcare diagnostics, autonomous vehicles, fraud detection, natural language processing.	Continuous (e.g., crop yield prediction based on environmental data).	Predictive/adaptive optimization (data-driven decision-making and pattern recognition).	Used to predict crop yields and recommend crops based on climatic and soil conditions (Haldorai et al., 2024).	Dataset = **1000** samples, R^2 = **0.93,** MAE = **8%**	equires high-quality data and computational resources.
Precision Agriculture Technologies	Crop health monitoring, smart	Continuous (e.g., real-time	Data-driven resource optimization	Used to monitor crop health and optimize	Sensors: **20** fields, **15%** water saved,	High implementation costs and the

(PATs): PATs integrate advanced technologies such as IoT, GPS, and remote sensing to optimize.	irrigation systems, yield prediction, soil analysis.	monitoring of soil moisture and crop health).	(IoT/ML-based real-time resource allocation).	irrigation systems to conserve water (Getahun et al., 2024).	**10%** yield increase	need for technical expertise.
Constrained Multi-Objective Evolutionary Algorithms (CMOEAs): are advanced algorithms designed to handle constrained multi-objective optimization problems.	Structural engineering (safety constraints), water resource management, transportatio n logistics.	Both continuous and discrete, depending on the problem.	Constrained multi-objective optimization (ha ndles constraints alongside conflicting goals).	Used to optimize land use and resource allocation in sustainable agricultural planning (Fan et al., 2017)	**5** objectives, **100+** constraints, 30% time saved.	Computational complexity and the need for careful parameter tuning.
Linear Programming (LP) Mathematical approach that seeks to maximize or minimize a linear objective function subject to linear equality and inequality constraints.	Resource allocation, production planning, land-use optimization	Continuous or mixed	Centralized Optimization	Water allocation modeling in semi-arid zones (Dantzig, 1963)	2 constraints, **3** variables, optimal in 0.2 sec	Cannot handle non-linear or conflicting objectives; limited adaptability in multi-objective rural planning
Greedy Algorithm Iterative heuristic that makes locally optimal choices with the hope of finding a global optimum.	Task assignment, scheduling, basic planning	Discrete	Local, one-pass optimization	Quick crop selection for small cooperative farms (Cormen, T & Stein, C., 2009)	Time**: 0.01** sec, 85% local efficiency, 20 parcels	Suboptimal in complex problems; no guarantee of global optimum; ignores long-term trade-offs

❖ BKPACS Algorithm

The BKPACS (Bounded Knapsack Problem Ant Colony System) algorithm is an extension of the Ant Colony Optimization (ACO) metaheuristic, specifically adapted to handle bounded knapsack-type problems with multiple constraints. It was introduced by Khelifa and Laouar (2021) in the context of urban development and land-use planning.

While BKPACS has not yet been applied in Algerian agriculture, its structure is particularly well-suited to multi-objective optimization under strict resource limitations such as land area, water availability, and crop diversity. This study explores its applicability in a novel domain **sustainable agricultural planning** demonstrating its potential to support decentralized and scalable decision-making in real-world rural contexts.

8. A Critical Evaluation of Optimization Approaches and Multi-Level Holonic Systems

Optimization methodologies are a pivotal element in addressing complex agricultural planning problems, especially given the variety of criteria that must be taken into account, such as cost, profitability, and sustainability. The literature has demonstrated widespread reliance on a range of algorithms, such as evolutionary algorithms, mathematical programming, and artificial intelligence techniques, due to their ability to find effective solutions in dynamic and unstable environments such as the agricultural environment.

In parallel, recent years have witnessed growing interest in holonic systems, particularly those built on multi-level architectures. These systems have proven their effectiveness in several fields, such as industry, transportation, and logistics, due to their decentralized, flexible management and effective coordination across different levels. However, despite the use of this model in a number of sectors in Algeria, the agricultural sector remains far from such smart solutions, as no actual applications using holonics have been recorded in this context to date.

The tables provide a concise summary of the most important optimization approaches, on the one hand, and the most prominent previous works that adopted multi-level holographic systems, on the other. This evaluation aims to position our project within the map of previous work, highlighting its originality and importance in developing a smart and sustainable agricultural planning system.

9. Conclusion

This chapter combined the theoretical foundations of Holonic Systems and Multi-Agent Architectures, emphasizing their potential for decentralized and intelligent agricultural planning. It also provided a structured literature review, highlighting key contributions and revealing limitations in traditional and flat planning systems. The review showed a clear lack of scalable, Holonic models adapted to Algeria's agricultural context. While several works address optimization, most fail to integrate strategic alignment, multi-level coordination, and adaptability. These findings justify the choice of a holonic structure to meet both global objectives and local realities.

The next chapter presents the methodology adopted for modeling the proposed system and structuring real agricultural data into a scalable decision-support architecture.

Chapter 3:

Design and Methodology of a Holonic Multi-Agent System for Sustainable Agricultural Planning in Algeria



1. Problem Statement and Research Motivation

In order to address the growing challenges of sustainable agricultural planning in Algeria, we propose a holonic decision support system that reflects the complexity and multi-scale nature of the agricultural sector. The system is structured around four hierarchical levels local, district, regional, and national each composed of agents that operate autonomously while remaining integrated within a larger collaborative framework.

The approach is based on real data collected from the Directorate of Agricultural Services in Tebessa, which serves as a pilot case study. These data will later support simulations and evaluations of potential planning strategies. To accurately represent agent roles, interactions, and decision-making processes, we use formal modeling tools such as UML and AUML, to capture behavioral scenarios and negotiation mechanisms.

In the following sections, we define the system's structure, describe the roles of agents at each level, present the data modeling process, and explain the methodological flow that guides the development of our intelligent, scalable, and sustainable planning system.

2. Overview of the Proposed Holonic System

To design an effective and scalable decision support system for sustainable agricultural planning, we adopt a structured methodological approach that reflects the multi-level nature of agricultural governance in Algeria. The implemented system is based on a holonic architecture, which allows each level (local, regional, national) to function autonomously while collaborating with the others in a coherent and goal-oriented manner.

The overall methodology integrates real agricultural data, agent-based modeling, simulation, and optimization processes. It guides the development of the system from data collection to solution evaluation, ensuring alignment with national sustainability goals. The figure below illustrates the general methodological framework adopted in this project, highlighting each key phase and its interactions.

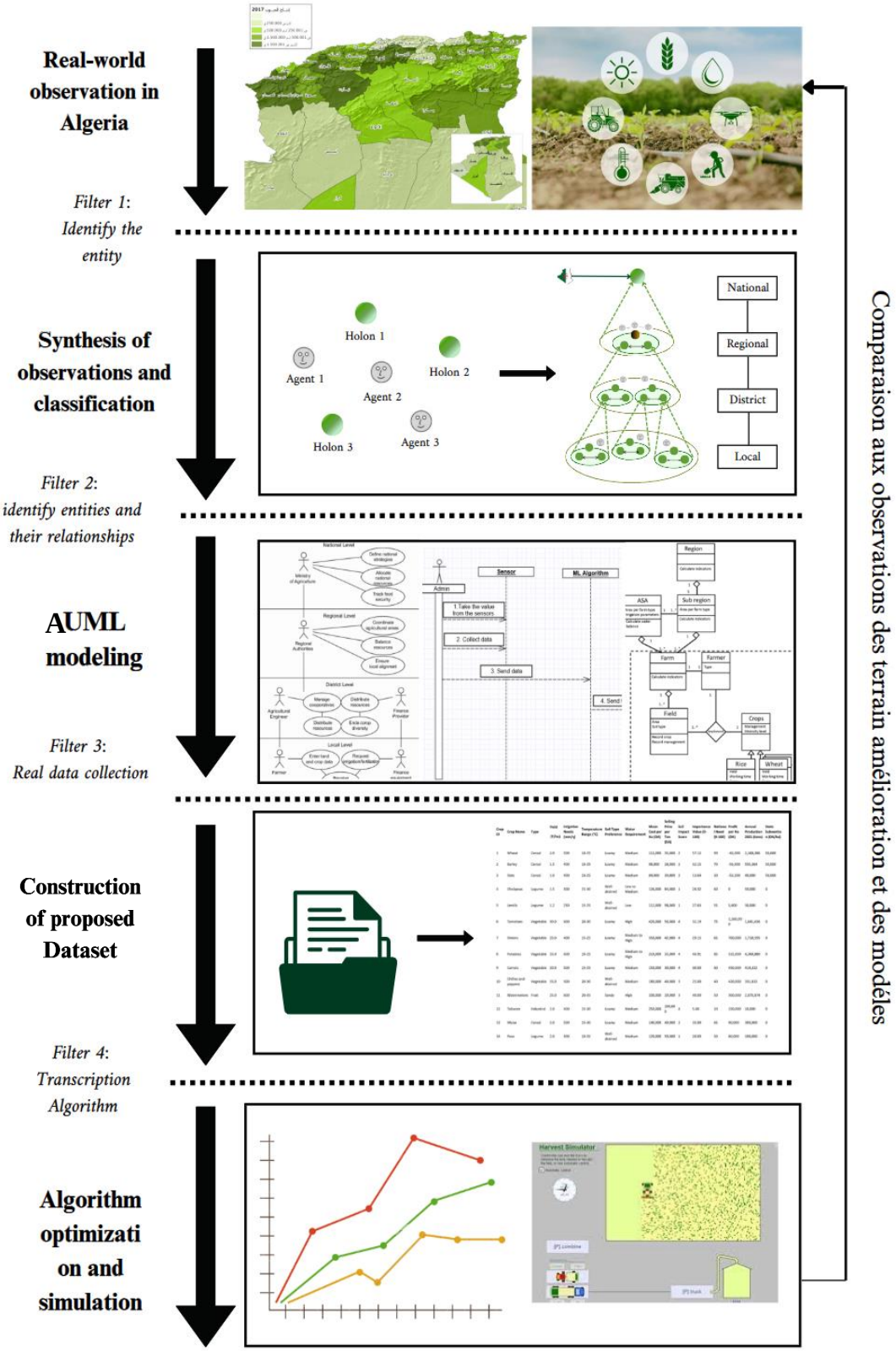


Figure 3. 1 General modeling approach.

3. Case Study: Tebessa Region

As part of this work and in order to implement the proposed methodological approach, we selected the wilaya of Tebessa as a case study. This choice is justified by the region's agricultural richness, the diversity of its farms, and the availability of local data. Instead of immediately addressing the entire Algerian territory, we opted to begin at the local level to validate our model in a concrete and gradual way.

This decision allowed us to adopt a more realistic and focused approach, particularly by facilitating the collection of reliable and up-to-date information. To this end, we conducted a field visit to the agricultural services of the wilaya (Direction of Agricultural Services of Tebessa - DSA), where we were able to consult official documents, interview officials, and obtain statistical files regarding various agricultural holdings, production, cultivated areas, technical resources, as well as support and funding programs.

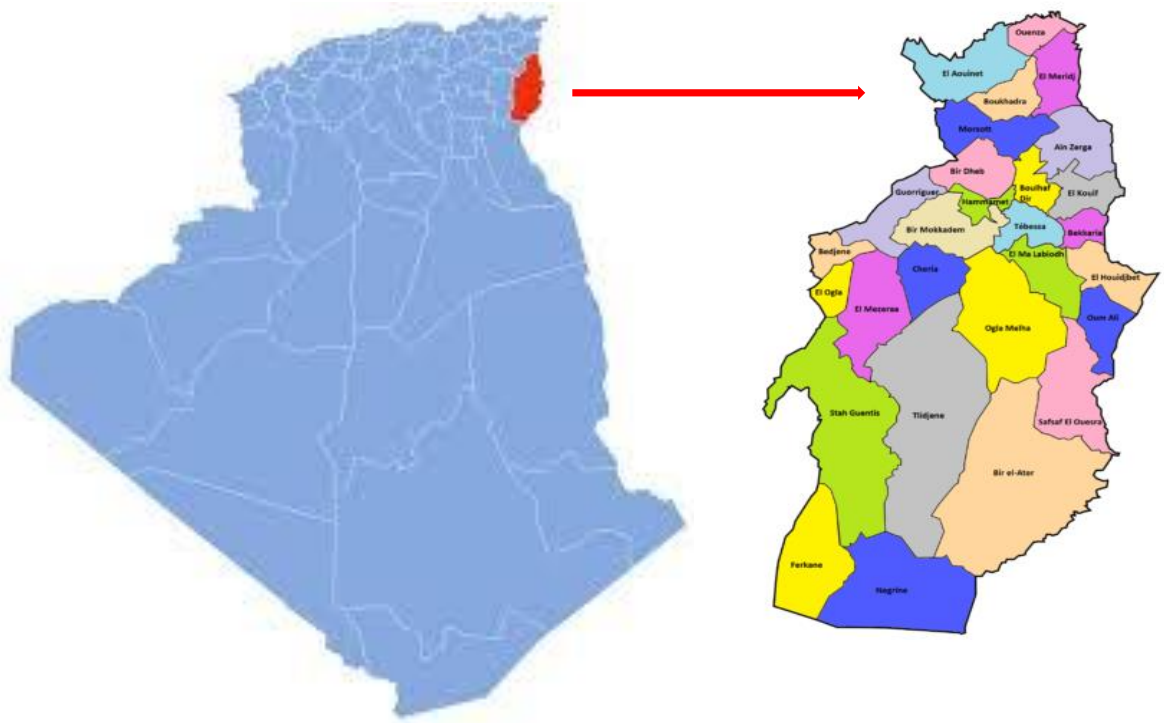


Figure 3. 2 map of wilaya tebessa municipality.

The following diagram illustrates the hierarchical structure adopted in the holonic agricultural planning system, as applied to the case of Tebessa. The system is organized into four

interconnected levels, starting from the national level and progressively descending to the local level, where individual agricultural parcels are managed. This structure provides a clear under standing of information flow and decision-making within the holonic framework.

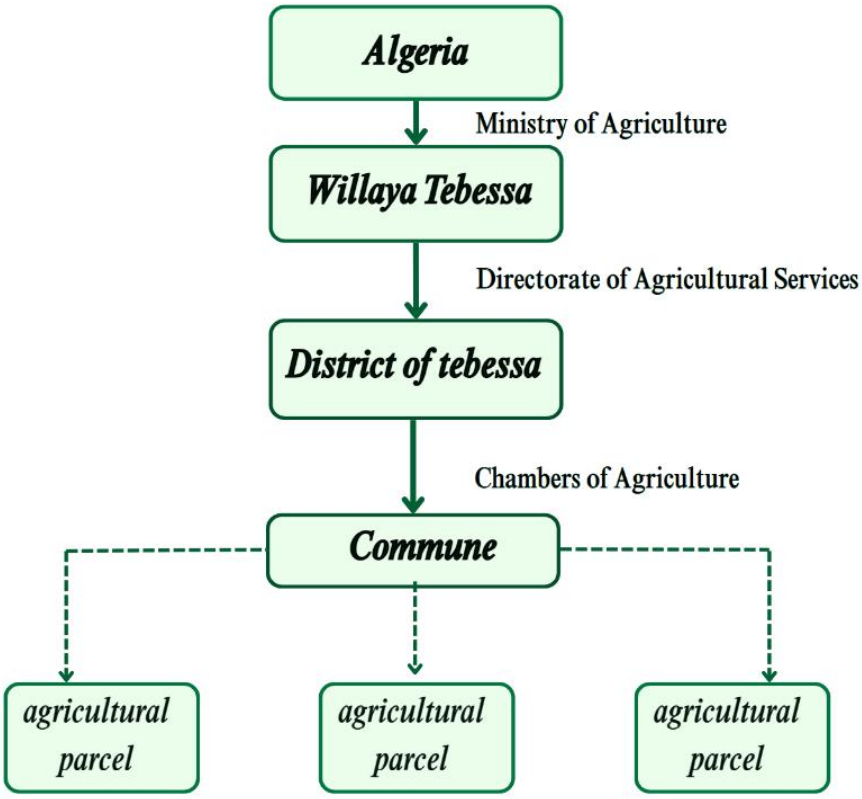


Figure 3. 3 Hierarchical Representation of Agricultural Planning Levels in Tebessa.

4. Agent-Based Modeling of the Holonic System

4.1 Definition of Holons and Their Roles

The holonic approach provides a decentralized and modular framework for managing complex agricultural systems by organizing decision-making entities (holons) and their operational agents across multiple levels. Informed by fieldwork and consultations with the Directorate of Agricultural Services, the following table outlines a structured representation of the proposed system, detailing the roles and interactions of both holons and agents at the local, regional, and national levels, in alignment with the principles of sustainable agricultural planning.

Table 3. 1 Distribution of Holons, Agents, and Their Roles by Planning Level.

Element / Level	Holon	Agents	Responsibilities of Agent	Interactions	Description level
National (Level n+3)	Ministry of Agriculture, Rural Development and Fisheries	○ National Planners ○ strategic decision-makers	✓Set national goals (food security, self-sufficiency) ✓Aggregate data from regions to balance crop distribution. ✓Planning (determining access policy)	• Supervises Regional Authorities. • Negotiates with international bodies for imports/exports.	This level is Responsible for national strategies (security, auto insurance) and the location of resources to pay (engrais, equipment).
Regional (Level n+2)	-Directorate of Agricultural Services for each state (Wilaya), -Banks and financing companies (CRMA, CNMA, BADR)	○ Regional Authorities, ○Agronomists ○financial officers	✓ Prevent overproduction of single crops (e.g., wheat in the Tell Atlas region). ✓ Ensure water resource sustainability (e.g., Sahara irrigation projects). ✓ Align farm decisions with regional soil/climate conditions. ✓Responsible for funding and program monitoring.	• Receives quotas from the National level. • Coordinates with District Cooperatives	This level coordinates agricultural areas, balances crops and resources (water, soil) to avoid overproduction and align local decisions with national objectives.
District Level (Intercommunal) (Level n+1)	-Local Chambers of Agriculture, Municipalities, Cooperatives	○District coordinating committees. ○ Agricultural technicians ○ area experts ○ Representatives of chambers.	✓ Mediate between farms and regional authorities. ✓ Organize shared resources (e.g., machinery rentals). ✓ Promote crop diversity.	• Collects farm data for regional reporting. •Implements pest control programs.	This level Manages local cooperatives, facilitates the sharing of resources (machines, seeds) and oversees crop diversity within a district.

Local (Level n)	-The exploitations (farms). - Land plot (parcel)	○ Exploiter (Farmers)	✓Collaborate with neighboring farms to avoid monoculture. ✓Reporting feedback based on real field conditions. ✓Report local issues.	• Negotiates crop plans with the District Cooperative. • Manages plot-level resources.	Basic unit where farmers optimize crops on their land (choice of plants, irrigation) while collaborating with neighboring farms for sustainability.

➢ Definitions of Key Terms

- **Ministry of Agriculture, Rural Development and Fisheries**: A central government body responsible for national agricultural policies, resource allocation (e.g., fertilizers, equipment), and ensuring alignment with goals like food security and self-sufficiency.
- **National Planners/Strategic Decision-Makers**: High-level officials who set national agricultural strategies, balance regional data, and establish import/export policies.
- **International Bodies**: External organizations (e.g., FAO, WTO) with which the national ministry negotiates trade agreements or resource partnerships.
- **Directorate of Agricultural Services (Wilaya)**: A regional administrative Present in every state of the country body overseeing agricultural activities, enforcing quotas, and managing projects
- **CRMA, CNMA, BADR**: Regional banks/financial institutions (e.g., *CRMA*: Regional Agricultural Credit Mutual; *BADR*: Agricultural and Rural Development Bank) responsible for funding farms and monitoring regional programs.
- **Local Chambers of Agriculture**: District-level organizations that mediate between farmers and regional authorities, providing technical support and resource coordination.
- **Exploitations (Farms)**: Individual agricultural units where farmers cultivate crops, manage irrigation, and collaborate with neighbors to avoid monoculture.
- **Land plot:** Plot: refers to a division into plots, a plot plan of a farm or a municipality,

4.2 Hierarchical Structure of the Proposed Holonic System

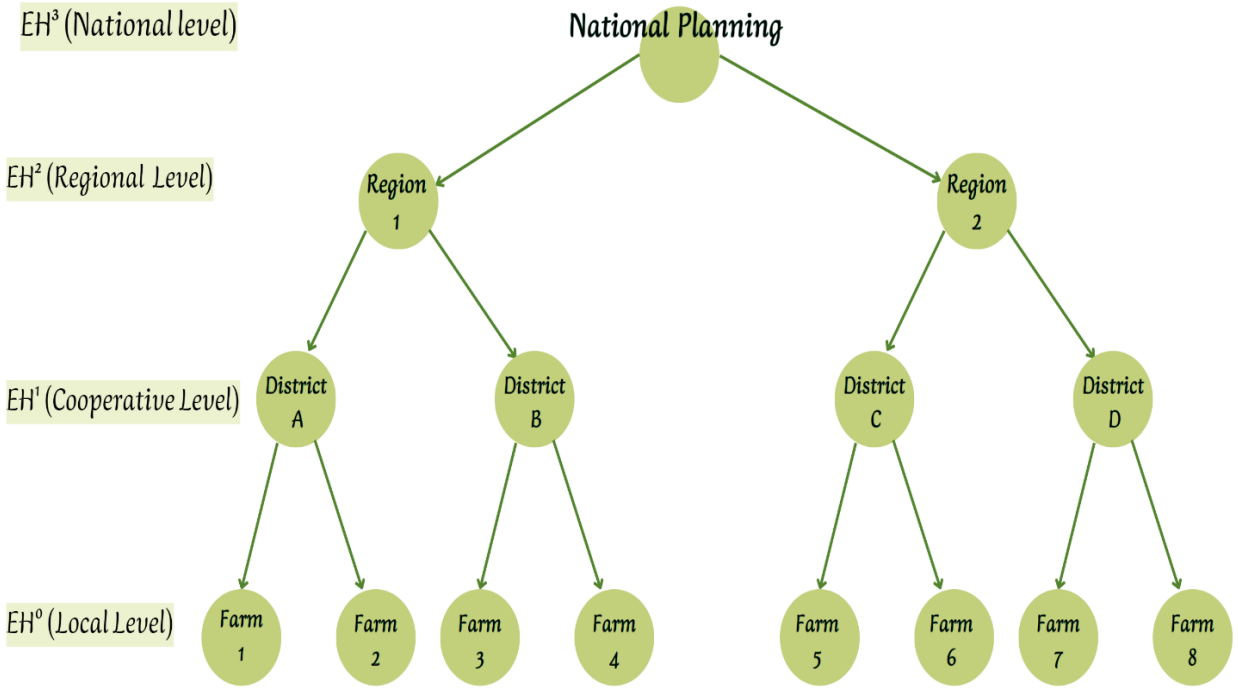


Figure 3. 4 Hierarchical of Multi-Level Holonic Structure**.**

This section presents the general structure of the holonic system designed for sustainable agricultural planning in Algeria. This system consists of three interconnected levels, as shown in the image below **Figure 3.5**. Each level includes a group of agents distributed within relatively independent holons, each responsible for performing specific tasks related to agricultural data collection, analysis, decision-making, and planning improvement.

This architecture aims to provide a flexible, scalable, and collaborative framework that allows each holon to operate independently to meet local needs, while maintaining its ability to interact and coordinate with other holons across different levels. This decentralized hierarchical organization reflects the philosophy of the holonic system, ensuring a balanced flow of information and guidance from the bottom up and back.

Coordination and communication between holons is based on a hybrid model that combines autonomy with structured collaboration, allowing the system to dynamically adapt to changes in agricultural conditions, regional priorities, and national strategies. Through this design, the system seeks to achieve optimal solutions that take into account sustainability goals, cost-effectiveness, and resource constraints, with the aim of supporting smarter and more flexible agricultural planning in Algeria.

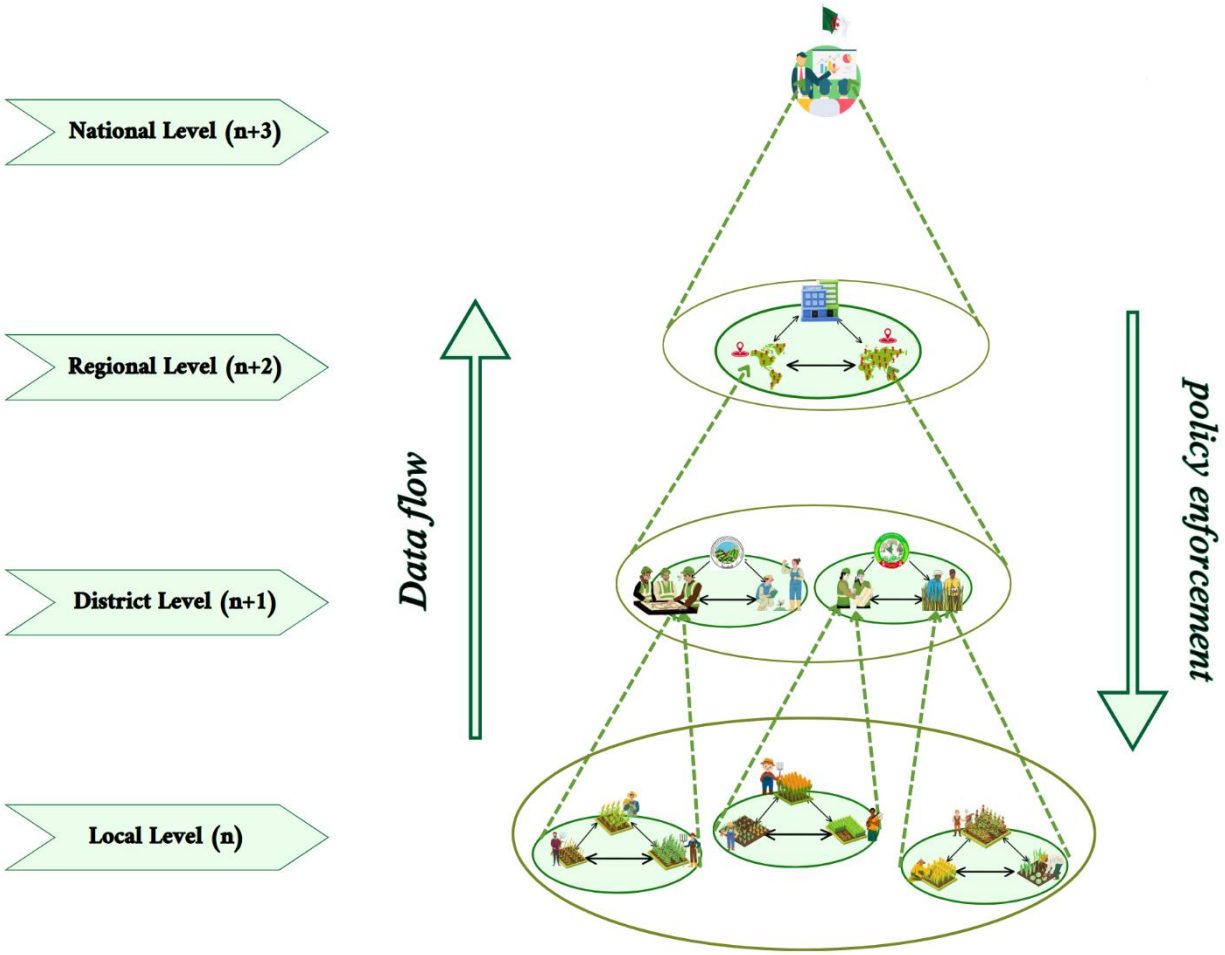


Figure 3. 5 Architecture of the proposed holonic system
For sustainable agriculture planning in Algeria.

5. AUML-Based System Modeling

The design methodology adopted in this work is based on modeling the holonic agricultural planning system using a multi-agent approach, aiming to move from theoretical concepts to a structured and practical representation. We employ AUML (Agent Unified Modeling Language) as an effective tool to describe the system's components and define the interactions between agents

across the different levels: local, district, regional, and national. This methodology allows for an accurate representation of agent roles, assigned tasks, and communication patterns, reflecting the decentralized nature of the holonic system. Moreover, this approach provides a comprehensive framework that will support the simulation phase and the implementation of optimization algorithms, ensuring the development of efficient and sustainable solutions aligned with the needs of agricultural planning in Algeria.

5.1 Use Case Diagram « Holonic MAS for Sustainable Agricultural Planning in Algeria »

The following diagram presents the Use Case representation of the Holonic Multi-Agent System for Sustainable Agricultural Planning in Algeria. The diagram highlights the different interactions between agents operating at the national, regional, and local levels. It clarifies the primary roles and responsibilities of each agent within the system, including both individual and collaborative functions.

The representation also illustrates shared use cases across levels and includes the use of “include” and “extend” relationships to reflect complementary and optional behaviors. The modeling follows the AUML (Agent Unified Modeling Language) approach, which provides a precise and expressive way to capture agent interactions. This contributes to a better understanding of the system’s architecture and lays the foundation for a comprehensive simulation model.

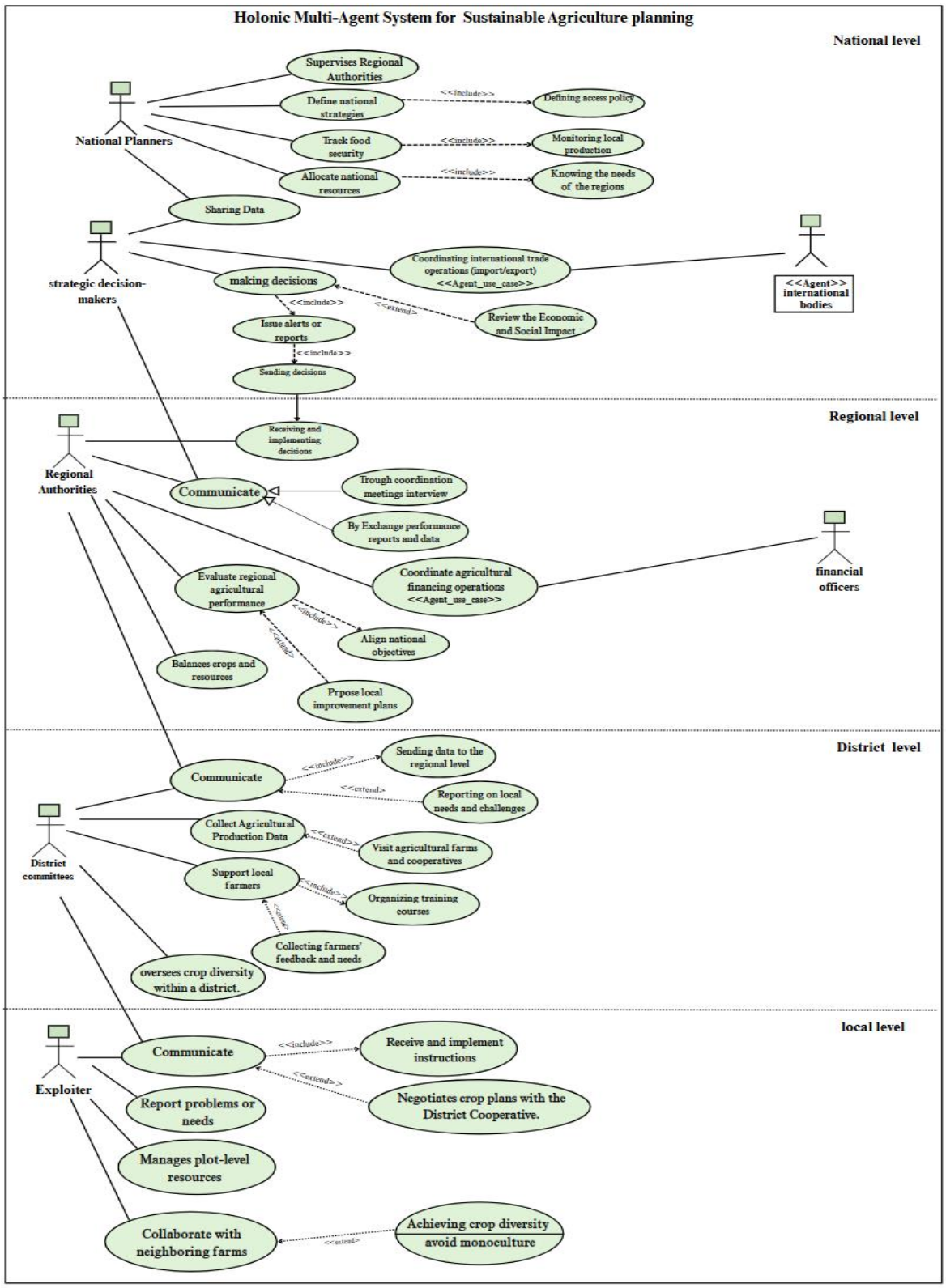


Figure 3. 6 Global Use Case Diagram of the Holonic Agricultural Optimization System.

5.2 AUML Sequences Diagrams

Sequence diagrams are used to describe the dynamic behavior of the system by illustrating the chronological flow of messages exchanged between agents involved in a particular use case. They provide a clear visualization of how agents interact, and coordinate tasks at various hierarchical levels. In this section, we focus on modeling a selection of the most significant and representative use cases from each level of the holonic system namely, the local, district, regional, and national levels. This choice is made intentionally to highlight key functional scenarios that best demonstrate the collaborative nature of our system. Through these diagrams, we aim to offer a deeper understanding of the operational logic, communication structures, and decision flows that characterize each level. Each sequence diagram is presented separately, organized by level, and reflects realistic agent behavior within the agricultural planning process.

➢ Sequence Diagram of the Use case "Making Decision"

This sequence diagram provides a detailed representation of the interactions between agents involved in the "Making Decision" use case at the national level. It captures the communication flow initiated by the national decision-making agent, who receives synthesized reports and key performance indicators from regional-level agents. Upon receiving this information, the national agent proceeds to analyze and compare the aggregated data with predefined national agricultural objectives and sustainability criteria. Based on this evaluation, the agent formulates strategic decisions and forwards them to the relevant authorities or systems for implementation and monitoring. This diagram highlights the top-down coordination approach and the critical role of the national level in aligning insights with overarching agricultural planning goals within the holonic system. It also reflects the holistic nature of the system, where decision-making is informed by real-time data collected from lower levels in a structured and collaborative manner.

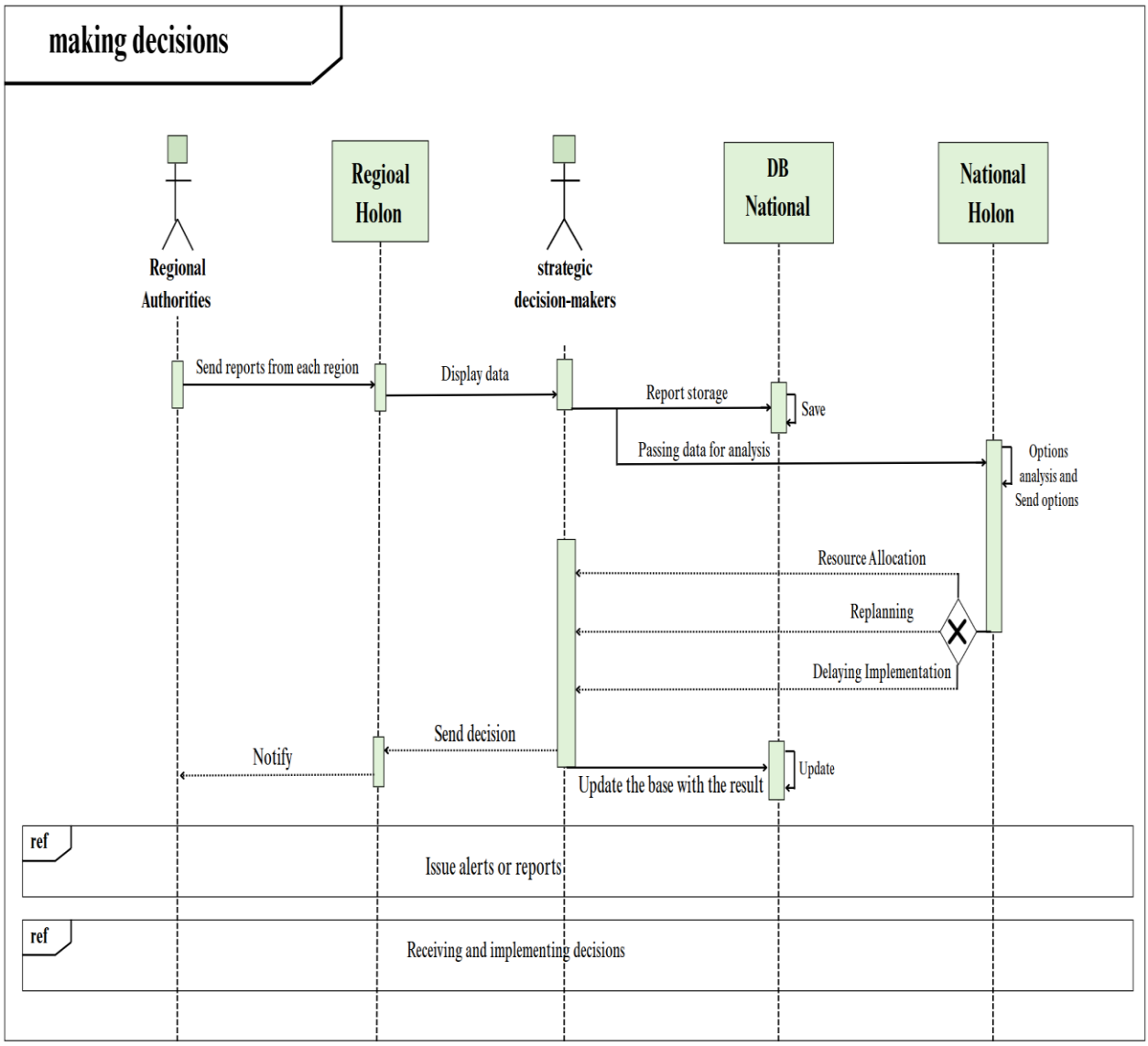


Figure 3. 7 Sequence Diagram of the "Making Decision" Use Case at the National Level.

➢ Sequence Diagram of the Use Case "Evaluate regional agricultural performance

This sequence diagram models the interactions involved in the "Evaluate Regional Agricultural Performance" use case, situated at the regional level of the holonic system. In this scenario, the regional evaluation agent plays a central role in gathering detailed performance reports from district-level agents. These reports typically include data related to crop yields, resource utilization, irrigation efficiency, and sustainability indicators. The regional agent processes and analyzes the information to identify patterns, detect inefficiencies, and assess overall regional

productivity in alignment with predefined objectives. This evaluation process is critical for providing feedback to both national decision-makers and local stakeholders, ensuring that strategies can be adjusted or optimized accordingly. The sequence of interactions reflects how the holonic model supports decentralized evaluation while maintaining a coordinated and structured flow of information upward and downward through the system hierarchy.

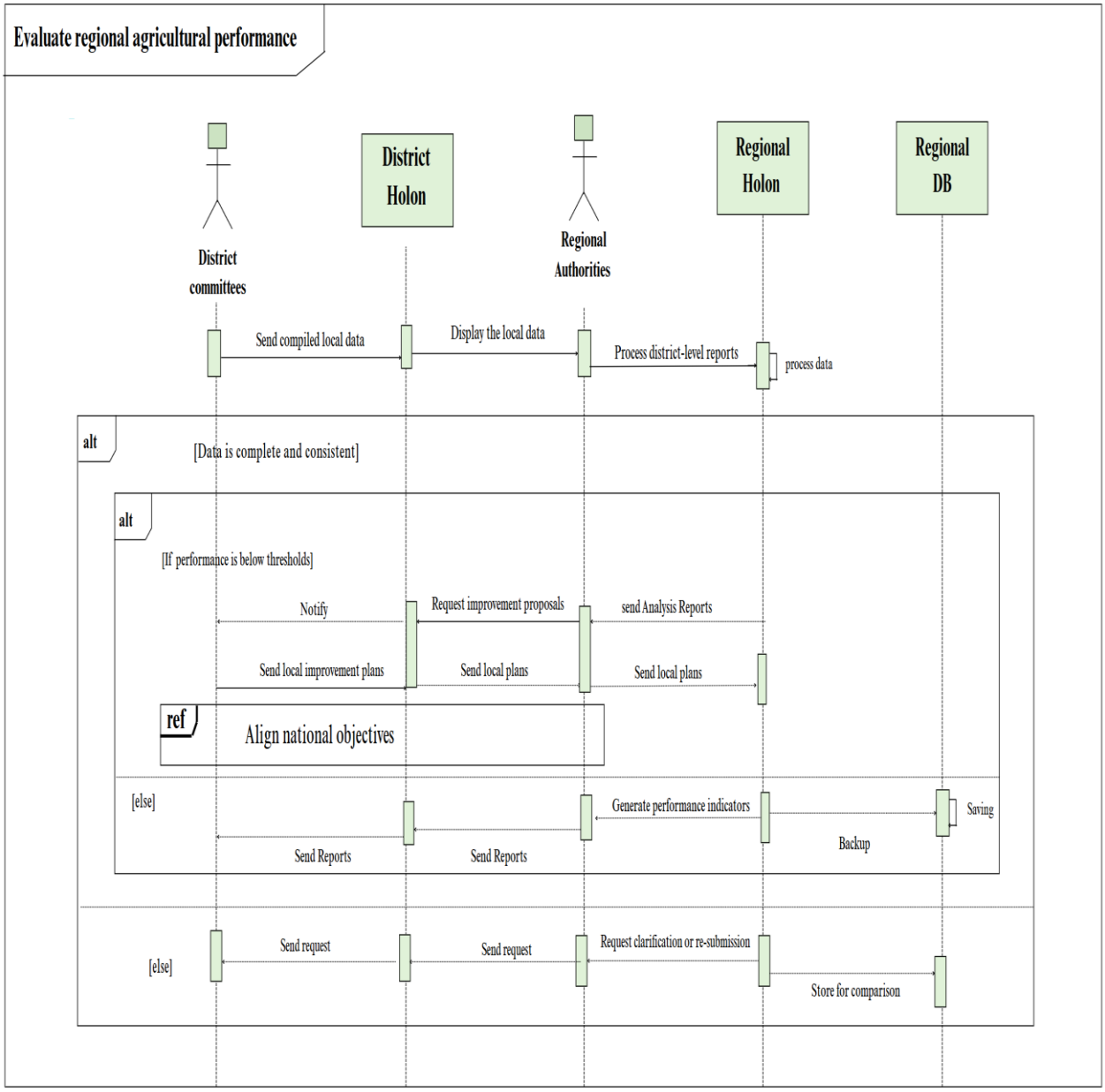


Figure 3. 8 Sequence Diagram of the "Evaluate Regional Agricultural Performance" use case at the regional level.

➢ Sequence Diagram of the Use Case "Collect Agriculture Production Data"

This sequence diagram illustrates the execution of the “Collect Agriculture Production Data” use case at the district level. In this process, the district agent interacts with multiple local agents such as farm representatives to gather raw data on agricultural production. This includes information on harvested quantities, crop types, input usage, and environmental conditions observed during the production period. The district agent consolidates this data, checks for consistency and completeness, and formats it into structured reports for regional analysis. Ensuring that localized data is accurately captured, validated, and made available for regional performance evaluation and national planning.

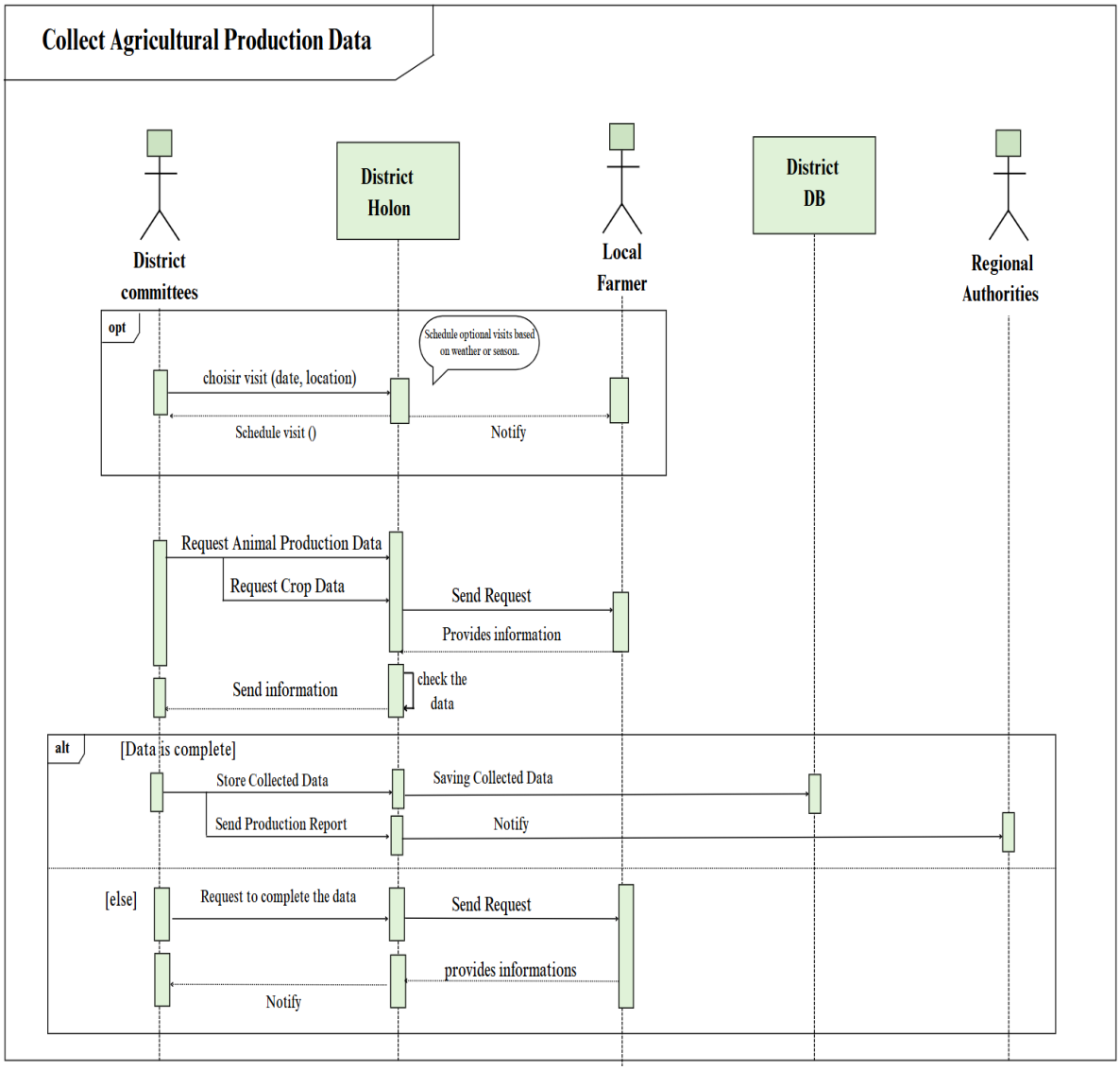


Figure 3. 9 Sequence Diagram of the "Collect Agriculture Production Data" use case at the district level.

➢ Sequence Diagram of the Use Case "Manages plot-level resources"

This sequence diagram focuses on the farmer's role in managing plot-level agricultural resources. Acting as the local agent within the holonic system, the farmer monitors resource availability such as water, fertilizers, and equipment using both field observations and local data inputs. Based on these insights, the farmer makes real-time decisions to request allocate resources from the district committes efficiently and ensure sustainable, optimized plot performance.

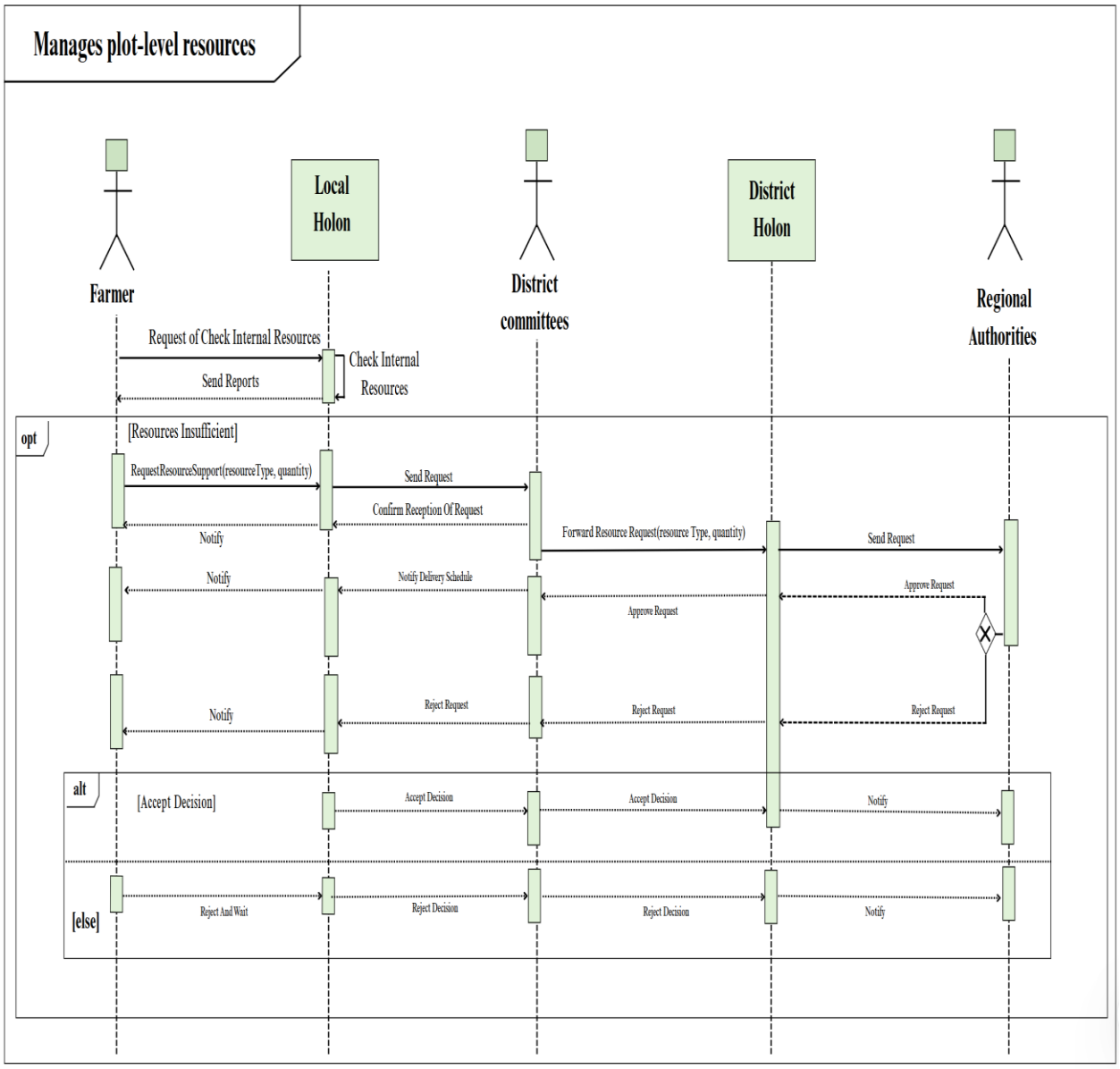


Figure 3. 10 Sequence Diagram of the "Manages plot level resources" use case at the local level.

6. Agricultural Dataset Construction

6.1 Collection Data and Preprocessing

The creation of our dataset followed these structured steps:

1. Identifying Data Sources

We identified relevant institutions likely to provide useful information, such as the DSA of Tébessa, local agricultural subdivisions, and official agricultural planning documents

2. Field Visit and Data Retrieval

We conducted a visit to the DSA, where we accessed official documents (in PDF, Excel, and paper formats) containing information on:

- ✓ The number and types of agricultural holdings (small, medium, large),
- ✓ Main crops (cereals, legumes, tree crops, etc.),
- ✓ Cultivated and irrigated areas,
- ✓ Access to resources (water, equipment, funding),
- ✓ Support programs such as CRAMA loans and government subsidies.

➢ **Problem Encountered in the Agricultural Data Collection Phase**

During the initial stages of this project, we conducted a data collection phase in collaboration with the agricultural services of the wilaya of Tebessa. However, we were faced with a major challenge: the **lack of complete and structured data** necessary for accurate modeling of our holonic agricultural planning system. Despite our efforts to gather available information, many essential data points were missing or fragmented, making it difficult to use them directly in our simulations and decision-making models.

6.2 Protocol 1: Regional Crop Catalogue Construction

The first protocol involved building a regional catalogue that aggregates general characteristics of each agricultural area, such as climate, soil type, available resources, and irrigation. This catalogue serves as a contextual reference, allowing us to interpret and validate the specific parcel-level data in a broader agricultural framework.

In order to support data-driven decision-making and ensure an effective simulation process, we structured our **agricultural crop catalogue** with a set of critical attributes that reflect both technical and economic aspects of regional crops. Below is a description of each selected feature:

- **Region Name**: The administrative region or wilaya where the crop is cultivated.
- **Crop Name**: The specific name of the crop (e.g., wheat, barley, olives).
- **Crop Type**: The general classification of the crop (e.g., cereal, vegetable, and fruit).
- **Yield (T/ha)**: The average production output per hectare, expressed in tons.
- **Irrigation Needs (mm/year)**: The annual water requirement for optimal crop growth, measured in millimeters.
- **Temperature Range (°C)**: The ideal temperature interval in which the crop can thrive.
- **Soil Type Preference**: The soil characteristics that best suit the crop (e.g., clay, sandy, loamy).
- **Water Requirement**: A qualitative or quantitative assessment of the crop's water demand (e.g., high, moderate).
- **Mean Cost per ha (DA)**: The average cost of cultivating one hectare, including inputs such as seeds, fertilizers, and labor, in Algerian Dinars.
- **Selling Price per Ton (DA)**: The average market price per ton of the crop, in Algerian Dinars.
- **Soil Impact Score**: A score that reflects the crop's impact on soil health, fertility, and sustainability (lower is better).
- **Importance Value (0–100)**: A relative score indicating the strategic or economic importance of the crop at the national level.
- **National Need (0–100)**: A score that reflects how much the country needs this crop based on food security, imports, and demand.
- **Profit per ha (DA)**: The net economic gain from cultivating one hectare of this crop, calculated as revenue minus cost.
- **Annual Production (2021–2024) (tons)**: The recorded or estimated yearly production in tons over a four-year period.
- **State Subvention (DA/ha)**: The financial support provided by the government per hectare for this crop.

Table 3. 2 Regional Data Catalogue.

Region Name	Crop Name	Crop Type	Yield (T/ha)	Irrigation Needs (mm/y)	Temperature Range (°C)	Soil Type Preference	Water Requirement	Mean Cost per Ha (DA)	Selling Price per Ton (DA)	Soil Impact Score	Importance Value (0-100)	National Need (0-100)	*Profit per Ha (DA)*	*Annual* Production (2021-2024) (tons)	*State Subvention (DA/ha)*
Ferkane	Wheat	Cereal	2.0	400	10-25	Loamy	Medium	112,000	35,000	2	57.12	90	42,000	2,168,386	50
Negrine	Barley	Cereal	1.5	400	10-25	Loamy	Medium	98,000	28,000	2	32.15	70	56,000	555,364	50
Bir El Ater	Wheat	Cereal	2.3	420	11–25	Sandy-Loamy	Medium	115,000	34,000	2	58	80	44,000	650,000	50
Hammamet	Oats	Cereal	1.0	400	10-25	Loamy	Medium	84,000	30,800	2	13.64	30	53,200	40,000	50
Gourigueur	Chickpeas	Legume	1.5	300	15-30	Well-drained	Low to Medium	126,000	84,000	1	28.32	60	50,000	0	0
Birmokadem	Lentils	Legume	1.2	250	15-25	Well-drained	Low	112,000	98,000	1	27.63	55	5,600	30,000	0
Tebessa	Tomatoes	Vegetable	30.0	600	20-30	Loamy	High	420,000	56,000	4	32.19	75	1,260,000	1,641,636	0
El houidjebet	Onions	Vegetable	25.0	400	15-25	Loamy	Medium to High	350,000	42,000	4	29.15	65	700,000	1,710,595	0
El Malabiod	Potatoes	Vegetable	15.0	600	10-25	Loamy	Medium	210,000	35,000	4	46.91	85	315,000	4,360,880	0
Oum Ali	Garlic	Vegetable	6.5	490	14–26	Loamy	Medium	165,000	46,000	3	37	70	135,000	150,000	0
Ain Zerga	Carrots	Vegetable	20.0	500	15-25	Loamy	Medium	150,000	30,000	4	30.00	60	450,000	414,322	0
Boukhadra	Chillies	Vegetable	15.0	500	20-30	Well-drained	Medium	180,000	40,000	3	25.00	50	420,000	351,832	0
El Ma Labiod	Potatoes	Vegetable	16.0	610	10–25	Loamy	High	220,000	36,000	4	50	85	330,000	4,600,000	0
Bekkaria	Watermelons	Fruit	25.0	600	20-35	Sandy	High	200,000	20,000	3	40.00	50	300,000	2,075,874	0
Stah Guentis	Tobacco	Industrial	2.0	400	15-30	Loamy	Medium	250,000	20,000	2	5.00	10	150,000	10,000	0
Morsott	Maize	Cereal	3.0	400	15-30	Loamy	Medium	140,000	40,000	2	35.00	65	900,000	300,000	0

6.3 Protocol 2: Parcel Data Table Construction

The second protocol consists of constructing a **detailed dataset** that represents **individual agricultural parcels** across the studied regions. Each row in the table corresponds to a specific parcel and includes key agronomic attributes that define its current status and potential.

To support localized analysis and ensure scalability across administrative levels, we built a detailed dataset of agricultural parcels. This table organizes parcel-level data while linking it to

broader territorial units. Each column serves a specific role in representing the spatial, agronomic, and operational characteristics of the agricultural system.

- **Region**: The broader administrative division (e.g., Wilaya) in which the district and parcels are located.
- **District**: A mid-level administrative unit (e.g., Daïra), grouping several local areas.
- **Local Area**: The specific commune or locality where the parcel exists.
- **Parcel**: A unique identifier for each agricultural plot or unit of cultivation.
- **Area (ha):** The surface area of the parcel, measured in hectares.
- **Main Crop**: The primary crop currently cultivated on the parcel.
- **Alternative Crop**: A potential or secondary crop that can be cultivated in rotation or substitution.
- **Soil Type**: The soil classification of the parcel, influencing its suitability for different crops.
- **Total Local Area (ha)**: The total cultivable land within the corresponding local area (commune), used for reference and aggregation.
- **Availability of Irrigation**: Indicates whether the parcel has access to irrigation systems (e.g., yes/no).
- **Average Yield (quintals/ha)**: The average production output per hectare for the main crop, expressed in quintals.
- **Exploitation Rate (%)**: The percentage of the parcel's total area that is actively cultivated or utilized.

Table. 3. 3 Agricultural Parcel Dataset.

Region	District	Local Area	Parcel	Area (ha)	Main Crop	Alternative Crop	Soil Type	Total Local Area (ha)	Availability of Irrigation	Average Yield (quintals/ha)	Exploitation rate (%)
Tebessa	South	Negrine	Parcel 1	45	Wheat	Barley	Clay	25000	Partial	18	82%
Tebessa	South	Negrine	Parcel 2	55	Olive	Vegetables	Sandy	25000	No	12	65%
Tebessa	South	Negrine	Parcel 3	130	Palm	Olive	Sandy	25000	Yes	25	88%
Tebessa	South	Negrine	Parcel 4	90	Barley	Wheat	Clay	25000	No	15	40%
Tebessa	South	Negrine	Parcel 5	150	Olive	Vegetables	Rocky	25000	Partial	14	75%
Tebessa	South	Negrine	Parcel 6	600	Wheat	Barley	Clay	25000	Yes	20	90%
Tebessa	South	Negrine	Parcel 7	850	Vegetables	Palm	Mixed	25000	Yes	30	78%
Tebessa	South	Negrine	Parcel 8	1.200	Palm	Olive	Sandy	25000	Yes	27	85%
Tebessa	South	Negrine	Parcel 9	1.500	Barley	Wheat	Clay	25000	No	16	70%
Tebessa	South	Negrine	Parcel 10	20.480	Wheat	Barley	Sandy	25000	Partial	19	55%
Tebessa	Southeast	Bir El-Ater	Parcel 1	25	Wheat	Barley	Clay	5000	Yes	22	85%
Tebessa	Southeast	Bir El-Ater	Parcel 2	45	Olives	Vegetables	Sandy	5000	No	13	60%
Tebessa	Southeast	Bir El-Ater	Parcel 3	60	Barley	Legumes	Loamy	5000	Partial	14	72%
Tebessa	Southeast	Bir El-Ater	Parcel 4	80	Vegetables	Legumes	Sandy	5000	Yes	18	95%
Tebessa	Southeast	Bir El-Ater	Parcel 5	100	Wheat	Sunflowers	Clay	5000	Yes	20	68%
Tebessa	Southeast	Bir El-Ater	Parcel 6	150	Olives	Almonds	Rocky	5000	Partial	12	50%
Tebessa	Southeast	Bir El-Ater	Parcel 7	200	Legumes	Wheat	Loamy	5000	No	16	80%
Tebessa	Southeast	Bir El-Ater	Parcel 8	300	Almonds	Olives	Sandy	5000	Yes	19	88%
Tebessa	Southeast	Bir El-Ater	Parcel 9	1,000	Wheat	Barley	Clay	5000	Yes	24	63%
Tebessa	Southeast	Bir El-Ater	Parcel 10	3,040	Barley	Fallow	Sandy	5000	Partial	10	45%
Tebessa	Central	Bir Mokadem	Parcel 1	40	Wheat	Barley	Clay	6000	Yes	23	78%
Tebessa	Central	Bir Mokadem	Parcel 2	45	Olives	Almonds	Sandy	6000	No	11	65%
Tebessa	Central	Bir Mokadem	Parcel 3	60	Vegetables	Legumes	Mixed	6000	Yes	29	82%
Tebessa	Central	Bir Mokadem	Parcel 4	80	Barley	Wheat	Rocky	6000	No	15	55%
Tebessa	Central	Bir Mokadem	Parcel 5	100	Almonds	Olives	Sandy	6000	Partial	14	70%
Tebessa	Central	Bir Mokadem	Parcel 6	120	Wheat	Barley	Clay	6000	Yes	20	90%
Tebessa	Central	Bir Mokadem	Parcel 7	140	Vegetables	Legumes	Mixed	6000	Yes	30	85%
Tebessa	Central	Bir Mokadem	Parcel 8	500	Olives	Almonds	Sandy	6000	Partial	13	60%
Tebessa	Central	Bir Mokadem	Parcel 9	800	Barley	Fallow	Clay	6000	No	16	75%
Tebessa	Central	Bir Mokadem	Parcel 10	3,115	Wheat	Barley	Clay	6000	Yes	22	48%
Tebessa	Central	Maa Labied	Parcel 1	45	Potatoes	Legumes	Loamy	4000	Full	310	82%
Tebessa	Central	Maa Labied	Parcel 2	75	Wheat	Barley	Clay	4000	Partial	24	75%
Tebessa	Central	Maa Labied	Parcel 3	120	Vegetables	Legumes	Sandy	4000	Full	28	85%
Tebessa	Central	Maa Labied	Parcel 4	150	Barley	Fallow	Rocky	4000	None	12	40%
Tebessa	Central	Maa Labied	Parcel 5	200	Potatoes	Fallow	Loamy	4000	Full	290	80%
Tebessa	Central	Maa Labied	Parcel 6	300	Almonds	Olives	Sandy	4000	Partial	14	65%
Tebessa	Central	Maa Labied	Parcel 7	500	Wheat	Barley	Clay	4000	Partial	22	70%
Tebessa	Central	Maa Labied	Parcel 8	600	Potatoes	Legumes	Loamy	4000	Full	330	88%
Tebessa	Central	Maa Labied	Parcel 9	950	Legumes	Vegetables	Mixed	4000	Partial	18	78%
Tebessa	Central	Maa Labied	Parcel 10	1,060	Fallow	Barley	Rocky	4000	None	-	15%
Tebessa	Southwest	Oum Ali	Parcel 1	45	Barley	Legumes	Clay	6500	No	16	45%
Tebessa	Southwest	Oum Ali	Parcel 2	75	Wheat	Forage	Sandy	6500	Partial	18	65%
Tebessa	Southwest	Oum Ali	Parcel 3	120	Legumes	Chickpeas	Mixed	6500	Yes	24	85%
Tebessa	Southwest	Oum Ali	Parcel 4	150	Forage	Barley	Rocky	6500	No	12	40%
Tebessa	Southwest	Oum Ali	Parcel 5	200	Chickpeas	Legumes	Sandy	6500	Partial	20	70%
Tebessa	Southwest	Oum Ali	Parcel 6	300	Barley	Fallow	Clay	6500	Partial	14	60%
Tebessa	Southwest	Oum Ali	Parcel 7	500	Wheat	Forage	Loamy	6500	Yes	22	88%
Tebessa	Southwest	Oum Ali	Parcel 8	800	Legumes	Chickpeas	Mixed	6500	Yes	26	90%
Tebessa	Southwest	Oum Ali	Parcel 9	1,200	Forage	Barley	Rocky	6500	No	10	30%
Tebessa	Southwest	Oum Ali	Parcel 10	3,110	Wheat	Fallow	Sandy	6500	Partial	17	55%
Tebessa	Northeast	Boukhadra	Parcel 1	50	Potatoes	Carrots	Clay	3600	Yes	280	90%
Tebessa	Northeast	Boukhadra	Parcel 2	80	Wheat	Lentils	Mixed	3600	Partial	22	70%
Tebessa	Northeast	Boukhadra	Parcel 3	120	Tomatoes	Peppers	Sandy	3600	Yes	260	85%
Tebessa	Northeast	Boukhadra	Parcel 4	150	Fruit Trees	Olives	Rocky	3600	No	16	35%
Tebessa	Northeast	Boukhadra	Parcel 5	200	Carrots	Potatoes	Clay	3600	Partial	240	75%
Tebessa	Northeast	Boukhadra	Parcel 6	300	Wheat	Fallow	Sandy	3600	No	18	50%
Tebessa	Northeast	Boukhadra	Parcel 7	400	Potatoes	Legumes	Loamy	3600	Yes	300	95%
Tebessa	Northeast	Boukhadra	Parcel 8	600	Legumes	Vegetables	Mixed	3600	Partial	20	65%
Tebessa	Northeast	Boukhadra	Parcel 9	800	Fallow	Barley	Rocky	3600	No	-	15%

7. Summary of Thesis Contributions of This Chapter

A structured holonic architecture was established, introducing four hierarchical levels local, district, regional, and national to support decentralized agricultural planning. Each level was modeled with dedicated agents whose roles, interactions, and responsibilities were defined using both UML and AUML formalisms. The methodology integrated real-world constraints such as water, land, and crop priorities, aligning technical system design with national agricultural objectives.

Communication protocols and agent behaviors were formally specified, ensuring coherent coordination across levels. The chapter also proposed a scalable and modular design, capable of adapting to diverse regional needs. These contributions lay the groundwork for implementing a multi-agent system focused on sustainable, intelligent, and context-aware agricultural decision-making in Algeria.

8. Conclusion

This chapter established the methodological foundation for the development of our holonic optimization system in the context of sustainable agriculture. It detailed the modeling of agent interactions and the hierarchical structure of planning across local, district, regional, and national levels. In response to data limitations, we introduced two complementary protocols: the construction of a regional data catalogue and the creation of detailed parcel-level datasets. These strategies combined real and simulated data to ensure consistency, completeness, and contextual accuracy. Collectively, they enable reliable simulation, effective resource planning, and informed, multi-level decision-making.

Chapter 4:

Experimentation & Evaluation



1. Introduction

This chapter presents the experimental evaluation of the holonic optimization system developed for sustainable agricultural planning. Building upon the methodological framework and structured datasets, we move toward simulating real agricultural scenarios using parcels from the Tébessa region. Each parcel is treated as a decentralized decision unit with its own resources and constraints. We first define the process for generating simplified project tables from the complete dataset. Simulations are then carried out to evaluate execution time and solution quality. As the number of projects increases, the system's scalability is tested, revealing challenges in generating feasible solutions. To overcome these, a holonic strategy is applied by producing local sub-solutions and aggregating them. This approach enhances performance and supports robust, adaptive agricultural planning.

2. Focus on Agricultural Parcels in Tebessa

As a case study, of Tebessa an agriculturally significant region in eastern Algeria where our holonic system has been structured and deployed. The optimization focuses on the lowest hierarchical level, namely the agricultural parcels.

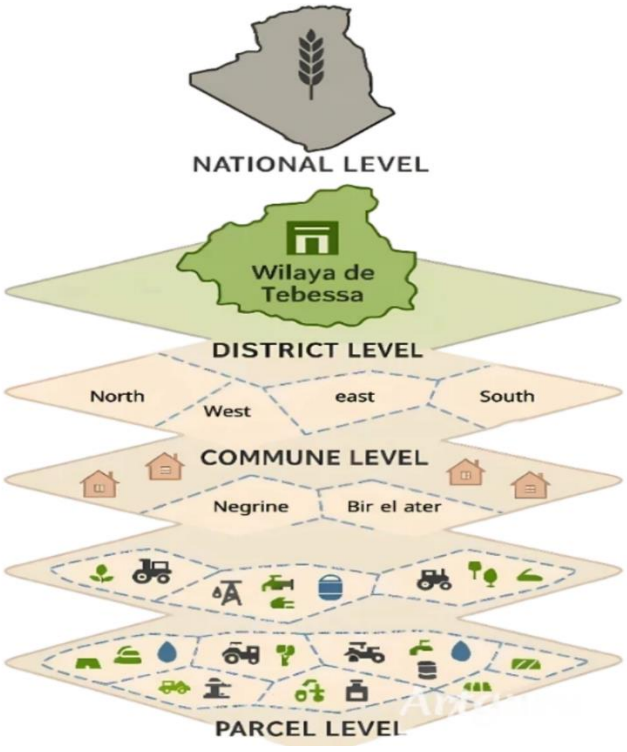


Figure 4. 1 Representation of hierarchical level in Tebessa.

Focusing on the local level where agricultural parcels serve as the atomic units of decision-making. Each parcel characterized by unique features such as available water resources, soil type, crop potential, and surface area. These variations play a critical role in how decisions are modeled, simulated, and optimized. The following image illustrates a real view of agricultural parcels in Tebessa, serving as the spatial foundation for our simulations.

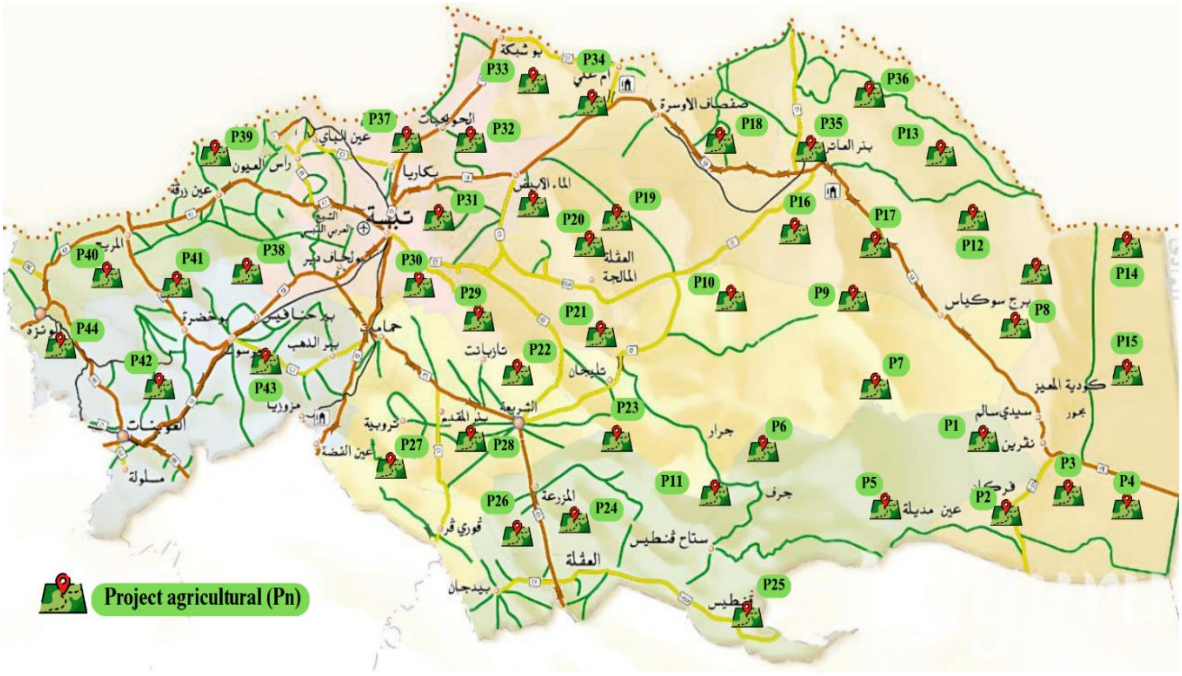


Figure 4. 2 a real view of agricultural parcels in Tebessa.

3. Data Extraction and Transformation for Simulation

In order to move to the experimental phase, we extract a representative subset from the complete agricultural catalog. This step consists of generating agricultural project tables containing the essential information for the evaluation. Will serve as the basis for performance tests of the optimization algorithms.

The transformation process includes filtering relevant attributes, standardizing values, and adapting the structure of the original data to fit the input requirements of the optimization algorithms. This manual and logical construction step highlights the importance of preparing a coherent and realistic testing dataset. The resulting table reflect practical agricultural scenarios

derived from real-world conditions in the Wilaya of Tebessa and will serve as the basis for performance tests of the optimization algorithms.

Table 4. 1 Agricultural project data.

Project	Area (ha)	Seeds Qty (unit)	Cost (DA)	Profit (DA)	Objective (ha)
P1	73	2336	1,646,077	2,166,175	60
P2	308	8932	6,124,272	6,472,236	263
P3	111	3219	2,374,401	2,778,991	107
P4	23	598	508,875	1,065,141	18
P5	134	4690	2,651,592	3,187,522	114
P6	114	2964	2,315,682	2,764,672	104
P7	83	2822	1,873,808	2,217,606	78
P8	42	1470	912,366	1,277,322	30
P9	144	3600	3,500,352	4,098,992	93
P10	282	8742	5,530,866	5,871,623	276
P11	112	3696	2,576,560	3,085,905	87
P12	234	7254	4,934,358	5,477,277	183
P13	62	1860	1,448,258	1,909,172	47
P14	95	2565	1,883,850	2,398,349	64
P15	150	4500	3,483,150	3,957,903	117
P16	108	3024	2,688,768	3,108,138	78
P17	41	1025	805,486	1,245,733	25
P18	386	9650	7,788,322	8,339,535	238
P19	250	7250	4,570,250	4,993,427	174
P20	207	6417	3,851,235	4,386,878	150

4. Experimental Setup and Tested Algorithms

This section presents the methodology followed to conduct the experimental evaluation of the proposed holonic optimization system. The goal of the experimentation is to assess both the efficiency and the effectiveness of the system in generating sustainable agricultural plans. The representative subset of the constructed dataset was used to simulate realistic planning scenarios. The evaluation process involved running multiple tests under different configurations and analyzing the results using defined performance metrics.

4.1 Simulation Environment

The simulation environment was built using "Python" to model realistic agricultural planning scenarios within the holonic system. A selected subset of real data from the Tebessa region was used to create structured test tables representing parcel characteristics. The environment supports multi-level simulation (local, district, regional) and allows the integration of optimization

algorithms. It ensures consistent, configurable, and repeatable testing conditions for later performance evaluation.

4.2 Selection Algorithms

To assess the performance of optimization algorithms applied to agricultural land-use planning, we define a set of quantitative metrics that evaluate solutions across economic, ecological, and policy-aligned dimensions. These metrics enable fair comparison between different methods such as Linear Programming (LP), Greedy Heuristic, Genetic Algorithm (GA), Simulated Annealing (SA), Weighted Sum Method (WSM), and our proposed algorithm BKPACS.

Among these, Linear Programming and Greedy Heuristic were analyzed at a theoretical level due to their simplicity and historical use in agricultural optimization. However, given the multi-objective nature and resource-constrained complexity of our problem, they were deemed unsuitable for our simulation context.

As such, three algorithms were selected for full experimental evaluation:

- **Genetic Algorithm:** is a widely adopted metaheuristic known for its flexibility and adaptability across a broad range of optimization problems. It serves as a solid baseline for comparison, as a flexible metaheuristic baseline.
- **Weighted Sum Method:** is one of the simplest and most interpretable multi-criteria aggregation methods, which makes it a useful benchmark for understanding solution quality in a straightforward context.
- **BKPACS:** the proposed hybrid algorithm in this work, combines knapsack constraints and ant colony intelligence to address scalability, resource allocation, and optimization in complex environments like agriculture.

The pseudocode for each of the implemented algorithms is presented in the annexes for clarity and reproducibility. The pseudocode for Genetic Algorithm is available in **Annex 1**, for Weighted Sum Method in **Annex 2**, and for the proposed BKPACS in **Annex 3.**

5. Evaluation Metrics for Algorithm Comparison

To ensure an accurate and comprehensive evaluation of the optimization algorithms applied in this study, several quantitative metrics were defined. Each metric reflects a different aspect of solution performance, from accuracy to efficiency and economic impact. The following indicators were selected:

5.1 Distance to Strategic Objectives

This metric measures how far the obtained planted area is from the predefined target objective. It quantifies the deviation in terms of percentage, regardless of whether the algorithm overshoots or undershoots the target.

$$D_t(x) = \sum_{i=1}^{n} |x_i - t_i| \Big/ t_i$$

- $D_t(x)$: Distance to Objective
- x_i: Planted Area allocated to crop i
- t_i: Target area for crop i based on national needs

A value of zero indicates a perfect match with the target; while higher values reflect greater deviation and therefore lower performance, (Lower values indicate better alignment with planning goals).

5.2 Total Cost

This metric calculates the cumulative cost of all the agricultural projects selected by the algorithm.

$$C(x) = \sum_{i=1}^{n} c_i x_i$$

Where:

- $C(x)$: Total cost
- c_i: Cost per hectare for crop i
- x_i: Allocated area for crop i

A lower total cost is generally preferable, especially when optimizing for resource efficiency. However, it must be balanced with solution quality and profit.

Unit: Million Algerian Dinars ($\times 10^6$ DA).

5.3 Total Profit

This metric measures the total expected profit generated by the selected agricultural project by the algorithm.

$$P(x) = \sum_{i=1}^{n} p_i x_i$$

Where:

- $P(x)$: Total profit
- p_i: Profit per hectare for crop i
- x_i: Area allocated to crop i

A higher profit value reflects the economic effectiveness of the solution proposed by the algorithm.

Unit: Million Algerian Dinars ($\times 10^6$ DA).

5. 4 Execution Time

This metric indicates the time required for the algorithm to generate a solution. It reflects the computational efficiency and scalability of the method.

$$T(x) = t_{end} - t_{start}$$

Where:

- $T(x)$: Runtime in seconds (s).
- t_{end}, t_{start} End and start times of execution.

While faster execution is advantageous, it must not compromise the quality or relevance of the solution.

5.5 Quality of Solution

To enable fair and comprehensive comparison across optimization algorithms, we aggregate multiple evaluation metrics into a single weighted quality function. This allows us to assess solutions based on their overall trade-off between economic performance and Distance to objective. The composite quality score Q(x) is defined

$$Q(x) = w_c \cdot C(x) + w_p \cdot P(x) + w_t \cdot D_t(x) + w_v \cdot V(x)$$

Where:

- $C(x)$: total cost (DA),
- $P(x)$: total profit (DA),
- $D_t(x)$: deviation from strategic crop targets,
- $V(x)$: constraint violation count,

w_c, w_p, , w_t, w_v: normalized weights assigned to each component such that $w_C + w_P + w_t + w_v = 1$.

Each weight reflects the importance of its corresponding objective, allowing for stakeholder-driven tuning of the optimization process. Lower values of $Q(x)$ indicate better overall performance. This function serves as the core evaluation mechanism throughout our experiments.

To enhance interpretability and enable intuitive comparisons across algorithmic results, we reformulate the original quality function Q(x) into a normalized percentage-based expression. While the initial version of the function:

$$Q(x) = w_c \cdot C(x) + w_p \cdot P(x) + w_t \cdot D_t(x) + w_v \cdot V(x)$$

Is mathematically sound, it does not directly yield a value bounded within the [0,100]% range. To address this, and to ensure that Quality scores can be interpreted as performance percentages, we normalize each component and derive a new formulation as follows:

$$Q(x) = (w_c \cdot C_{norm}(x) + w_p \cdot P_{norm}(x) + w_t \cdot D_{norm}(x) + w_V \cdot V_{norm}(x)) \times 100$$

Where:

- $C_{norm}(x) = 1 - \frac{C(x)}{C_{max}}$
- $P_{norm}(x) = \frac{P(x)}{P_{max}}$
- $P_{norm}(x) = \frac{P(x)}{P_{max}}$
- $D_{norm}(x) = 1 - \frac{V(x)}{V_{max}}$

A value close to 100% indicates that the solution is highly accurate and meets the target objective effectively.

6. Results and Discussion

The following table presents the results obtained from the application of three optimization algorithms **Genetic Algorithm (GA)**, **Weighted Sum Method (WSM)**, and **BKPACS** across three experimental scenarios involving 20, 100, and 1000 agricultural projects. These scenarios were simulated using the test datasets derived from the original catalog as described previously.

Each solution was evaluated using the defined metrics: distance to objective, quality of solution, total cost, total profit, and execution time. The results aim to provide a comparative view of the algorithms' performance in terms of accuracy, efficiency, and economic output.

This experimental comparison highlights the strengths and weaknesses of each algorithm in addressing agricultural planning challenges within the context of a holonic decision-making system.

Table 4. 2 Experimental results of the algorithms test.

Algorithm	Planted Area (ha)	Target Objective (ha)	Distance to Objective	Quality of Solution	Total Cost (×10⁶ DA)	Total Profit (×10⁶ DA)	Execution Time (s)	Selected Project
Case study :20 Project								
Genetic Algorithm	930	2306	0.5967	40.33 %	19,42	23,93	4.2	10
WSM Algorithm	2303	2306	0.0013	99.86%	47,17	53,10	0.002	12
BKPACS Algorithm	2265	2306	0.0177	98.22%	47,56	55,99	0.002	18
Case study :100 Project								
Genetic Algorithm	13830	20679	0.3312	66.88%	278,82	337,51	12.54	54
WSM Algorithm	20675	20679	0.0002	99.98%	204,93	233,14	0.01	94
BKPACS Algorithm	20673	20679	0.0003	99.97%	204,73	233,52	0.0095	97
Case study : 1000 Project								
Genetic Algorithm	173742	212129	0.181	81.9%	200,97	983,10	34.56	830
WSM Algorithm	20572	212129	0.0332	96.67%	2040,81	2342,58	0.4003	1000
BKPACS Algorithm	205266	212129	0.0323	96.76%	2052,99	2352,98	0.3685	1000

7. Analysis Experimental Results

7.1 Comparative Performance of Algorithms

After the value of the performance of the three algorithms tests (Genetic Algorithm, WSM, and BKPACS), we have one series of tests on the three main contents of 20, 100 and 1000 projectors. The resulting results include more analyzes: the distance to the object, the quality of the solution, the total cost, the total profit and the execution time and profit to facilitate the lecture and comparison. This is, a series of graphic synths illustrating the performances of different algorithms with different characters.

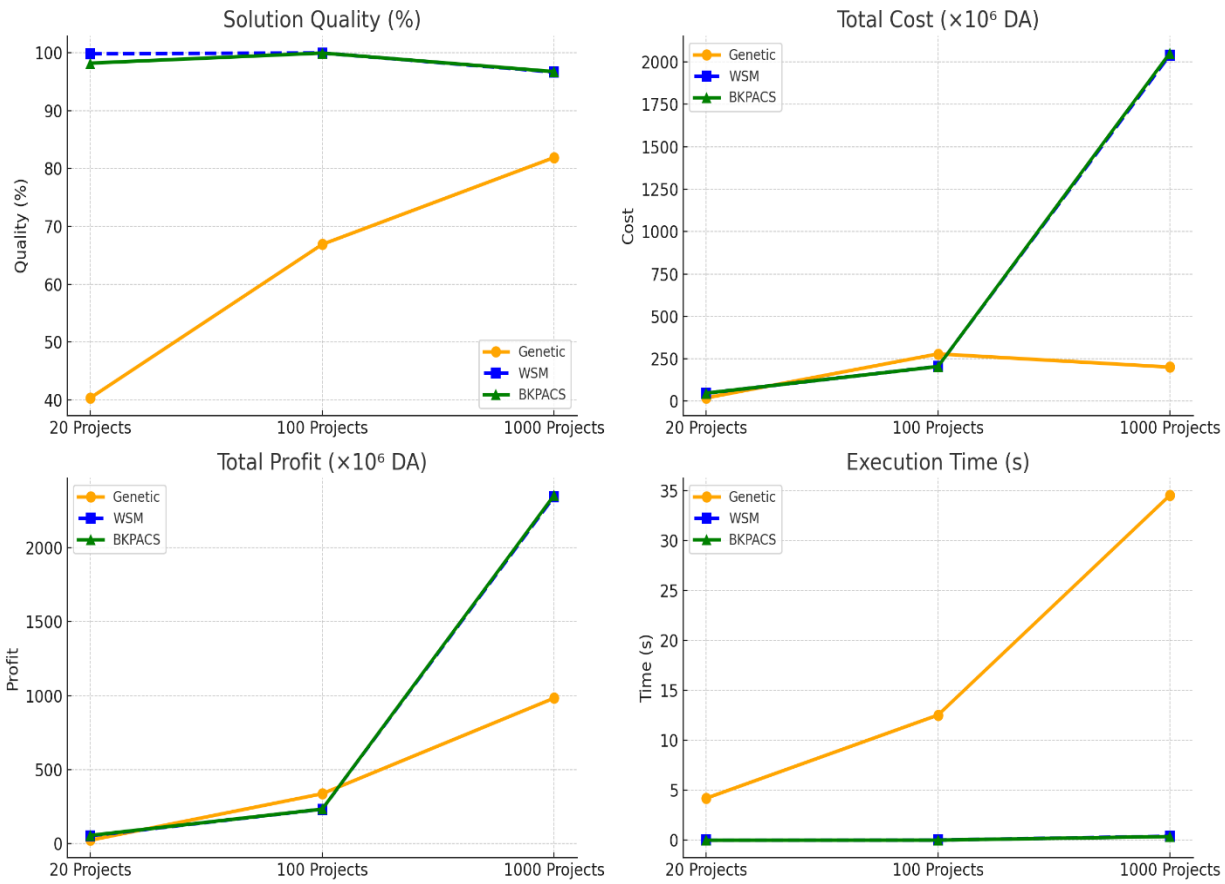


Figure 4. 2 Comparative Analysis of Algorithms across Different Case Studies.

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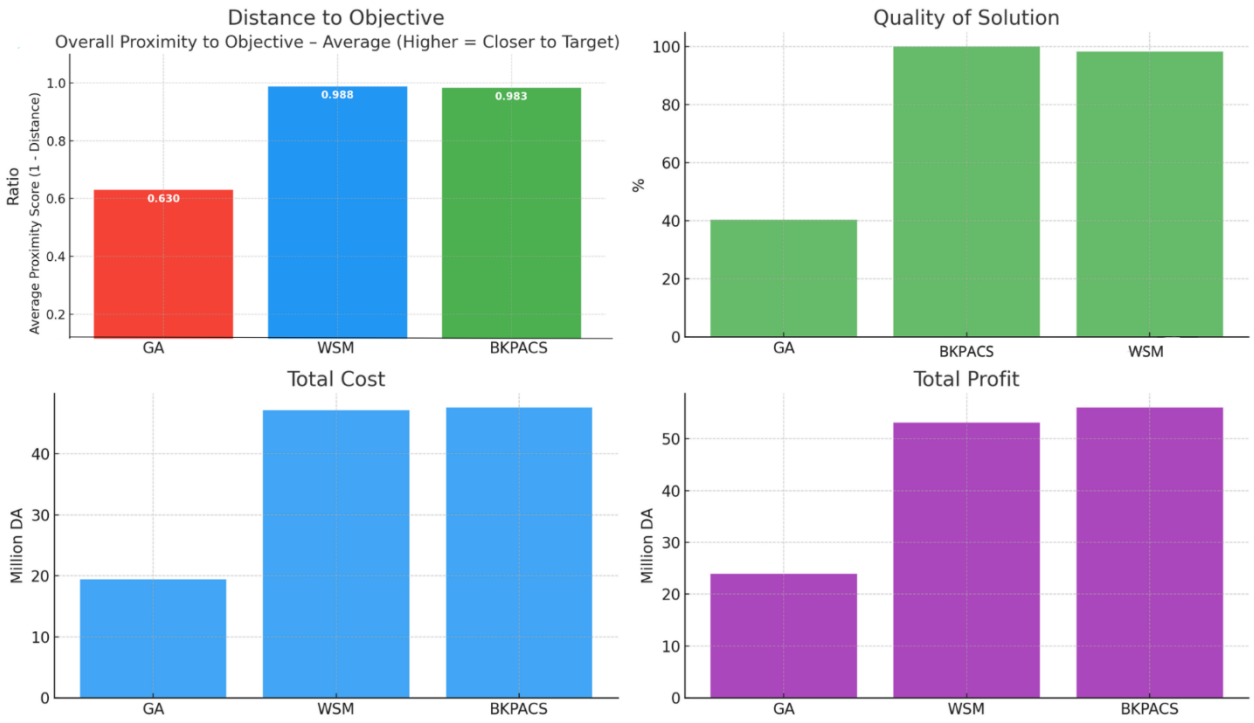


Figure 4. 3 Metrics Performance Comparison.

To provide a global understanding of the performance of the three tested algorithms Genetic Algorithm (GA), Weighted Sum Method (WSM), and BKPACS a general comparative analysis was conducted. This analysis aggregates the results obtained from three different case studies. The purpose is to identify not only which algorithm performs best in isolated scenarios, but also which one demonstrates consistent efficiency, scalability, and applicability to real-world agricultural planning. The following table summarizes the key strengths, weaknesses, and overall evaluation of each algorithm

Table 4. 3 Comparative Performance of Optimization Algorithms Based on Key Metrics.

Algorithm	Strengths	Weaknesses	Overall Performance
Genetic Algorithm (GA)	- Low cost especially for small-scale cases - Easy to implement	- Poor quality especially for small-scale (40.33%) - Large distance to target - Long execution time (up to 34.56s)	Weak performance overall. Not precise, unstable in quality and return.
Weighted Sum Method (WSM)	- Best quality (up to 99.98%) - Closest solution to the target - Very fast execution	- Very high cost (over 2000M DA for 1000 projects) - Sometimes less profitable than BKPACS	Highly accurate but expensive and less efficient for large scales.

BKPACS	- Excellent balance between quality, profit, and cost - Stable across all scales - Best profitability	- Slightly more costly than GA - Slightly less accurate than WSM in precision	Most practical and well-balanced, ideal for sustainable agricultural planning.

7.2 Execution Time and Scalability

From the chart, we clearly observe that the execution time increases progressively with the size of the project across all algorithms. Whether using the Genetic Algorithm, WSM, or BKPACS, the computational time rises as we move from 20 to 100 and then to 1000 projects. This indicates a direct relationship between project scale and processing time, which becomes more noticeable in large-scale applications.

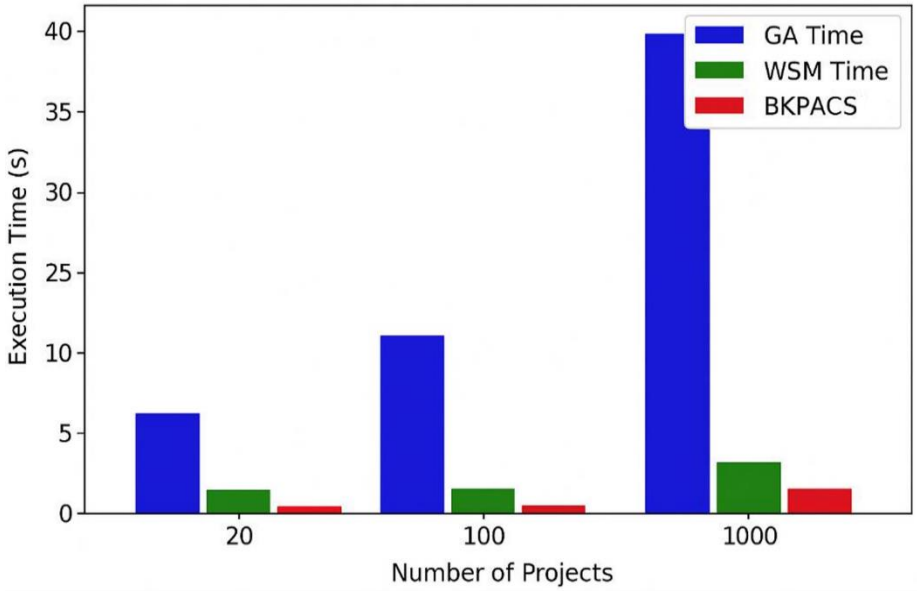


Figure 4. 4 Comparison of implementation time by number of projects.

8. Selection Algorithm for Holonic Agricultural Planning

Based on the results presented in the comparative analysis, a final selection of the most suitable algorithm for agricultural planning within the proposed holonic system is now made. The decision is supported by both visual and tabular representations, focusing on the performance of each algorithm when scaling from small- to large-scale planning

Table 4. 4 Comparative of Optimization Algorithms.

GA	Provides **lowest cost solutions**, but at the expense of **lower quality** and **lower profit**. Suitable for small-scale problems, but **execution time increases significantly** with scale.
WSM	Offers **very high-quality solutions** and **very fast execution**, but tends to result in **higher total costs** and **slightly lower profit** than BKPACS. Efficient but less balanced.
BKPACS	Delivers a **very high-quality solution**, with a **good balance between cost and profit**, and **fast execution time**. Its performance remains stable across scales. **Most suitable** for large, national-level planning.

Considering all the observed results, BKPACS emerges as the most appropriate algorithm for integration within the proposed holonic agricultural planning system. It offers a balanced compromise between efficiency, profitability, and scalability, making it the ideal choice, especially for national-level applications that require stability across multiple decision-making levels.

BKPACS is selected as the primary optimization algorithm to be used within the holonic system for agricultural planning.

8.1 Scalability Challenges in Local Solutions

As the scale of agricultural planning problems increases from a few dozen projects to several hundred or thousands the process of generating initial feasible solutions becomes progressively more complex and time-consuming. While algorithms such as WSM and BKPACS are capable of producing optimized results rapidly once the problem is formulated, the pre-optimization phase, particularly solution generation, introduces a significant computational burden.

In small-scale cases, the time required to generate a complete solution space is negligible and has little impact on overall performance. However, in large-scale contexts such as national-level planning involving hundreds or thousands of projects the number of possible combinations grows exponentially. This leads to a bottleneck effect, where the system spends a substantial amount of time simply identifying valid configurations before any optimization can occur.

8.2 Proposed Solution: Holonic Optimization System

To address the scalability limitations identified in large-scale agricultural planning particularly those related to the increasing time required for solution generation this work proposes a Federated Holonic Optimization System, inspired by the “System of Systems” paradigm. The core idea is to decompose the global planning task into multiple smaller, manageable subsystems, each corresponding to a specific holon (e.g., municipality, district, region).

In this architecture, each holon independently handles its own localized planning problem using an appropriate optimization algorithm, such as BKPACS. These holons operate in parallel, generating local optimal solutions based on their specific constraints and datasets. Once generated, these partial solutions are aggregated hierarchically moving from the local to district, regional, and finally national levels forming a complete, integrated solution that preserves both global objectives and local specificity

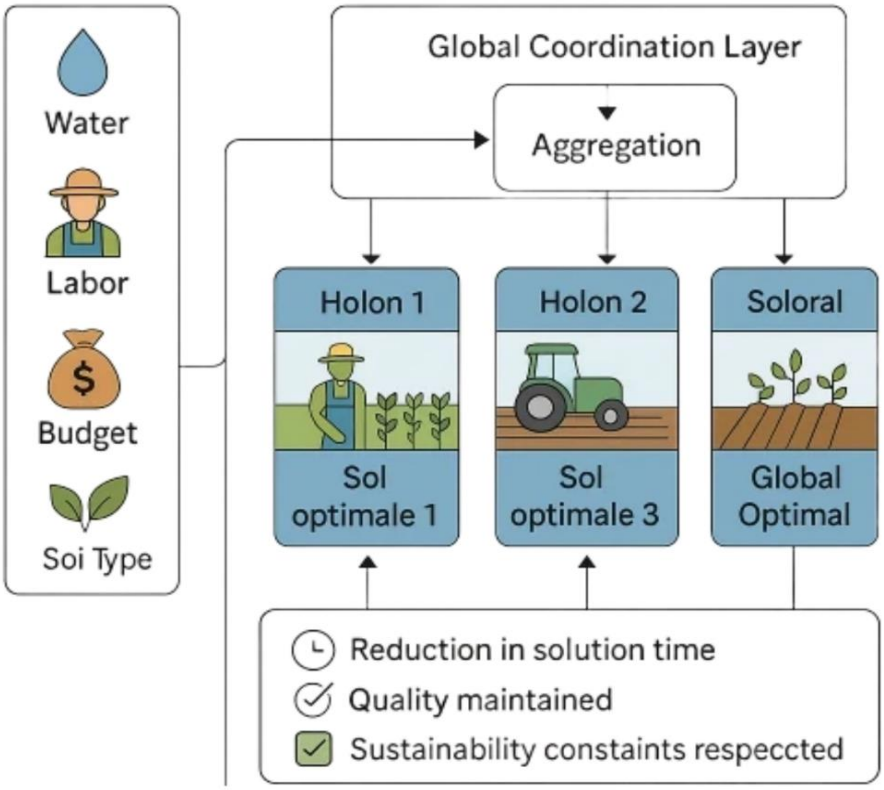


Figure 4. 5 Federated Holonic optimization process.

9. Application of BKPACS with Real-World Constraints and Dataset

After selecting the holonic system as a scalable solution for national-level agricultural planning, we apply the BKPACS algorithm to generate and evaluate optimal solutions. Each local holon, corresponding to a specific region, contains a set of agricultural parcels with unique characteristics such as land area, soil type, and compatible crop types.

For each project (denoted as **P**), we define its initial planting plan per unit (hectare), associated cost, expected profit, and the quantity of main and alternative crops to be planted. For example, a parcel with 150 ha might allocate 70 ha to the main crop and 20 ha to an alternative crop (**P1:** main

crop: 70/170 ha, alternative crop: 20/170 ha). The government typically provides seeds, while the farmers implement the plantation plan, meaning actual sowed quantities may vary by parcel.

The algorithm must respect multiple constraints:

- ✓ **Water availability** in the region (total water resource to be distributed across parcels).
- ✓ **Planting capacity** per parcel (cannot exceed available area).
- ✓ **Crop-specific limitations**: maximum quantity allowed for both main and alternative crops.
- ✓ **Cost limitation**: overall cost should not exceed a predefined threshold.
- ✓ **Profit maximization**: among all feasible solutions, the one maximizing profit is preferred.

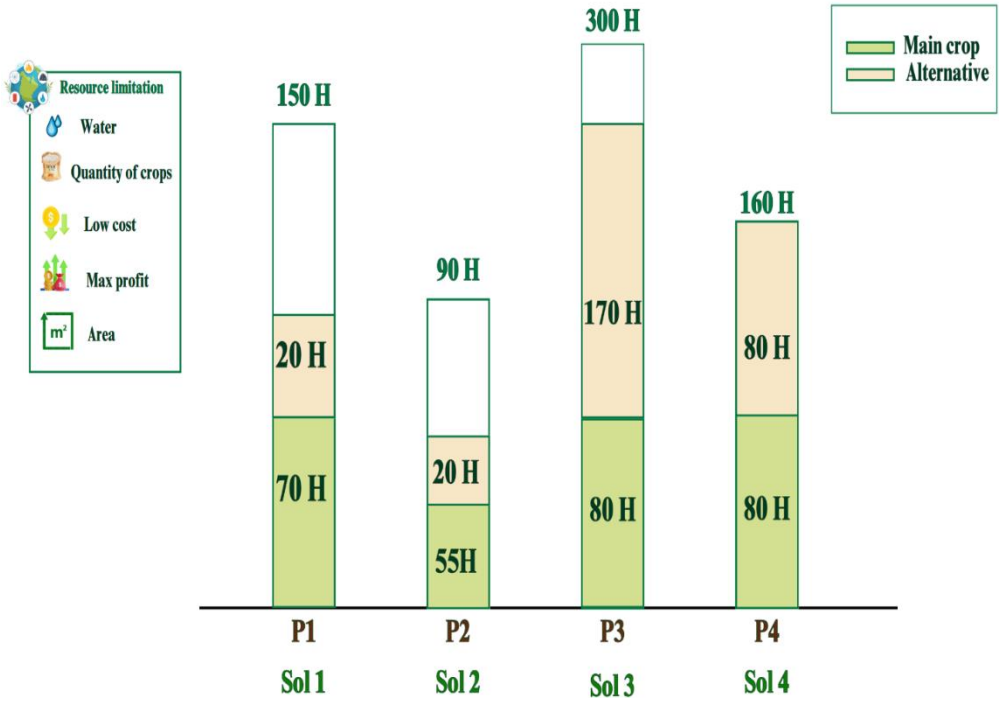


Figure 4. 6 Solution generation structure by BKPACS.

BKPACS generates candidate solutions (combinations of crop distributions per parcel) in a guided but semi-random fashion. It iteratively tests different planting configurations while ensuring all resource constraints are respected. These include water distribution, area limits, crop quantities, and financial boundaries. Once local solutions are validated, they are aggregated into a global solution at the national level, in line with the holonic principle of bottom-up synthesis.

10. Best Feasible Solution – Local Holon Simulation

After selecting BKPACS as the core algorithm for the holonic agricultural planning system, we conducted a preliminary simulation at the local holon level, focusing specifically on the **Bir El**

Ater and **Negrine** regions located in the Tebessa province. This region was selected due to its representative agricultural diversity and the availability of real-world data.To carry out the test; we extracted the actual dataset of agricultural parcels corresponding to Bir El Ater and Negine from the complete regional agricultural database (**Table 3.3**) each parcel entry included surface area, compatible crops, and associated resource constraints. Additionally, we referred to the official regional resource catalog (**Table 3.2**) to define the physical limitations, including:

- ✓ Maximum water availability.
- ✓ Total cultivable area per parcel.
- ✓ Cost thresholds per project.
- ✓ Crop-specific quantity limits.
- ✓ Profit maximization objective.

The BKPACS algorithm was then applied on this dataset to generate and evaluate multiple planting configurations per parcel, taking into account both "main crops" and "alternative crops". Each candidate solution was checked against all constraints, and only feasible ones were retained. The best among them, in terms of profit and sustainability, was selected as the "optimal solution" for this local holon.

11. Evaluation Criteria for Local Holonic Planning

11.1 Crop Diversity Index (Entropy-Based)

Diversity is essential for sustainable agriculture and soil health. We use the Shannon entropy function to quantify how evenly crops are distributed:

$$H(x) = \sum_{i=1}^{n} \left(\frac{x_i}{T}\right) \log\left(\frac{x_i}{T} + \varepsilon\right), T = \sum_{j=1}^{n} x_j + \varepsilon$$

Where:

- $H(x)$: Entropy-based diversity index.
- T: Total cultivated area.
- ε: Small constant to avoid division by zero.

A higher value indicates greater biodiversity and more resilient land-use patterns.

11.2 Constraint Adherence

Constraint adherence ensures that the plan respects physical and environmental limits. Violations include exceeding: - Maximum parcel area - Water availability - Fertilizer limits - Soil suitability rules

We count the number of constraint violations in each solution:

$$V(x) = \sum_{j=1}^{m} I_{violation_j}$$

Where:

- $V(x)$: Constraint violation count
- m: Number of constraints
- $I_{violation_j}$: Indicator function (1 if *violated*, 0 *otherwise*)

Fewer violations indicate more realistic and implementable plans.

11.3 Water Use

This function computes the total irrigation demand of a given crop allocation plan, It serves as a key metric for evaluating the resource efficiency and environmental sustainability of agricultural planning solutions.

$$W_{total}(x) = \sum_{i=1}^{n} x_i \, r_i$$

Where:

- x_i: Surface area (in hectares) allocated to crop i.
- r_i: irrigation requirement of crop i (in mm/year).
- n: Total number of crop allocations across all parcels.
- $W_{total}(x)$: Total irrigation demand for the solution x_i expressed in millimeters.

11.4 Sustainability Factor

As a new contribution of this research, we introduce the sustainability factor $S(x)$, which combines multiple indicators into one score reflecting long-term ecological balance.

$$S(x) = s_w \cdot \left(1 - \frac{W(x)}{W_{total}}\right) + s_f \cdot \left(1 - \frac{F(x)}{F_{total}}\right) + s_d \cdot H(x)$$

Where:

- $W(x)$: Total water used
- $F(x)$: Total fertilizer used
- $H(x)$: Entropy-based diversity index
- $s_w + s_f + s_d$=1: User-defined weights representing sustainability priorities

This factor encourages planners to prioritize solutions that not only generate short-term economic returns but also support long-term land productivity and ecological balance.
These metrics serve as the foundation for evaluating the quality of solutions generated by different algorithms and comparing architectural models in the following sections.

11.5 Cost per Parcel

To estimate the financial investment required for each agricultural parcel, we compute the cost as a function of the total cultivated area and the average cost per hectare, as shown in the following equation:

$$C_i = ({a_i}^{main} + {a_i}^{alt}).\gamma_i$$

Where:

- C_i: cost of parcel i (in millions of DA).
- ${a_i}^{main}$: area (in ha) allocated to the main crop in parcel$i$.
- ${a_i}^{alt}$: area (in ha) allocated to the alternative crop in parcel i.
- γ_i: average cost per hectare for the crop combination (in DA/ha), normalized to $\times 10^6$ DA.

11.6 Profit per Parcel

The profit generated from each parcel is calculated based on the allocated crop areas, their expected yields, and corresponding market prices, as represented in the equation below:

$$P_i = ({a_i}^{main}.{y_i}^{main}.{s_i}^{main}) + ({a_i}^{alt}.{y_i}^{alt}.{s_i}^{alt})$$

Where:

- p_i: profit of parcel i (in millions of DA).
- ${a_i}^{main}, {a_i}^{alt}$: areas allocated to main and alt crops (in ha).

- y_i^{main}, y_i^{alt}: yield per hectare (in tons/ha).

- s_i^{main}, s_i^{alt}: selling price per ton (in DA/ton), normalized to $\times 10^6$ DA

11.7 Strategic Alignment Score

Strategic alignment evaluates how well the solution adheres to national agricultural policies and priorities, such as promoting high-importance crops.

$$S_t(x) = \sum_{i=1}^{n} |x_i - t_i|$$

Where:

- $S_t(x)$: Strategic alignment score

- x_i: Actual area allocated to crop i

- t_i: Target area for crop i based on national needs

Smaller deviations from strategic targets indicate better policy compliance.

12. Result of Holonic System by the Algorithm BKPACS

To assess the real-world applicability of the proposed holonic system, we conducted a localized implementation of the BKPACS algorithm on two selected regions within the Tebessa province: Bir El Ater and Negrine. . The objective was to generate optimized planting configurations that respect environmental, technical, and economic constraints. The results below present the detailed output of the system at the parcel level, including crop allocation, resource consumption, and sustainability performance..

The optimal plan includes a diverse allocation of crops across 10 agricultural parcels. Below is the detailed configuration.

Table 4. 5 Result of holonic system by the algorithm BKPACS.

Holon 1: Bir el Ater								
Parcel	**Main Crop**	**Alt Crop**	**Main Area (ha)**	**Alt Area (ha)**	**Water Use (mm)**	**Cost (×10⁶ DA)**	**Profit (×10⁶ DA)**	**Sustainability Factor**
P1	Wheat	Barley	18.28	6.72	10029	0.274	0.104	0.379
P2	Olives	Vegetables	29.75	15.25	17312	0.482	0.240	0.498
P3	Barley	Legumes	41.8	18.2	20089	0.579	0.215	0.372
P4	Vegetables	Legumes	65.88	14.12	40469	1.195	0.448	0.376
P5	Wheat	Sunflowers	71.09	28.91	41421	1.121	0.448	0.4
P6	Olives	Almonds	116.52	33.48	48348	1.300	0.756	0.582
P7	Legumes	Wheat	153.82	46.18	65541	2.069	0.787	0.381
P8	Almonds	Olives	194.64	105.36	109464	2.984	1.539	0.516
P9	Wheat	Barley	863.41	136.59	410438	11.230	4.277	0.381
P10	Barley	Fallow	2735.52	304.48	957433	25.990	9.574	0.368
Global Solution								
Water Used Total (mm)		1721997						
Cost Total (DA)		472199641						
Profit Total (DA)		184079508						
Total Sustainability Score		4 out of 10						
Holon 2: Negrine								
P1	Wheat	Barley	19.07	25.92	15407	4.37	2.90	0.312
P2	Olive	Vegetables	18.59	36.40	26491	14.64	9.32	0.569
P3	Palm	Olive	84.40	45.59	70480	38.66	27.74	0.496
P4	Barley	Wheat	47.50	42.49	31249	8.762	5.84	0.311
P5	Olive	Vegetables	50.34	99.66	72381	39.97	25.46	0.570
P6	Wheat	Barley	320.32	279.6	212032	58.60	39.12	0.309
P7	Vegetables	Palm	268.6	581.3	568131	284.07	219.19	0.535
P8	Palm	Olive	778.2	421.7	650192	356.73	255.86	0.496
P8	Barley	Wheat	778.9	721	522101	146.11	97.33	0.310
P10	Wheat	Barley	14067.2	6312.7	7520728	4.37	2.90	0.306
Global Solution								
Water Used Total (mm)		9689192						
Cost Total (DA)		2958339081						
Profit Total (DA)		2030716109						
Total Sustainability Score		4.21 / 10						

13. Discussion and Validation of Results

The results obtained from the BKPACS algorithm in both Bir El Ater and Negrine demonstrate a practical, well-balanced agricultural planning outcome that respects real-world constraints. The proposed system successfully allocated diversified crop plans across all parcels, integrating both main and alternative crops to enhance flexibility and resilience.

In Bir El Ater, the system achieved a total profit of **184 million DA** with moderate water use (**1.72 million mm**) and an overall sustainability score of **4/10**, reflecting realistic and environmentally aware decisions. In Negrine, the algorithm showed even greater profitability, exceeding **2 billion DA**, while maintaining similar sustainability performance (**4.21/10**). This difference is justified by the predominance of high-value crops like palm, olive, and vegetables in Negrine, which are adapted to the local agro-climatic conditions.

What makes these results particularly compelling is that they are **grounded in actual data**, adhere to all constraints (area, cost, water, crop limits), and are generated from a multi-objective system. Despite not aiming for theoretical optimums, the BKPACS algorithm produces **feasible, realistic, and implementable plans** that can genuinely support sustainable land use policy in Algerian agriculture.

14. Comparative Evaluation: Holonic System vs Traditional and Anarchic Models

Evaluation of the Holonic System: Comparative Study with Flat and Anarchic Agent Architectures, to validate the selection of the Holonic System as the most appropriate architecture for national-level agricultural planning; we conducted a comparative evaluation with two alternative systems:

- A Flat (Centralized) System, and
- An Autonomous Anarchic Agent System (fully decentralized and uncoordinated agents).

This comparison based on multiple performance dimensions that are crucial in complex decision-making environments such as agriculture. These criteria include Profitability, Diversity, Strategic Alignment, System Stability, Architectural Complexity, and Sustainability. The evaluation is based both on real experimental outcomes (from our simulation) and on theoretical insights and characteristics known from each architecture's behavior in such contexts. The comparison was based on a set of six critical criteria relevant to complex, multi-actor planning environments:

The following table summarizes the qualitative and quantitative performance of each system:

- ✓ **Profitability:** Measures the system's ability to maximize total profit generated from agricultural projects. Higher profitability reflects more effective resource allocation and decision-making strategies.

- ✓ **Diversity:** Refers to the variety of crops and resource distributions achieved within the solution. A higher level of diversity indicates flexibility, better adaptation to local conditions, and reduced monoculture risk.
- ✓ **Strategic Alignment:** Indicates how well the decisions made by the system align with long-term strategic and sustainable development goals, across all organizational levels.
- ✓ **Stability:** Reflects the system's ability to maintain coherent and reliable performance under changes or disturbances. A stable system is resilient and avoids collapse when individual components are modified.
- ✓ **Complexity:** Assesses the architectural difficulty of implementing and managing the system. This includes communication structure, control mechanisms, and modularity.
- ✓ **Sustainability:** Measures the system's capacity to ensure long-term viability by balancing environmental, economic, and social factors. A sustainable system promotes efficient use of resources and adaptability to future challenges.

Table 4. 6 Comparative Evaluation of System Architectures.

Criterion	Holonic System	Flat System (Centralized)	Anarchic Agents System
Profit	- Very High.	- Medium because the lack of intelligent distribution of resources.	- Unstable because of chaotic decisions.
Diversity	- High diversity of crops and assignments.	- Low to medium Similar plans.	- Medium but not directed.
Strategic Alignment	-Decentralization guided by sustainable objectives. - Clear and Multi-level	- Centralized Without local air conditioning. - Limited/Static	- Weak/Non-aligned - No coordination
Stability	- Flexible and Strong consistency between levels - Stable and Coordinated	- Weak because Changing any element leads to a general imbalance.	-Very weak - Each unit acts alone
Complexity	-Medium (modular, distributed control).	- High complexity Because of the centralization of the decision.	- Low complexity But ineffective
Sustainability	- Moderate to High With the possibility of improvement	-Low because ignores local optimization,	-Very weak Because resources are not distributed efficiently

As shown in the comparative evaluation table, the Holonic System consistently outperforms both the Flat (Centralized) and Anarchic Agent architectures across nearly all evaluation dimensions. It achieves the highest level of profitability while maintaining crop diversity, strategic coherence, and system stability.

In contrast, the centralized system suffers from rigid structures and poor adaptability, while the anarchic model lacks coordination, leading to instability and inefficient resource allocation.

These findings confirm that the holonic architecture offers a balanced and scalable solution, capable of adapting to both global and local agricultural planning needs while maintaining strategic direction and sustainability.

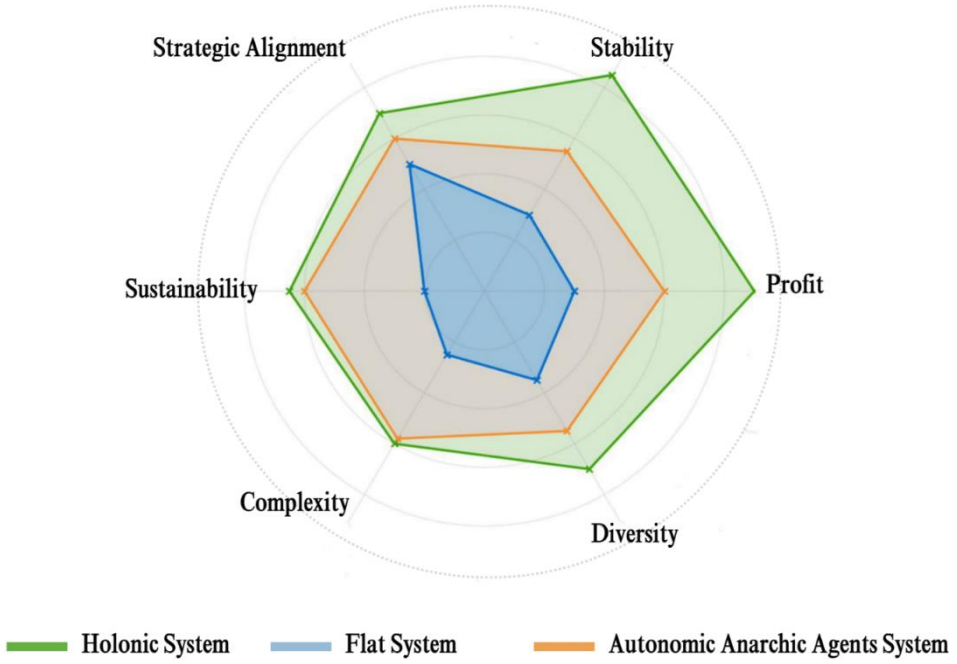


Figure 4. 7 Comparision of system Architectures Across Key Dimensions.

15. Conclusion

This chapter evaluated the effectiveness of the proposed holonic optimization system using real-world agricultural data from the Tébessa region. Three algorithms were tested, and BKPACS consistently delivered the best balance between accuracy, speed, and sustainability. In large-scale testing, it achieved over 96% solution quality with minimal execution time.

At the local level, the system produced realistic planting plans in Bir El Ater and Negrine, respecting resource constraints such as water, budget, and land capacity. The total profit reached 184 million DA in Bir El Ater and exceeded 2 billion DA in Negrine.

Sustainability scores remained moderate but stable across both zones The sustainability scores reached 4.00/10 in Bir El Ater and 4.21/10 in Negrine, showing meaningful alignment with environmental goals. These results demonstrate the system's ability to generate feasible, scalable, and adaptive solutions.

Overall, BKPACS combined with the holonic model shows strong potential for supporting sustainable agricultural strategies in Algeria.

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General conclusion and prospects



General Conclusion and Prospects

This thesis proposed a novel holonic optimization system for sustainable agricultural planning in Algeria. By addressing the structural limitations of centralized planning and the fragmentation challenges of decentralized models, the system introduced a hybrid architecture based on multi-agent holonic structures that operate at local, district, regional, and national levels. Through the integration of real-world data, agent-based modeling (AUML), and advanced optimization algorithms most notably BKPACS the system offers a scalable, intelligent framework that enhances decision-making, resource allocation, and sustainability in agriculture.

The case study of the Wilaya of Tébessa demonstrated the feasibility and effectiveness of the proposed approach. It highlighted how local holons can generate partial yet relevant solutions that contribute meaningfully to national-level agricultural strategies. Moreover, the comparative analysis of optimization algorithms confirmed the suitability of holonic structures in dealing with complex, multi-objective agricultural challenges.

However, despite the promising outcomes, certain limitations were observed especially concerning data availability, simulation scalability, and the integration of environmental constraints. These elements provide valuable insights and open the door for future research.

Prospects:

In future work, we aim to enhance this prototype system into a fully operational tool capable of supporting real-time planning decisions across Algeria. A key ambition is to integrate the model with national agricultural data infrastructures, enabling automated and dynamic updates. We hope to deploy this system at scale, starting with regional agricultural offices, and gradually expanding towards a national-level platform. The ultimate goal is to transition from simulation to a real-world, data-driven system that helps optimize agricultural resources sustainably and equitably across the country.

This work represents an essential step towards the digital transformation and sustainable development of Algerian agriculture. It demonstrates that intelligent, decentralized systems when properly designed and grounded in real-world data can offer impactful and pragmatic solutions to complex socio-economic problems.

Bibliography

Abdelkader, M., & Delali, A. (2012). Support system based on GIS and weighted sum method for drawing up of land suitability map for agriculture. Application to durum wheat cultivation in the area of Mleta (Algeria). *Spanish Journal of Agricultural Research*, *10*(1), 34–43. https://doi.org/10.5424/sjar/2012101-293-11

Adam, E., & Mandiau, R. (2005). Roles and Hierarchy in Multi-agent Organizations. In M. Pěchouček, P. Petta, & L. Z. Varga (Eds.), *Multi-Agent Systems and Applications IV* (Vol. 3690, pp. 539–542). Springer Berlin Heidelberg. https://doi.org/10.1007/11559221_55

Agadi, R., Sakhraoui, K., Von Hirschhausen, C., & Kebir, N. (2023). Sustainable Farming through Decentralized Energy Systems: Opportunities and barriers: The Promise of the WEF nexus approach in Algeria's Energy Transformation. *E3S Web of Conferences*, *433*, 03001. https://doi.org/10.1051/e3sconf/202343303001

Agriculture algérienne M1 Rural. (n.d.).

ART+026_BJB_JUL_2024. (n.d.).

Benbekhti, S. E., Bouknadil, M., Boulila, H., & Zeghoudi, A. (2024). Socioeconomic Challenges on Algeria's Progress toward SDG2 (Zero Hunger): Public Spending, Agriculture, and Economic Resilience. *SocioEconomic Challenges*, *8*(4), 1–18. https://doi.org/10.61093/sec.8(4).1-18.2024

Bernhard, A. T., Jungbluth, S., Karnoub, A., Sidorenko, A., Motsch, W., Wagner, A., & Ruskowski, M. (2024). I4.0 Holonic Multi-agent Testbed Enabling Shared Production. In J. Soldatos (Ed.), *Artificial Intelligence in Manufacturing* (pp. 231–250). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-46452-2_13

Bessaoud, P. O., Khechimi, W., & Pellissier, J.-P. (2019). *Rapport de synthèse sur l'agriculture en Algérie*.

Boudjemaa, K. (2020). *Système intelligent d'aide à la décision pour la planification du projet urbain*.

Castellanos Serrano, L. T., Castellanos Suárez, J. A., Universidad Autónoma Chapingo. Departamento de Sociología Rural, Pérez Vivar, M. A., & Universidad Autónoma Chapingo. Departamento de Fitotecnia. (2024). Optimización de sistemas de soporte de decisiones en agricultura mediante IA: Un enfoque integrado. *e-CUCBA*, *11*(21), 150–155. https://doi.org/10.32870/e-cucba.vi21.333

Chetouh, N. (2024). *Modeling of Agricultural Production Using Input- Output Analysis Technique A Quantitative Study of the Algerian Economy for the Period 2005-2019*.

Clark, H., Jeong, N. S., & Jeong, S. (2019). Concurrent Gain and Bandwidth Improvement of a Patch Antenna with a Hybrid Particle Swarm Optimization Algorithm. *2019 IEEE 20th Wireless and Microwave Technology Conference (WAMICON)*, 1–3. https://doi.org/10.1109/WAMICON.2019.8765432

Cormen, T, & Stein, C. (2009). *Http://www.cs.kent.edu/%7Ed...*

Cossentino, M., Gaud, N., Galland, S., Hilaire, V., & Koukam, A. (2007). A Holonic Metamodel for Agent-Oriented Analysis and Design. In V. Mařík, V. Vyatkin, & A. W. Colombo (Eds.), *Holonic and Multi-Agent Systems for Manufacturing* (Vol. 4659, pp. 237–246). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74481-8_23

Dantzig, G. B. (1963). *Linear Programming and Extensions*.

Deen, S. M. (2002). Cooperating Agents for Holonic Manufacturing. In V. Mařík, O. Štěpánková, H. Krautwurmová, & M. Luck (Eds.), *Multi-Agent Systems and Applications II* (Vol. 2322, pp. 119–133). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-45982-0_5

Dong, M. W. Y. (2023). *A Survey on Multi Agent System and Its Applications in Power System Engineering*.

Draou, A. (2022). Enhancing Food Security by Moving towards a Sustainable Agricultural System: A Case Study of Algeria in Light of the COVID-19 Pandemic. *Finance and Business Economies Review*, *6*(3), 70–90. https://doi.org/10.58205/fber.v6i3.310

El Hassani, S. K. (2013). La Dépendance Alimentaire en Algérie: Importation de Lait en Poudre versus Production Locale, Quelle Evolution? *Mediterranean Journal of Social Sciences*. https://doi.org/10.5901/mjss.2013.v4n11p152

Elhami, Mahmoud Ghasemi, G., Morteza, T., & abadi, M. (2022, Elhami). *Optimization of energy ratio, benefit to cost and greenhouses gasses using metaheuristic techniques (genetic and particular swarm algorithms) and data envelopment analysis: Recommendations for mitigation of inputs consumption (a case crop: Edible onion)—Elhami—2022—Environmental Progress & Sustainable Energy—Wiley Online Library*. https://aiche.onlinelibrary.wiley.com/doi/epdf/10.1002/ep.13889#

Fan, Z., Fang, Y., Li, W., Lu, J., Cai, X., & Wei, C. (2017). A comparative study of constrained multi-objective evolutionary algorithms on constrained multi-objective optimization problems. *2017 IEEE Congress on Evolutionary Computation (CEC)*, 209–216. https://doi.org/10.1109/CEC.2017.7969315

Farid, A., & Ali, W. (2024). Algerian Agricultural Development Policies and Trends for the Realizing of Food Security: In A. Ahmadi (Ed.), *Advances in Finance, Accounting, and Economics* (pp. 35–41). IGI Global. https://doi.org/10.4018/979-8-3693-3932-9.ch003

Febriandiela, F., Frinaldi, A., & Magriasti, L. (2024). Critical Analysis of Decentralization Theory in the Context of Local Government: A Literature Review. *Adabi : Journal of Public Administration and Business*, *11*(1), 1–13. https://doi.org/10.62066/jpab.v11i1.13

Gaad, D., Belahmadi, M. S. O., Kerrour, N., & Haddad, R. (2024). Implementation of Climate-Smart Agriculture (CSA) in Algeria, Towards Climate Resilient Growth Path: The caseof Biofertilizer Application. *2024 4th International Conference on Embedded & Distributed Systems (EDiS)*, 330–332. 2024 4th International Conference on Embedded & Distributed Systems (EDiS). https://doi.org/10.1109/EDiS63605.2024.10783245

Gerber, C. (2002). *Flexible Autonomy in Holonic Agent Systems*.

Getahun, S., Kefale, H., & Gelaye, Y. (2024). Application of Precision Agriculture Technologies for Sustainable Crop Production and Environmental Sustainability: A Systematic Review. *The Scientific World Journal*, *2024*(1), 2126734. https://doi.org/10.1155/2024/2126734

Giorgi, F., Jones, C., & Asrar, G. R. (2009). *Addressing climate information needs at the regional level: The CORDEX framework*.

Giret, A., & Botti, V. (2004). Holons and agents. *Journal of Intelligent Manufacturing*, *15*(5), 645–659. https://doi.org/10.1023/B:JIMS.0000037714.56201.a3

Haldorai, A., R, B. L., Murugan, S., & Balakrishnan, M. (2024). Significance of AI in Smart Agriculture: Methods, Technologies, Trends, and Challenges. In A. Haldorai, B. L. R, S. Murugan, & M. Balakrishnan, *Artificial Intelligence for Sustainable Development* (pp. 3–25). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-53972-5_1

Hong-han, Z., & Rui-zhong, M. (2011). A modeling methodology for MAS based on AUML. *2011 International Conference on Uncertainty Reasoning and Knowledge Engineering*, *2*, 185–188. https://doi.org/10.1109/URKE.2011.6007940

Kareska, K. (2024). *Challenges and Strategic Solutions for Sustainable Agriculture* (SSRN Scholarly Paper No. 5016508). Social Science Research Network. https://doi.org/10.2139/ssrn.5016508

Korchi, M., & Bendjaballah, O. (2023). *(PDF) REINVENTING URBAN AGRICULTURE IN ALGERIAN URBAN POLICIES: STAKEHOLDERS' VISIONS AND OPERATIONAL STRATEGY*. https://www.researchgate.net/publication/380374821_REINVENTING_URBAN_AGRICULTURE_IN_ALGERIAN_URBAN_POLICIES_STAKEHOLDERS'_VISIONS_AND_OPERATIONAL_STRATEGY

Koval, V., Dmytryshyn, R., Srivastava, P., Vdovenko, N., Alekseieva, K., & Grabovski, D. (2024). Regulation of Rural Competitiveness Development in Fishery and Animal Husbandry Exports. *IOP Conference*

Series: Earth and Environmental Science, *1429*(1), 012009. https://doi.org/10.1088/1755-1315/1429/1/012009

Küster Filipe, J. (2004). Giving Life to Agent Interactions. In M. D. Ryan, J.-J. Ch. Meyer, & H.-D. Ehrich (Eds.), *Objects, Agents, and Features* (Vol. 2975, pp. 98–116). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-25930-5_7

Lin, C.-C., Deng, D.-J., Kang, J.-R., & Liu, W.-Y. (2021). A Dynamical Simplified Swarm Optimization Algorithm for the Multiobjective Annual Crop Planning Problem Conserving Groundwater for Sustainability. *IEEE Transactions on Industrial Informatics*, *17*(6), 4401–4410. IEEE Transactions on Industrial Informatics. https://doi.org/10.1109/TII.2020.3029258

MADRP. (2021). https://madr.gov.dz

Mariani, S., & Omicini, A. (2023). *Special Issue ``Advances in Multi-Agent Systems'': Editorial*.

Marichal, G. N., González, E. J., Marichal, G. N., & González, E. J. (2009). *Intelligent MAS in System Engineering and Robotics* (intelligent-mas-system-engineering-robotics) [Chapter]. Https://Services.Igi-Global.Com/Resolvedoi/Resolve.Aspx?Doi=10.4018/978-1-60960-818-7.Ch204; IGI Global Scientific Publishing. https://doi.org/10.4018/978-1-60960-818-7.ch204

McFarlane, D. C., & Bussmann, S. (2003). Holonic Manufacturing Control: Rationales, Developments and Open Issues. In S. M. Deen (Ed.), *Agent-Based Manufacturing: Advances in the Holonic Approach* (pp. 303–326). Springer. https://doi.org/10.1007/978-3-662-05624-0_13

Mella, P. (2009). *The Holonic Perspective in Management and Manufacturing*. *5*(1).

Mohamed, A., & Abdelaziz, C. (2024). COMPARING THE PERFORMANCE OF PUBLIC AND PRIVATE SECTOR AGRICULTURAL INSTITUTIONS IN THE ALGERIAN ECONOMY DURING THE PERIOD 1974-2021. *International Journal of Professional Business Review*, *9*(11), e05125. https://doi.org/10.26668/businessreview/2024.v9i11.5125

Mokhati, F., Boudiaf, N., Badri, M., & Badri, L. (2007). Translating AUML Diagrams into Maude Specifications: A Formal Verification of Agents Interaction Protocols. *The Journal of Object Technology*, *6*(4), 77. https://doi.org/10.5381/jot.2007.6.4.a2

Noui, A., Kamli, M., & Guesbaya, Z. (2024). Technical-Economic Study of the Agri-Food Investment Project "Big Milk Production Unit in Algeria- 4000 Dairy Cows". *International Journal of Agricultural Economics*, *9*(6), 287–294. https://doi.org/10.11648/j.ijae.20240906.11

Nwagboso, I. C. (2012). *Rural Development As Strategy for Food Security and Global Peace in The 21st Century*. *3*.

Oulmane, A., Ameur, F., Bouzid, A., & Boudedja, K. (2022). A functional-structural approach to analyzing agricultural innovation systems in the dairy milk sector of the region of Ghardaïa—Algerian Northern Sahara. *New Medit*, *21*(05). https://doi.org/10.30682/nm2205g

Öztürk, M. (2024). An Agro-Food Planning System: Democratic, Decentralized, Holistic, and Voluntary Participatory. *Sustainability*, *16*(21), 9441. https://doi.org/10.3390/su16219441

Pooja, D. M. V. (2023). The Study of Fundamental Concepts of Agent and Multi-agent Systems. *Tuijin Jishu/Journal of Propulsion Technology*, *44*(3), Article 3. https://doi.org/10.52783/tjjpt.v44.i3.1592

Potluri, S., Satpathy, S., Basa, S. S., & Zuorro, A. (2024). *AI in Agriculture for Sustainable and Economic Management* (1st ed.). CRC Press. https://doi.org/10.1201/9781003451648

Pournaras, E., Yadhunathan, S., & Diaconescu, A. (2020). Holarchic structures for decentralized deep learning: A performance analysis. *Cluster Computing*, *23*(1), 219–240. https://doi.org/10.1007/s10586-019-02906-4

Public Procurement Law. Retrieved 13 April 2025, from https://www.mf.gov.dz/index.php/ar/activites-ar/1212-2023-08-13-15-52-56

Riene, D., & Touati, B. (2023). The extent of economic success of the sustainable agricultural development strategy in the desert environment. *International Journal of Membrane Science and Technology*, *10*(2), 3056–3065. https://doi.org/10.15379/ijmst.v10i2.3043

Saad, M. (2022, April 27). «15 معلومة» حول خطة الجزائر للتحول إلي الزراعة الذكية لتحقيق الأمن الغذائي. *اجري توداي الزراعة اليوم*". https://agri2day.com/2022/04/27/15-معلومة-حول-خطة-الجزائر-للتحول-إلي-ا/

Sabah, G., & Rabie, A. (2024). The reality of agricultural investment in algeria and its role in achieving food security: An analytical study of the wheat market in Algeria (2016-2022). *Brazilian Journal of Business*, *6*(3), e72685. https://doi.org/10.34140/bjbv6n3-026

Salazar, L. A. C., Alvarado, O. A. R., & Chacón, E. (2018). *Implementing Industrial Control Automation for Holonic Manufacturing Systems Based on the Production Unit Architecture*.

Seika. (n.d.).

Sisto, R., Fernández-Portillo, L. A., Yazdani, M., Estepa-Mohedano, L., & Torkayesh, A. E. (2022a). Strategic planning of rural areas: Integrating participatory backcasting and multiple criteria decision analysis tools. *Socio-Economic Planning Sciences*, *82*, 101248. https://doi.org/10.1016/j.seps.2022.101248

Sisto, R., Fernández-Portillo, L. A., Yazdani, M., Estepa-Mohedano, L., & Torkayesh, A. E. (2022b). Strategic planning of rural areas: Integrating participatory backcasting and multiple criteria decision analysis tools. *Socio-Economic Planning Sciences*, *82*, 101248. https://doi.org/10.1016/j.seps.2022.101248

UN MODÈLE MULTI-AGENTS POUR L'ÉTUDE DES SYSTÈMES DE TRANSPORT FLEXIBLE EN MILIEU URBAIN. (n.d.). Retrieved 14 April 2025, from https://www.lecfc.fr/new/articles/231-article-12.pdf

Verma, G. (2024). A Comparative Study on Environmental and Economic Benefits of Centralized Versus Decentralized Solid Waste Management Systems. *International Journal for Research in Applied*

Science and Engineering Technology, *12*(6), 1775–1781. https://doi.org/10.22214/ijraset.2024.63416

Wang, Z. (2024). *Research on Key Issues and Pathways to Address "Agri-*.

Yaohong, W., Firdaus, R. B. R., Xu, J., Dharejo, N., & Jun, G. (2025). China's Rural Revitalization Policy: A PRISMA 2020 Systematic Review of Poverty Alleviation, Food Security, and Sustainable Development Initiatives. *Sustainability*, *17*(2), 569. https://doi.org/10.3390/su17020569

Zaraté, P., Mme, A., Alvarez, A. E., Sakka, A., & Camilleri, G. (2023). *Group Decision Support for agriculture planning by a combination of Mathematical Model and Collaborative Tool*.

Zhang, G., Lu, J., & Gao, Y. (2015a). Tri-level Multi-follower Decision Making. In G. Zhang, J. Lu, & Y. Gao, *Multi-Level Decision Making* (Vol. 82, pp. 121–171). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-46059-7_6

Zhang, G., Lu, J., & Gao, Y. (2015b). Tri-level Multi-follower Decision Making. In G. Zhang, J. Lu, & Y. Gao, *Multi-Level Decision Making* (Vol. 82, pp. 121–171). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-46059-7_6

Lammoglia, A. (2017). UN MODÈLE MULTI-AGENTS POUR L'ÉTUDE DES SYSTÈMES. *CFC (probablement Cahiers Francophones de la Communication ou une revue similaire)*, *numéro 231*, 153.

Annex



Annex 1 – Pseudocode of GA Algorithms

GA(S)

parameter(s): S – set of blocks
output: superstring of set S

Initialization :
$t \leftarrow 0$
Initialize P_t *to random individuals from* S^*
EVALUATE-FITNESS-GA(S, P_t)

while *termination condition not met*
do
- *Select individuals from* P_t *(fitness proportionate)*
- *Recombine individuals*
- *Mutate individuals*
- EVALUATE-FITNESS-GA$(S, modified\ individuals)$
- $P_{t+1} \leftarrow$ *newly created individuals*
- $t \leftarrow t + 1$

return *(superstring derived from best individual in* P_t*)*

procedure EVALUATE-FITNESS-GA(S, P)
S – *set of blocks*
P – *population of individuals*
for each *individual* $i \in P$
do
- *generate derived string* $s(i)$
- $m \leftarrow$ *all blocks from* S *that are not covered by* $s(i)$
- $s'(i) \leftarrow$ *concatenation of* $s(i)$ *and* m
- $fitness(i) \leftarrow \frac{1}{\|s'(i)\|^2}$

Annex 2 – Pseudocode of WSM Algorithms

Algorithm 1: Weighted-sum method (WSM)

Require: Number $k_{\max} \in \mathbb{N}$ of discretization points, $\alpha_{\text{tol}} > 0$;

Return : Discrete approximations $\tilde{\mathcal{P}}_s^{sw}$ and $\tilde{\mathcal{P}}_f^{sw}$ of weakly Pareto stationary points and front;

Set $\tilde{\mathcal{P}}_s^{sw} = \tilde{\mathcal{P}}_f^{sw} = \emptyset$;

for $i = 1, \ldots, k_{\max}$ **do**

  Set $\alpha_2 = \alpha_{\text{tol}} + (1 - 2\alpha_{\text{tol}}) \frac{i-1}{k_{\max}-1}$;

  Solve (9) with weight $(1 - \alpha_2, \alpha_2)$, check (10) and save a solution as u^i;

  Set $\tilde{\mathcal{P}}_s^{sw} = \tilde{\mathcal{P}}_s^{sw} \cup \{u^i\}$, $\tilde{\mathcal{P}}_f^{sw} = \tilde{\mathcal{P}}_f^{sw} \cup \{\hat{\mathcal{J}}(u^i)\}$;

Annex 3 – Pseudocode of BKPACS Algorithms

Algorithm 1 BKPACS Algorithm for Parcel-Level Crop Allocation

function OPTIMIZEPARCEL(*parcels*, *crops*, *weights*)
  Initialize pheromone levels $\tau_i \leftarrow 1.0$ for all crops i
  Initialize best solution $x^* \leftarrow \{\}$
  for all iterations $t = 1$ to T **do**
    Construct new solution x using ant behavior:
    Set remaining_area $\leftarrow$ parcel area
    while remaining_area ¿ threshold **do**
      Compute heuristic value $h_i = \frac{p_i}{c_i + w_s \cdot S_i}$
        ▷ Profit per unit cost adjusted by sustainability score
      Compute selection probability:

$$P(i) \propto \tau_i^{\alpha} \cdot h_i^{\beta}$$

      Select crop i based on $P(i)$
      Allocate random area $a \in [0.1, \min(k_i, remaining_area)]$
      Update pheromone:

$$\tau_i \leftarrow (1 - \rho)\tau_i + \Delta\tau_i$$

      if x improves over x^* **then**
        $x^* \leftarrow x$
      end if
    end while
  end for
  return Best solution x^* and evaluation metrics
end function