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Proposal of a Model of Irrigation Operations Management for Exploring the Factors That Can Affect the Adoption of Precision Agriculture in the Context of Agriculture 4.0

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Abstract: Agriculture is undergoing a profound change related to Agriculture 4.0 development and Precision Agriculture adoption, which is occurring at a slower pace than expected despite the abundant literature on the factors explaining this adoption. This work explores the factors related to agricultural Operations Management, farmer behavior, and the farmer mental model, topics little explored in the literature, by applying the Theory of Planned Behavior. Considering the exploratory nature of this work, an exploratory multi-method is applied, consisting of expert interviews, case studies, and modeling. This study's contributions are a list of factors that can affect this adoption, which complements previous studies, theoretical propositions on the relationships between these factors and this adoption, and a model of irrigation Operations Management built based on these factors and these propositions. This model provides a theoretical framework to study the identified factors, the relationships between them, the theoretical propositions, and the adoption of Precision Agriculture. Furthermore, the results of case studies allow us to explore the relationships between adoption, educational level, and training. The identified factors and the model contribute to broadening the understanding of Precision Agriculture adoption, adding Operations Management and the farmer mental model to previous studies. A future research agenda is formulated to direct future studies.

Keywords: precision agriculture; adoption; sensing technologies; irrigation; Agriculture 4.0; operations management; farmer mental model; center pivot; model

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1. Introduction

Agriculture is currently undergoing a profound change [1] due to a new technological revolution [2,3] related to the development of Agriculture 4.0 and the diffusion of technologies, such as the Internet of Things (IoT), big data, artificial intelligence, and cloud computing [4,5]. Agriculture is also experiencing a technological transformation related to the adoption of Precision Agriculture (PA), which, after 20 years of research, is not consolidated [6]. Despite the expected economic gains [7], PA adoption is often perceived as not occurring immediately [8], and it is progressing at a slower speed than predicted [9] due to several factors; among them, the lack of farmer knowledge about the use of PA technologies plays an important role in business outcomes [10]. There is a lack of consensus on whether PA improves farm profitability, in addition to the little attention paid to perceptions of PA profitability from the farmer's perspective [11].

Despite the abundant literature on the factors affecting PA adoption [12–14], factors related to Operations Management in agriculture [15] and farmer behavior [16,17], specifically their beliefs that are the basis of the farmer mental model [18,19], are little explored. In most studies, the factors are organized in models based on the theory applied in the research, like the Technology Acceptance Model [17] and Utility Maximization [20]. Theories for studying human behavior, such as the Theory of Planned Behavior (TPB) [21], were applied in rare cases in previous studies [22]. The TPB provides a solid conceptual framework useful for analyzing farmer behavior [23–25].

Operations Management (OM), applied in an agriculture context, as well as in manufacturing and services organizations, is the function associated with the design and management of the transformation processes of inputs into outputs [26] and supports designing, planning, scheduling, and executing operations involving humans and machines [27,28]. However, the factors affecting PA adoption related to the modeling of irrigation OM are scarce in the literature [15].

There is a limited availability of publications that delve into the farmer mental model within studies focusing on the adoption of Precision Agriculture (PA) [18,19]. Applying the concept of the mental model allows for an understanding of farmer decision making, linking perceptions, attitudes, and beliefs with behavior [29]. Farmers do not only make decisions based purely on economically rational motivations but also consider social and intrinsic objectives [30].

In the context of this ongoing technological revolution, Agriculture 4.0 has been developed through the evolution of PA [6,31]. Technologies included in the concept of Agriculture 4.0 allow us to improve planning and control in agricultural production [32], allowing us to follow plant and yield development progress through information collected by sensors [33] and to access a large amount of site-specific data to make more accurate decisions in farm management [34]. Most of the research carried out on Agriculture 4.0 is more theoretical [31,35]. Moreover, overemphasis is placed on high-tech solutions to the detriment of the inclusion and exclusion effects of Agriculture 4.0 technologies [36] and the social impacts of these new technologies [37,38], as well as to the factors related to OM, farmer behavior, and the farmer mental model, which can all affect PA adoption.

Therefore, in this work, we aim to contribute to filling the identified gaps, answering the following research questions: (1) What are the factors related to irrigation OM that can affect the adoption of PA in the context of Agriculture 4.0? (2) What are the factors related to the farmer's behavior, focusing on the mental model, that can affect the adoption of PA in the context of Agriculture 4.0? (3) What are the factors related to the modeling of irrigation operations, with a focus on OM and the farmer mental model?

To answer these questions, in this study, we aim to achieve the following research objectives: (1) exploring the factors related to irrigation OM that can affect the studied adoption; (2) exploring the factors related to farmer behavior, focusing on the mental model, that can affect the studied adoption; and (3) modeling the irrigation operations, with a focus on OM and the farmer mental model, to understand and formalize the relationships between adoption and the identified factors.

This work is characterized as exploratory since little research has been conducted on the topics being studied, an insufficient number of studies exists to document the research problems, and the variables and theory base are unknown. Exploratory study can help to develop theoretical propositions and frameworks [39,40]. This research adopts an exploratory multi-method made up of expert interviews, case studies, and the modeling of irrigation operations [39,41–43].

The empirical results of 27 expert interviews and two case studies on farms were used to develop the irrigation OM model [41]. For modeling, the Integration Definition for Function Modeling (IDEF0) technique was applied, which offers a standard and widely used approach to develop the conceptual models of systems [44], like farms; to represent products, controls, restrictions, and resource information in the same diagram [45]; and to identify system components, data requirements, and information flows [46].

Irrigation operations are the object of study in this research, according to the international project "Smart Water Management Platform" (SWAMP), in which context this study is carried out. The SWAMP project aims to bring the IoT concept to Precision Irrigation and to develop irrigation systems to optimize water use [47].

As for the scope of the research, in line with the SWAMP project, the farmer or farm manager is the central actor in the decision-making process on a farm, depending on its business and organizational structure [48]. Furthermore, in the literature and in the results of expert interviews and case studies, common factors between adoption and decision making in irrigation OM can be identified. According to the research objectives, the behavior "decision making in agricultural OM" is outside the scope of this work.

Considering the research gaps identified and the research objectives, the empirical results of this work contribute to theoretical progression in the literature on the adoption of PA, adding a set of factors related to OM and farmer behavior, including this mental model. The organization of these factors in a framework represents the irrigation OM and relationships between the factors in a structured way, contributing to an explanation of the adoption. The empirical results suggest a change in the farmer mental model in the adoption of OM models inspired by the industry. The results of the case studies also contribute to exploring the relationship between the adoption and some factors, such as educational level and training.

In addition to theoretical contributions, this research also provides a practical contribution. The proposed model can be used for the development of an Irrigation Management System (IMS), integrating the agronomic management of a crop and the irrigation OM.

A future research agenda is formulated, based on the results achieved, the theoretical propositions generated from the results of expert interviews and case studies, and the scope of the work.

This work is structured with the Materials and Methods in Section 2. Section 2.1 introduces the literature review; Section 2.2 describes the exploratory multi-method. The results of the study are displayed in Section 3. A discussion of the findings is provided in Section 4, and the limitations and the research agenda are covered in Section 5. At the end, Section 6 draws the conclusions.

2. Materials and Methods

This section presents the literature analyzed and the method applied in this work.

2.1. Literature Review

In this section, previous studies on Precision Agriculture adoption, Agriculture 4.0, Operations Management, farmer behavior, and Theory of Planned Behavior are analyzed to identify the theoretical concepts useful for studying the adoption and for identifying the topics that can be considered factors that can affect PA adoption (theoretical basis) and for collecting the factors that can affect the adoption cited in these studies (empirical basis). The theoretical concepts, topics, and factors analyzed in this section constitute the theoretical and empirical bases in conducting expert interviews, case studies, and building the model of irrigation OM. The definitions of Precision Agriculture and Agriculture 4.0 used in this work are also reported.

2.1.1. Precision Agriculture, Precision Irrigation, and Factors Affecting the Adoption

In the literature, there was no consensus on the definition of PA before 2019, when the International Society for Precision Agriculture [49] proposed the official definition that this work uses. This lack of a shared definition has made studying adoption difficult. In addition, the kind of technologies [50], like yield mapping, variable rate application, and remote sensing [7,51], affects the adoption.

The PA concept encompasses Precision Irrigation (PI), which is included in the PA technologies that can optimize crop responses for applied water units [16,52]. PA technologies for irrigation enable farmers to collect site-specific data that provide valuable quantitative information for effective irrigation management [53]. PI, despite being recent and still poorly studied, has great potential to contribute to improving irrigation efficiency, thus increasing economic returns with a reduction in energy use [54]. The irrigation systems used can be classified as sprinkler (e.g., center pivot), surface, and drip systems [55]. In the SWAMP project, center pivot and drip systems were studied [47].

Regardless of the irrigation system used, it is particularly important to accurately estimate the irrigation water requirement. According to the research carried out in the SWAMP project, this study applies the Food and Agriculture Organization version of the Penman Monteith model [56,57] and the approach based on the water balance [58,59] to estimate the irrigation water requirement.

The extensive number of studies on PA adoption direct the attention of researchers towards several factors, such as characteristics of farmers (e.g., age, educational level, computer use, training), farm characteristics (e.g., size, location), benefits (e.g., reduced water use), and barriers (e.g., software cost, funding sources) [13,14,60,61]. The factors related to values and beliefs determining the farmer behavior [29] and the factors associated with the agricultural OM [15] have been little studied. Most works apply the survey method [17], while qualitative methods are little used [62–65]. Regarding Precision Irrigation, its adoption is also influenced by factors, like soil quality, water cost, energy cost, crop type [16,66].

2.1.2. Agriculture 4.0 and Factors That Can Affect the Adoption

Agriculture 4.0 has a vague and unclear definition. A commonly accepted definition does not exist, and it is not entirely clear where the term Agriculture 4.0 originated [35,67]. Some researchers consider Agriculture 4.0 to be an evolution of PA [6,31,68]. According to them and to the study of Precision Irrigation adoption in pilot farms in the SWMP project, this research uses the following definition of Agriculture 4.0:

> "*Agriculture 4.0 is a management strategy, evolution of precision agriculture, realized through the automated collection, integration and analysis of temporal, spatial and individual data, collected by IoT sensing technologies and farm resources, making in this way possible the generation of knowledge, to support the design of applications for the farmer decision making process in irrigation operations management*". [69] (p. 21)

Most studies on Agriculture 4.0 are theoretical, but empirical works are increasing [70,71]. Research dealing with OM is still rare [32,72].

Agriculture 4.0 has the potential to bring numerous benefits, like water and energy cost decreases [73]. Through the automatic collection, integration, and analysis of data from different sources, Agriculture 4.0 allows us to generate knowledge and support the farmer in decision making, potentially increasing farm profitability [4]. Information gathered by sensors can be utilized to follow the plant and yield development progress [33].

Factors that can affect the adoption related to OM and farmer behavior include planning and control in agricultural production, degree of mobility of the production facilities [32], skills to operate equipment, limited knowledge, and capacity to adopt and to understand the technology [37].

2.1.3. Operations Management in Agriculture and in Irrigation

Operations Management is the management of a systemic transformation process to convert a set of inputs into outputs. These inputs include labor, equipment, raw materials, and information, while the outputs are goods and services. OM serves as a continuous improvement process to enhance quality, productivity, and customer satisfaction [74]. Its purpose is to plan and control the operations necessary to produce the goods and services demanded by the customer [28]. Production Planning and Control (PPC) is one of the core functions of OM. It aids in resource planning and utilization to ensure maximum productivity, quality, and competitiveness [75].

In agriculture, OM is responsible for designing, planning, scheduling, and executing operations involving humans and machines. An operation (e.g., seeding, fertilization, and irrigation) links resources and materials processed and produced [28,32,76]. The operations are performed with men and machines [77,78]. Resources include land, working hours, machinery, and equipment [76,79]. A management model for agricultural machinery operations, which is based on four management phases (planning, scheduling, operating, and controlling), was proposed by [27] (p. 71).

The vision of OM in agriculture has evolved since the 1950s: mechanization (1950s–1970s), work organization (1970s–1990s), information and communication technologies, automation (1990s–today), and robotics (in the future). In this evolution, the notions of planning and scheduling play a central role, leading to the need for advanced management, data acquisition, and analysis tools for making decisions [28].

Farmer decisions include decisions related to development stages (such as pesticide and irrigation applications); decisions related to planting (like choice of crop type, planting date); harvest and post-harvest decisions (such as harvest date) [80]. Decision making depends on uncontrollable factors (such as weather conditions) and factors that can be modified (like irrigation infrastructure) [76]. Decisions are influenced by farm planning, which involves seasonal determinations, such as types of crops to cultivate, equipment and workforce requirements, irrigation policies [81], operational production practices, and level of production costs [82]. In addition, the farmer must consider the timeliness of some operations and that some operations and decisions are interconnected [79]. Furthermore, many operations need to be performed in a specific order, such as field preparation [83].

Regarding OM in irrigation, two decisions take priority in planning: definitions of the amount of water to apply and of the irrigation time. These decisions are affected by factors like climate and crop development stages [55]. To decide the optimal level of irrigation for each field, at the beginning of each irrigation period, farmers need to consider other factors: water availability, irrigation costs, crop size, management zones, crops planted, and soil moisture [84]. Energy is currently one of the main production resources in irrigated agriculture, and its cost must always be considered in irrigation management [54]. The cost to irrigate a field is determined by the amount of water pumped and the cost to apply it. The factors that producers can influence include irrigation planning, application efficiency, pumping pressure required, type of energy used, distance from the water source, and unit cost of energy. The cost to pump water for irrigation depends on the type of energy used, like electricity and diesel fuel [85].

2.1.4. Farmer Behaviour, Theory of Planned Behaviour, and Farmer Mental Model

Theories Used to Explain the Adoption of Innovations

A range of purely economic-based models have been developed to predict farmer decision making [86], which can be modeled in terms of individual action to maximize profit [87] or expected utility [88]. There is also extensive rural sociological literature in which the farmer attaches significant importance to aspects of lifestyle and personal considerations, which interact with management decisions. This literature suggests that purely economic models cannot capture the full complexity of farmer motivation and behavior [87], as adoption is based on farmer perceptions [89].

Four theories can be considered references to develop models to analyze the farmer decisions for innovation adoption and to establish the basis for choosing explanatory factors [90]: Utility Maximization [88], Theory of Reasoned Action and Theory of Planned Behavior [21], and Technology Acceptance Model [91].

As a result of comparing these theories and considering that the TPB provides a solid conceptual framework [92] to structure the research, this work applies the TPB. This choice is also justified by the attention to human behavior when the person has partial control over the decision making [93], characteristic of the PA context in which access to information is a barrier for the adoption [16,94]. New PA technologies are often produced through developers, and there is a large knowledge gap between developers and users [95]. Furthermore, studies based on TPB analyze farmer behaviors in a deeper and more complete way, thanks to including the Subjective Norm and Perceived Behavioral Control constructs [96].

Theory of Planned Behaviour

The TPB is a well-known and frequently applied framework to predict and explain human behavior [97] and to also study farmer behavior, like the switch from traditional to pressurized irrigation [98]. Intentions to perform behaviors can be predicted from attitude towards the behavior (ATB), Subjective Norm (SN), and Perceived Behavioral Control (PBC). The more favorable the ATB and SN are, and the higher the PBC, the stronger the intention to perform the behavior must be [21].

In TPB research, it is important to clearly define the behavior under study in terms of target to which it is directed, action performed, context in which it occurs, and relevant period [97].

The TPB is open to the inclusion of additional predictors, if they can be shown to capture a significant proportion of the variance in intention or behavior [21], and to the inclusion of background factors (such as age, educational level, experience) that can influence people's beliefs [97].

The standard research methods developed over the years for the use of TPB are largely quantitative. Furthermore, the TPB can be used as a framework to guide the questions in qualitative research [99], as in this work.

Farmer Beliefs and Farmer Mental Model

The constructs ATB, SN, and PBC are related to beliefs about the behavior [21], which represent the information people have about a behavior, its consequences, the expectations of other people, and the impediments. By measuring these beliefs, the TPB has the potential to create the links between beliefs and behavior of an adopter of PA technologies [12].

The farmer beliefs, relative to the adoption of PA, are the basis of this mental model, built by the human mind through perception, experience, attitudes, knowledge, and the comprehension on the behavior [29]. The mental model is also relevant in decision making in agriculture. The use of farmer mental model has the advantage of a certain element of adaptation, and the drawback is the lack of precision, particularly in areas where the farmer is inexperienced. The use of computerized models allows the farmer to base their decisions on a more comprehensive set of information, gaining more precision [28]. The literature on factors affecting farmer decisions also considers conservatism, which is included in the beliefs underlying the farmer mental model [92].

This work considers, through expert interviews and case studies, the factors that can affect the adoption of innovations mentioned in this section, using the TPB as framework and focusing on farmer beliefs and his mental model, to broaden understanding of the determining factors of the PA adoption. The SN and factors related to PBC, which involve actors operating in farm ecosystem, are classified outside the scope of this study.

2.2. Method

Considering the exploratory nature of the research questions and the gaps in the theoretical and empirical basis on the factors that can affect the PA adoption, and on Agriculture 4.0, an exploratory multi-method was adopted, shown in Figure 1, consisting of interviews with experts, case studies, and the modeling of irrigation OM [39,42,43,46].

Multiple research fields were combined to triangulate the results of each method, to provide a more complete and deeper understanding of the factors that can affect the adoption of PA [43,100].

In this methodology, the researcher adopts multiple methods of data collection and data analysis. Data are collected in expert interviews and case studies to generate ideas and theoretical propositions and then to build a theoretical framework (model of irrigation OM) [39]. Interviews with experts [43] and case studies [42,101] in a pilot of the SWAMP project and on a farm in Brazil, in the State of Bahia, were conducted to identify factors that can affect the adoption and to formulate theoretical propositions for building a model of irrigation OM with the IDEF0 technique [41]. The objective of this approach was to induce emerging insights from empirical research [102], to develop theory [40,42,101]. Expert interviews and case studies are especially useful when the researcher does not know the variables to examine [39], for new areas of research or areas for which existing theory seems inadequate [101], like the explored adoption. Furthermore, as highlighted by [103], talking to experts in the exploratory phase of research is a more efficient method of data collection than, for example, quantitative surveys. Main characteristics are described below for each method.

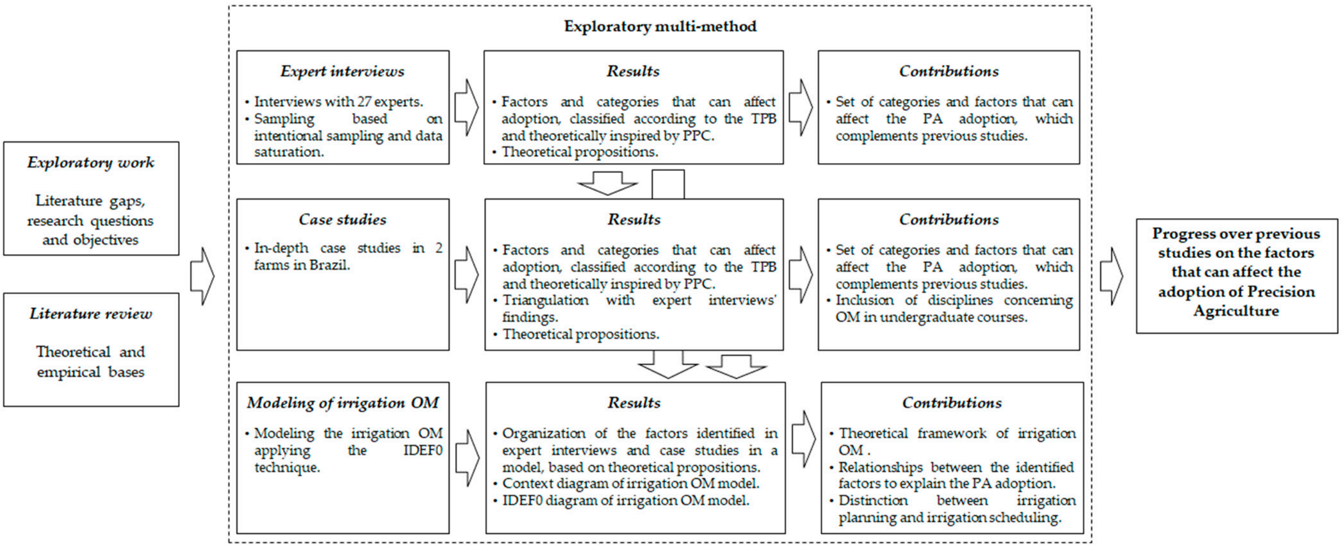

Figure 1. Exploratory multi-method.

2.2.1. Interviews with Experts

The expert interview is a qualitative method designed to draw on expert knowledge. According to the research objective, the researcher decides who to interview as an expert in their own field of knowledge [104]. In addition to exploring knowledge, an expert interview can be used to provide guidance on a recent or unclear thematic field and to generate theoretical propositions [103].

Due to the interdisciplinary nature of this project, 27 experts were selected for their expertise in agribusiness management, Precision Agriculture, irrigation, water resources management, and Operations Management. The protocol and questionnaire used in the interviews, illustrated in Supplementary Material A, were based on the precepts of the TPB [21] and focused on irrigation OM [105]. Additional questions were asked only if a participant response to the initial question did not cover certain topics of interest [106]. To reduce response bias, the definition of Agriculture 4.0 was not included in the questionnaire and was not provided to respondents [43,107].

To establish how many interviews to conduct, there are several factors affecting the sample size: population heterogeneity, budget, available resources, scope of the study, experience of the interviewer, availability of participants [108]. According to [106], in this work, intentional sampling was applied, with the aim of reaching data saturation (data saturation is the point in data collection and analysis when new information produces little or no change in the codes [106]) in relation to the codes (codes are theory or model building blocks on the basis on which the researcher arguments rest, according to the research question [106]) identified from data collected in the interviews and then in relation to the identified factors. So, the number of experts interviewed was 27, because when the 27th interview was completed, no new information was observed in the data. As, in this research, probabilistic sampling was not applied, the sample of experts interviewed is not representative. Furthermore, the codes ("deconstruction" of experts' knowledge) and the theoretically inspired perspective ("reconstruction" of experts' knowledge) were identified based on the knowledge of the literature on PA, Agriculture 4.0, OM, and farmer behavior [109]. The result was a review of the texts and terminology of the interviewees and the consequent creation of codes. This led to a "reconstruction of experts' knowledge" and to the representation of empirical results [104].

As a result of the evolution of the COVID-19 pandemic, it was not possible to access the university to use software to analyze the data collected in the interviews.

2.2.2. Case Studies

The researcher chooses single cases when the purpose is exploration and in-depth study [42], while he chooses multiple cases when the logic of replication in more cases is pursued rather than sampling [40,101]. Therefore, two in-depth case studies were conducted, considering the exploratory purpose for theory development and the possibility of carrying out in-depth studies.

In line with the objective of disseminating the SWAMP project results, case studies were conducted on two farms in Brazil: the first in the MATOPIBA pilot, and the second on a farm not involved in the project. To preserve and guarantee confidentiality, this company was named "Farm Bahia". The two case studies provided homogeneous characteristics in terms of interest in participating in research projects, farm size (industrial farm), location (State of Bahia), climatic region, irrigation system (center pivot), organizational structure (farm manager), and farmer characteristics (i.e., age, educational level, innovation capacity). Therefore, according to [40], these studies presented profiles to predict similar results.

The protocol for the case studies and the questionnaire with the objective of the interview, the context of which the research is part, and the proposed questions are shown in Supplementary Material B. The questions, based on the TPB precepts and focused on the irrigation OM, were the same as in the questionnaire used for the interviews with experts. Instead of the phrase "Agriculture 4.0", questions referred to sensors and drones, to be equipment the farmer could identify as representative of innovative technologies for irrigation, in addition to being equipment included in the context of Agriculture 4.0.

The data collection techniques applied were as follows: interviews, photos, farm reports, farm contracts, consultants' reports, and IMS database. The interviews were conducted remotely, and it was not possible to visit the farms due to the COVID-19 pandemic. To analyze the data collected in the case studies, the process of coding the data collected in the interviews with experts described in Section 3.1 is applied [63,64].

2.2.3. Modeling Techniques and IDEF0

In the literature, there are different techniques for modeling the structure, behavior, and organization of a company or information system, such as IDEF0 and Unified Modeling Language [44,45]. Considering that the IDEF0 is simple, it allows for the development of conceptual models of business models, and it is a standard governed by rules and conventions, representing data and resources in the same diagram. This work applied the IDEF0 technique to model the irrigation OM, also in accordance with the exploratory purpose of the question and research objectives. Furthermore, in the OM literature, the IDEF0 technique was applied by several authors to model PPC in companies in the manufacturing [46,110–112] and agricultural sectors [45].

An IDEF0 model involves a hierarchy of diagrams whose central components are boxes (representing a function: activity, action, process, operation) and arrows, representing an interface. An interface can be an input, entering the left box, transformed by the function and leaving the right box as output; a control, entering the top of the box and determining the function (i.e., procedure, command, worker experience); a mechanism, a tool or resource performing the function. Each box can be broken down to a lower level of detail, forming a hierarchy of information that is summarized in a tree of nodes [41].

3. Results

This section presents the results of the interviews with the experts, the case studies in the MATOPIBA pilot and on "Farm Bahia", and the model of irrigation OM. The data collected in the expert interviews and case studies, associated with the factors found in the theoretical and empirical bases of the literature, were used to identify the categories and factors that can affect the explored adoption. These data collected were coded based on the TPB constructs in scope (Attitude and Perceived Behavioral Control), on the categories and factors resulting from the literature review [21,101,109]. The coding process to identify the categories "Operations Management models inspired by the industry" and "Resources", and the factors "operations planning and control models", "resources (hardware—agricultural equipment, sensors)", is presented in Table 1.

Table 1. Example of coding process.

Theoretically Inspired Perspective: TPB, Production Planning and Control		**Deconstruction of the Knowledge**	**Reconstruction of the Knowledge**
TPB Constructs	**Literature**	**Interviews—Excerpts with Similar Topics**	**Categories**
Perceived Behavioral Control (impediments and obstacles, available resources and opportunities)	In agriculture OM is responsible for designing, planning, scheduling, and executing operations involving humans and machines [28]. Production Planning and Control (PPC) is one of the core functions of OM [75]. Agriculture 4.0 allows to improve planning and control in agricultural production [32]. Agriculture 4.0 allows to follow plant and yield development progress through information collected by sensors [33].	"*There are classic industry planning tools the farmer could use, such as PERT, CPM, and ABC costing system*", expert 1. "*The adoption of Agriculture 4.0 allows the farmer to optimize the use of resources, the use of water. The adoption of sensors improves irrigation and equipment planning so that irrigation is more effective*", expert 5.	Operations Management models inspired by the industry, Resources **Factors** Operations planning and control models, resources (hardware—agricultural equipment, sensors)

Responses from interviews and case study data were categorized based on TPB constructs and then analyzed to identify excerpts with similar topics from the interviews ("deconstruction" of the knowledge of experts and farm managers). Based on the factors identified in the literature on PA, Agriculture 4.0, farmer behavior, and OM, excerpts with similar topics were grouped into codes to define categories and factors ("reconstruction" of knowledge). The empirical results were framed by a theoretically inspired perspective [104], guided by the TPB and the introduction of inspired models from the industry, like the PPC.

The codes were organized into categories (e.g., "performance measures", "data access") and factors. The proposal to introduce industry-inspired models in irrigation was based on the factors related to OM analyzed in Section 3.1 from interviewed experts. This process was recursive, while in the analysis, it was necessary to return to a previous stage to verify the adequacy of generalizations [104]. In the analysis of data collected, a check was carried out to identify categories and factors found in other answers [40].

3.1. Results of Expert Interviews: Factors and Categories That Can Affect the Adoption

Between April and August 2021, 27 interviews with experts were carried out. Supplementary Material C summarizes the experts' profiles. The choice criteria were based on the interviewees' expertise in agribusiness management, PA, irrigation, water resource management, and OM. Experts with experience as researchers and in water resource management were included, considering the importance of this topic for this work. Initially, four experts were selected who illuminated the research questions. To select the other experts, the "snowball" sampling technique was adopted [113].

All interviews were conducted remotely because of the COVID-19 pandemic. A pilot interview was organized to test the questionnaire [102]. The questions were unambiguously formulated, and clarifying questions were asked to complete the expert answers [18]. All interviews were recorded and transcribed in full. Confidential and sensitive references or data were omitted or substituted to ensure the privacy and anonymity of the interviewee [106].

The answers of the experts interviewed were categorized and classified to produce the transcripts, with the results shown in Supplementary Material D. The factors and categories are shown in Table 2. The factors and categories are classified according to the TPB constructs and based on previous studies on PA, Agriculture 4.0, OM, and farmer behavior.

Table 2. Results of expert interviews: factors and categories that can affect the adoption.

TPB Constructs	Factors	Categories
Attitude	Crop water requirement, water use, energy use, cost of water use, cost of energy use, variable rate water use, production yield, profit, revenue, production cost.	Quantitative performance measures
	Management benefits, improvements in irrigation planning, improvements in irrigation control.	Qualitative performance measures
	Access to agronomic data, access to operational data.	Access to data
Perceived Behavioral Control	Technical training, managerial training, mental model, irrigation management, data-based management, farm management as a business.	Changes for the farmer
	Farm management, Operations Management, workforce qualification.	Changes for the farm
	Operations planning and control models, collaborative management models.	Operations Management models inspired by the industry
	Resources (inputs, hardware, people), inputs (water sources, water, energy), hardware (agricultural machinery, agricultural equipment, weather stations, soil probes, drones, satellites, sensors, Irrigation Management System, people (farmers, farm managers, workers, consultants).	Resources
Antecedent Factors	Age, educational level, income, experience in agriculture, familiarity with technologies, family of farmers, conservatism, managerial training, absorptive capacity, risk propensity, innovation capacity.	Farmer characteristics
	Farm size—family farm/industrial farm, farm location, crop type, cooperativism, production volume, product profitability.	Farm characteristics
	Technology type, equipment type, price, complexity.	Technology characteristics

Regarding the analysis of the interviews, if the quotes led to the identification of benefits and positive results expected following the adoption, the factors were classified in the attitude construct. If the quotes led to identifying obstacles, resources, and opportunities related to the adoption, the factors were classified in the PBC construct. The factors and categories identified in the responses to additional questions were included in the most proper factors and categories, based on the coding process. Factors unrelated to OM and relative to stakeholders in the farm ecosystem were classified as out of scope.

The benefits of the studied adoption can be measured through performance measures related to attitude, identifying quantitative or qualitative benefits that can be achieved with adoption. Quantitative performance measures are benefits to which a measurement can be associated concerning planning and the control of irrigation operations. All the experts pointed out that the adoption involves a cost reduction: irrigation water use and energy use reduction. Experts 11, 14, 16, 23, and 27 added that the adoption can lead to a rational use of water in terms of irrigation in the right amount, closer to the crop water requirement, at the right time and in the right place. The reduction in water use, and the relative cost, has an impact on energy savings, according to experts 2, 8, and 11: "*The farmer will have a water savings because he will be able to define the exact amount of water for that exact area, and with that he will be able to save energy which is one of the big problems in irrigated agriculture*", expert 11. Experts 23 and 25 emphasized that the reduction in water use, and the relative cost, affects an increase in production yield due to irrigation efficiency. Therefore, saving water and energy has a positive impact on the farm economic results, as suggested by experts 6, 11, and 16.

Regarding qualitative performance measures, the interviews allowed us to identify benefits related to irrigation management, as stated by expert 3 (management benefits compared to increased productivity) and expert 26 (changing from planning based on experience to planning based on data).

The explored adoption can bring benefits thanks to access to more organized data, promoting better operation planning and control, as reported by experts 16, 26, and 27. These benefits could be related to access to agronomic data on crops, soil, and climate, possibly due to the adoption of sensing technologies, according to experts 11 and 27. These data can be used to calculate the crop water requirement and irrigation water requirement. The farmer also has the possibility to access operational data related to irrigation operations, such as water availability, water flow, cost of water use, water access contract, and energy supply contract, according to experts 1, 17, 18, and 27.

Factors concerning the changes required for the adoption are classified into two categories: "Changes for the farmer" and "Changes for the farm".

As for the changes for the farmer, they must be trained to adopt PA technologies, as reported by experts 15 and 16. Expert 16 states that: "*The farmer must be trained and prepared in terms of knowledge and skills to use these technologies. If he doesn't understand it well, he most likely won't adopt correctly*".

Training includes technical training and management training, as reported by expert 13. Technical training is necessary for irrigation, to understand what irrigation is, what irrigated agriculture is, and that the agricultural field has variability, according to expert 17. Managerial training concerns specific skills for data analysis, planning, and management of new technologies, as reported by expert 6, who stated: "*It is necessary to change the farmer managerial training and the workforce qualification, because the adoption of Agriculture 4.0 involves the introduction of a production system that demands a set of specific skills, of data analysis, of handling machinery to operate according to the planning*". Experts 1, 10, 13, and 24 show that this change must overcome some challenges in terms of farmer perception, low levels of education, and training, including the areas of operation engineering and management. Expert 1 emphasized that: "*Planning is not easy for the farmer, because he was not trained for it, he understands little about operation engineering, and often those who advise the farmer do not have this training either*".

These challenges are linked to the need to change the farmer mental model, according to experts 2 and 20. Expert 14 stated that: "*The main barrier is cultural, in addition to the need to be trained to assimilate these technologies. And it depends on the farmer age, who mainly relies on his experience*". This mindset shift involves irrigation management, data-driven management, and managing the farm as a business. The farmer needs to change their belief that irrigating is different from applying water and irrigated agriculture is different from rainfed agriculture plus water, as highlighted by experts 4, 11, and 17. The farmer also needs to change his mental model to move from intuition and experience-based management to data-based management, which brings benefits to the planning of operations, as reported by experts 14, 15, and 26. Expert 21 stated that: "*The culture of many farmers is based on family and community knowledge, transmitted from father to son, rather than adoption of techniques from scientific knowledge. There is a gap between the supplier of knowledge, which leads to training and the ability to understand, and the farmer in the adoption of irrigated agriculture techniques*".

The shift to data-based management must also make farmers aware that water is a scarce resource. The adoption of sensing technologies can enable this change on water scarcity, which can be measured with a rational use of water, as said by experts 10, 19, 22, and 27.

Regarding the management of the farm as a business, the farmer has great difficulty in management, as reported by expert 12. Experts 5 and 23 added that the farm management must also include irrigation planning and control: "*Irrigation control is something that should always be considered in a planning process, which is part of managing a property*".

In addition to the changes for the farmer, the analysis of the interviews enables one to identify the factors classified in the category "Changes for the farm". For the studied adoption, farm management results as the central change, as reported by experts 14 and 10, which must be built on the basic functions of administration (planning, implementation, and control). The changes for the farm also involve the Operations Management, according to expert 6: "*The OM has developed with a short delay in Brazil. These are aspects of agricultural production that have not evolved at the same speed as the agronomic aspects*". Expert 1 highlighted that the OM is an area undervalued by the farmer because he does not have much knowledge about it. Expert 20 added to this with changes in organizational characteristics, such as control mechanisms and performance indicators, while expert 6 also emphasized the characteristics of integration between different systems within a farm to collect and analyze production data. Another factor classified in the changes for the farm is the qualification of the workforce, which is considered one of the cornerstones to overcome for adoption, according to experts 4, 6, 9, 12, and 19.

It is important to highlight that these changes related to the adoption studied must be gradual, and the adoption of Agriculture 4.0 is not a single path, as stated by experts 2, 4, 7, 12, and 26. Expert 12 said that "*Agriculture 4.0 has several stages and the farmer can move from the initial one, which do not involve robotization. The farmer can adopt with a more gradual process in which the cost-benefit analysis is easily identified*".

Concerning the category "Operations Management models inspired by the industry", experts 1 and 6 inspired the adoption of planning and control models of operations, which consist of planning, scheduling, and control of irrigation management. Expert 1 pointed out that these models are not yet applied in agriculture and suggested industry models such as PPC: "*There are planning tools, classic in the industry, such as PPC, for the planning of operations: the farmer would need to have process mapping, production flow, activities, times, costs of machines, labor, demand forecast. With this information, the farmer could create a proper decision making support system*".

Another opportunity available to the farmer, following the adoption, is constituted by collaborative management models, as reported by experts 16, 22, 25, and 27. Expert 16 suggested the use of a process of negotiated allocation of water: "*The water resources management agency can talk to the farmers to check who will plant, who will not, who will irrigate and who will not, to distribute the available water in the most critical period and prevent the farmer from planting*". Expert 25 inspired the adoption of the Just-in-Time (JIT) management model [114] to control the use of motors and pumps in irrigation systems for monitoring water abstraction in farms. The adoption of these collaborative models enables them to overcome some challenges related to irrigation planning and control in the case of shared management of water resources, ensuring the availability of water throughout a season for the farmer.

The analysis of the responses relative to the PBC also identifies the category "Resources", which includes inputs, hardware, and people. These resources are necessary for the management of information concerning the planning and control of operations, according to experts 1 and 27. The adoption of hardware makes it easier to achieve benefits for irrigation planning, as in the case of sensors: "*If the farmer works with sensors, he has more accurate data on water withdrawal and applied for irrigation. He can plan the irrigation system so that irrigation is more effective*", expert 5.

Regarding resources, experts 2, 3, 8, and 24 highlighted the role of consultants in irrigation planning. Expert 3 emphasized that: "*Companies that provide services on irrigation planning obtain data from equipment, sensors and have a team that processes this data and makes recommendations to the farmer*". These services are predominantly contracted by large producers, who normally have a skilled workforce, as reported by expert 2.

Based on the quotes from the experts, the explored adoption can also be affected by the farmer characteristics, farm characteristics, and technology characteristics, as highlighted by expert 1: "*The application of the technologies included in the concept of Agriculture 4.0 will have different speeds, according to the regions of the country, the farm and farmer characteristics, the product types. In some plants and some farms, Agriculture 4.0 should arrive faster*"; expert 5 shared this view.

Concerning the study of the benefits of the adoption, and according to the importance of the attitude construct for the benefits associated with the adoption and perceived by the farmer [86,115], it is important to emphasize the farmer characteristic "conservatism", as highlighted by expert 3: "*The rural producer does not believe in things, he wants to see things*". Expert 30 added: "*For the farmer to trust an innovation, he needs to see where it worked, it was tested, there are results and how he can adopt it*".

As reported by expert 1, the adoption can also be affected by the farm characteristics. Cooperativism is a factor that can help in the adoption and use of models for irrigation OM, such as hiring consultant services, according to experts 3 and 24.

3.2. Results of Case Studies: Factors That Can Affect the Adoption

To conduct the case studies, the MATOPIBA pilot and "Farm Bahia" were selected due to their qualities in innovative irrigation systems. Theoretical sampling was adopted [101] due to the characteristics of the farms linked to the theory and the literature addressed in this work, such as exploring the adoption in farm size—industrial farm and in center pivot irrigation system. The choice of "Farm Bahia", familiar with the participation in research projects, was also consistent with the objective of the SWAMP project to replicate the results in terms of models and solutions.

The research protocol was designed with the questions to be applied in the interviews and the specific data to be collected [21,101,105]. Interviews with the farm manager of the MATOPIBA pilot were conducted between January 2020 and December 2021 and with the "Farm Bahia" manager between June 2021 and December 2021. The farm was the unit of analysis, according to the SWAMP project objective and the research questions [40].

The factors that can affect the adoption resulting from the cases, shown in Table 3, were classified according to the TPB constructs and the theoretical and empirical bases, and were triangulated with the findings of expert interviews [40,43].

Table 3. Results of case studies: factors that can affect the adoption.

Categories	Factors	Farm Bahia	MATOPIBA Pilot
Farmer characteristics	Educational level	Degree	Degree
	Age	30–35 years	30–35 years
Farm characteristics	Farm size	9800 hectares	915 hectares
	Crop types	Soybean and corn	Soybean, corn, sorghum, and cotton
Performance measures	Quantitative Qualitative	Used Not adopted	Used Not adopted
Access to data	Access to agronomic data	Weather station, IMS	Weather station, IMS
	Access to operational data	Contract for access to water, contract for energy supply, IMS	Contract for access to water, contract for energy supply, IMS
Changes for the farmer	Technical training	Skilled farm manager	Skilled farm manager
	Managerial training	Access to the market	Access to the market
	Mental model	Minimization of the cost	Minimization of the cost
	Cost of water use	Not yet charged	Not yet charged
	Data-based management	Also experience	Also experience
	Farm management as a business	Used	Used
Changes for the farm	Farm management	Industrial farm	Industrial farm
	Operations Management	Undervalued area, untrained farm manager	Undervalued area, untrained farm manager
	Qualification of workforce	Low educational level	Low educational level
OM models inspired by the industry	Models of planning and control of operations	Undervalued area, untrained farm manager	Undervalued area, untrained farm manager

Table 3. *Cont.*

Categories	Factors	Farm Bahia	MATOPIBA Pilot
Resources	Water source	River	River
	Energy	Electric pumps and motors	Electric pumps and motors
	Agricultural machinery	17 center pivots	7 center pivots, reservoir
	Weather station	Located at the farm	Located at the farm
	Communication system	Internet—4G	Internet—4G
	Soil probe	Not adopted	Research project
	Satellite	Not adopted	Not adopted
	Irrigation system management	Used	Used
	Workforce	25 agricultural workers	16 agricultural workers
	Consultants	Support for planning, control and contract management	Support for contract management

Furthermore, a "within-case analysis" (factors in columns of Table 3) and a "cross-case pattern search" (patterns between the two cases identified considering the factors in each row and described in the text illustrating the table content) [101] were conducted.

3.2.1. Within-Case Analysis: "Farm Bahia"

"Farm Bahia" is managed by a farm manager who graduated in Agricultural Engineering. The authors' perception is that the manager's conservatism is low, and he has a propensity to risk in relation to the adoption of innovations. Quantitative measures related to the use of water and electrical energy are used on the farm, such as crop water requirement, water use, energy use, cost of water use, and cost of energy use, in addition to economic measures.

Regarding the access to agronomic data, a weather station supplies meteorological data. Crop, soil, and irrigation data are accessible through an IMS, which also provides operational data, such as production yield, revenue, and cost per center pivot. The electrical energy supply contract makes data on operating time and the cost of energy use available.

As for the changes for the farmer, the farm manager has technical and managerial skills since he has a degree in Agricultural Engineering. Management is based on data the and scientific method (e.g., water balance to estimate the irrigation water requirement), although experience is a relevant factor in irrigation planning and control. The skills related to OM are limited due to the low valuation of this area. The possibility of access to the market does not pose challenges. He is aware that the main changes are managerial, related to the need for training to use new technologies, to read the data correctly, and to manage irrigation planning and control. His mental model is aimed at minimizing energy use cost, due to the lack of a definition for water use cost.

Concerning the farm changes, the case study presents two changes. The first involves the OM, since this is an area undervalued and the manager is not skilled. Workforce qualification results in another key change due to the low educational level of the farm workers. These challenges can be overcome considering the size of the farm, its possibilities of accessing the market, farmer low conservatism, risk propensity, and capacity for innovation. In relation to the models of OM inspired by the industry, the case shows a gap in the adoption due to little importance of this area and low managerial training.

The farm manager uses the IMS for irrigation planning. The estimation of the crop water requirement, the planning of irrigation water requirement, and of irrigation time are conducted by consultants using the water balance approach. The nightly, daytime, and peak operating times of the center pivots are defined based on the energy supply contract. The farm manager planning objective is to minimize the cost of electrical energy use to take advantage of the nightly operating time. As for irrigation control, he manually analyzes soil moisture based on experience. Center pivot control operations are also performed manually because of the bad quality of electrical energy.

Regarding the resources, the contract for accessing water is formalized, but the cost of using irrigation water and the time and volume of abstraction are not defined yet.

3.2.2. Within-Case Analysis: Farm of the MATOPIBA Pilot

The MATOPIBA pilot farm is directed by a manager who graduated in Agricultural Engineering, with low conservatism and propensity to risk in relation to adoption innovations. Quantitative measures related to the use of water and electrical energy are used. The farm manager uses a weather station and an IMS to access agronomic data, while he uses the water access contract and the electrical energy supply contract for access to operational data.

As for the technical and managerial skills, for the MATOPIBA pilot, manager experience is still a crucial factor in irrigation planning and control. The changes for the farmer, mainly managerial, do not represent major challenges, due to the possibility of access to the market. Regarding technical training, the central challenge is where to irrigate based on soil probe data and, therefore, implementing the variable rate irrigation. His mental model is aimed at minimizing the cost of electrical energy use due to the lack of water use cost in the current contract. Regarding the farm changes, the case presents two changes related to OM and the qualification of the workforce. The MATOPIBA pilot manager administers irrigation planning with the support of the IMS. The irrigation water requirement is estimated weekly using a water balance approach. Irrigation water requirement and irrigation time are planned based on the cost of electrical energy use, which prioritizes nightly operating time. Nightly irrigation is more economical, as the cost of electrical energy use is ten-times lower than during the day. As for irrigation control, center pivot operations are performed manually based on experience. Regardless of the contract for access to water, the cost of water use, the time, and the volume of abstraction are not defined yet.

3.2.3. Cross-Case Pattern Search

The two farms present homogeneous factors in terms of farmer characteristics, farm characteristics (mainly farm size—industrial farm, farm location), quantitative and qualitative performance measures, access to agronomic data, access to operational data, changes for the farmer and for the farm, models of OM inspired by the industry, and resources. The IMS used by the two farms is provided by the same supplier. On both farms, the contract for access to water is formalized, but the cost of water use, the time, and the volume of abstraction are not defined yet.

In relation to the models of OM inspired by the industry, in the MATOPIBA pilot, the irrigation planning is administered by the farm manager, while in "Farm Bahia", the estimation of the crop water requirement, the planning of irrigation water requirement, and the irrigation time are conducted by consultants. The two farms have some of the heterogeneous characteristics of the irrigation system. In the MATOPIBA pilot, two center pivots are powered by electric pumps, and the others are supplied through a reservoir, which enables one to reduce evaporation during water distribution. In "Farm Bahia", all 17 center pivots are supplied directly from a river. As for sensing technologies, the MATOPIBA pilot is carrying out a project for the adoption of soil probes and performing variable rate irrigation. The farm manager is assisted by agronomic experts in planning irrigation water requirements. He also hires management consultants to control the electrical energy use and for some issues inherent to the supplier agency (i.e., high fixed monthly cost, low quality of electrical energy). The manager of "Farm Bahia" hires management consultant services for the renewal of the water access contract and technical consultants to remotely control the electrical energy use on a weekly basis.

3.3. Results of the Expert Interviews and Case Studies: Theoretical Propositions

The results of the expert interviews and case studies allow us to generate ideas and formulate theoretical propositions [39,40] to explain the relationships between the adoption and the identified factors. The theoretical propositions, which provide a solid foundation for modeling irrigation OM and to direct future research, are illustrated below in the order of categories and factors shown in Tables 2 and 3.

Theoretical proposition 1: According to experts 2, 3, 6, 8, 11, 14, 16, 17, 23, 24, 25, 26, and 27 and the two farm managers, the adoption of PA in the context of Agriculture 4.0 allows for achieving advantages and benefits that can be measured through quantitative performance measures. The adoption involves cost reductions in irrigation, water, and energy use; the reduction in water use, and the relative cost, also affects an increase in production yield due to irrigation efficiency; saving water and electrical energy has a positive impact on the economic results of the farm. Theoretical proposition 1a: Based on interviews with experts 3, 20, 26, and 27, the adoption allows us to obtain advantages and benefits that can be measured through qualitative performance measures.

Theoretical proposition 2: As stated by expert 16, the explored adoption can bring benefits thanks to the access to more organized data. Theoretical proposition 2a: According to experts 16, 26, and 27, access to more organized data allows for better operation planning and control. Theoretical proposition 2b: Based on interviews with experts 11 and 27, the benefits of the adoption may also be related to the access to agronomic data on the three pillars of crop, soil, and climate. Theoretical proposition 2c: As stated by experts 11 and 27, these data can be used to estimate the crop water requirement and irrigation water requirement. Theoretical proposition 2d: According to experts 1, 17, 18, and 27, access to agronomic data is provided by the adoption of sensing technologies. Theoretical proposition 2e: Based on interviews with experts 11, 17, 18, 24, and 27 and the two farm managers, the adoption of PA in the context of Agriculture 4.0 makes it possible to obtain benefits thanks to the access to operational data concerning irrigation operations. Theoretical proposition 2f: According to both farm managers, the IMS provides operational data. Theoretical proposition 2g: Based on interviews with both farm managers, the electrical energy supply contract provides data on operating time and the cost of energy use in different periods; the operating times of the center pivot are defined based on the electrical energy supply contract. Theoretical proposition 2h: As stated by all the farm managers, the contract for access to water provides data on the cost of water use, abstraction time, and volume.

Theoretical proposition 3: The explored adoption requires farmer changes. Theoretical proposition 3a: According to experts 1, 5, 6, 7, 10, 11, 13, 15, 16, 17, and 24 and the two farm managers, to adopt these technologies, the farmer must be trained. Training includes technical and management training; managerial training comprises skills for data analysis, planning, and the management of new technologies. Theoretical proposition 3b: Based on interviews with experts 2, 4, 11, 14, 17, and 20, the adoption requires changes in the farmer mental model, which involve irrigation management due to the need to change the belief that irrigating is different from applying water, and irrigated agriculture is different from rainfed agriculture plus water. Theoretical proposition 3c: As stated by experts 14, 15, 19, 20, 21, 22, 26, and 27, changes in the farmer mental model involve data-driven management, as moving from experience-based management to data-based management provides benefits for operations planning. Theoretical proposition 3d. According to experts 10, 19, 22, and 27, changes in the mental model include the farmer awareness that water is a scarce resource. The adoption of sensing technologies can make this change possible. The farmer needs to understand that the agricultural field has variability. Theoretical proposition 3e: Based on interviews with experts 5, 12, 23, and 24, changes in the mental model involve the management of the farm as a business. The farm management must include irrigation planning and control; the farmer often does not know the production cost and does not understand their costs and income. Theoretical proposition 3f: As stated by expert 18 and the two farm managers, to overcome the challenges related to changes, the farmer can access technology, finance, and educational markets.

Theoretical proposition 4: The explored adoption requires farm changes. Theoretical proposition 4a: Based on interviews with experts 6, 10, 14, 17, and 20, farm management must be based on the basic functions of administration. Theoretical proposition 4b: According to experts 6 and 20 and the two farm managers, changes are also necessary in organizational characteristics in integration between different farm systems. Theoretical proposition 4c: As stated by experts 1 and 6 and the two farm managers, changes include OM, which has not evolved at the same speed as agronomic management. Theoretical proposition 4d: Based on interviews with experts 4, 6, 9, 12, and 19 and all farm managers, the changes involve the workforce qualification, which is one of the main barriers to overcome for the adoption.

Theoretical proposition 5: As stated by experts 2, 4, 7, 12, and 26, the changes about the adoption studied are gradual. Theoretical proposition 6: According to experts 1, 3, 4, and 6, for the adoption, the farmer makes available models of planning and control of irrigation operations, inspired by models of the industry, such as PPC. Theoretical proposition 7: According to experts 16, 22, 25, and 27, for the adoption, the farmer has the possibility to use collaborative management models, which allow one to overcome some challenges related to irrigation planning and control in the case of shared management of water resources.

Theoretical proposition 8: Based on interviews with experts 1 and 27 and both farm managers, for the explored adoption, resources to manage information concerning OM must be available to the farmer. Theoretical proposition 8a: As stated by experts 2, 8, 9, 14, 17, and 18 and both farm managers, the resources include water and energy inputs. Theoretical proposition 8b: According to experts 2 and 5 and the farm managers, the resources include hardware, such as sensors, drones, and satellites. Theoretical proposition 8c: Based on interviews with experts 2, 3, 5, 8, and 24 and the two farm managers, the adoption of resources like sensors allows us to obtain benefits for operations planning. Theoretical proposition 8d: As stated by experts 2, 3, 8, 23, and 24 and the farm managers, the resources include people.

The explored adoption can be affected by the farmer characteristics, according to experts 1, 3, 4, 5, 8, 9, 10, 13, 14, 16, 20, 21, 30, and 32 (theoretical proposition 9), by the farm characteristics, as stated by experts 1, 2, 3, 5, 9, 16, 17, 23, 24, and 25 (theoretical proposition 10), and by the technology characteristics, based on interviews with experts 1, 5, 6, 8, 20, and 25 (theoretical proposition 11).

Propositions 1, 1a, 2, 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2g, 2h, 4d, 6, 8, 8a, 8b, 8c, 8d, and 10 support the proposal of the irrigation OM model presented in Section 3.4. The factors educational level, training, access to data, and resources (people—consultants) are discussed in Section 4.3. Other factors, out of the scope of this paper, will be analyzed in the future research agenda.

3.4. Model of Irrigation OM

A model of irrigation OM is built, based on theoretical propositions, factors identified in theoretical and empirical bases, and factors identified in expert interviews and case studies. This model, developed with the IDEF0 technique, is inspired by the PPC model, according to theoretical proposition 6. This irrigation OM model supports the development of theory on the adoption of PA in the context of Agriculture 4.0. The model of irrigation Operations Management (context diagram), shown in Figure 2, defines the scope of the model and describes the modeling of the top-level function.

The context diagram is broken down into four functions, creating child diagrams and the model of irrigation OM (IDEF0 diagram), as shown in Figure 3: irrigation planning, irrigation scheduling, irrigation execution, and irrigation control. Each of the sub-functions may be decomposed in lower-level child diagrams. The description of the IDEF0 diagram shows the identified factors and the pertinent theoretical propositions.

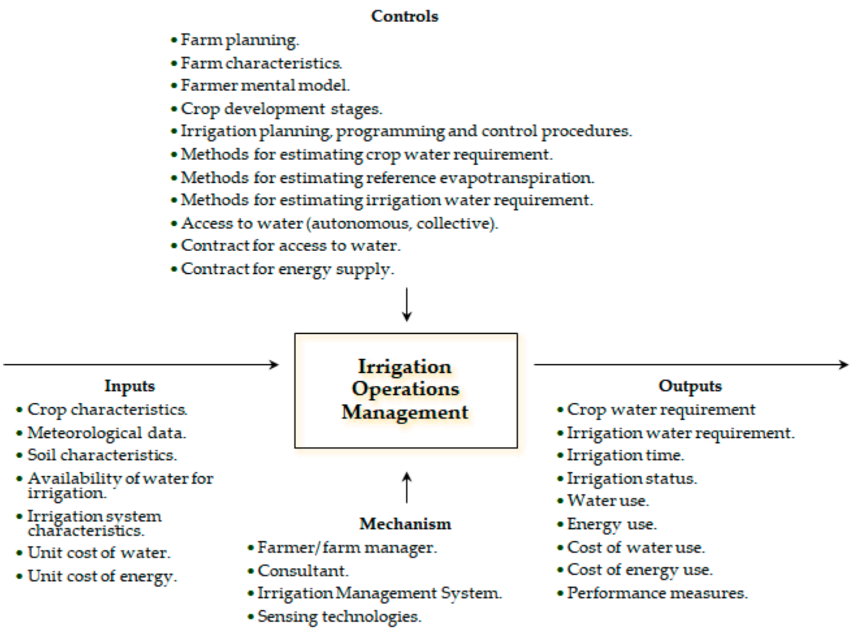

Figure 2. Model of irrigation OM (context diagram).

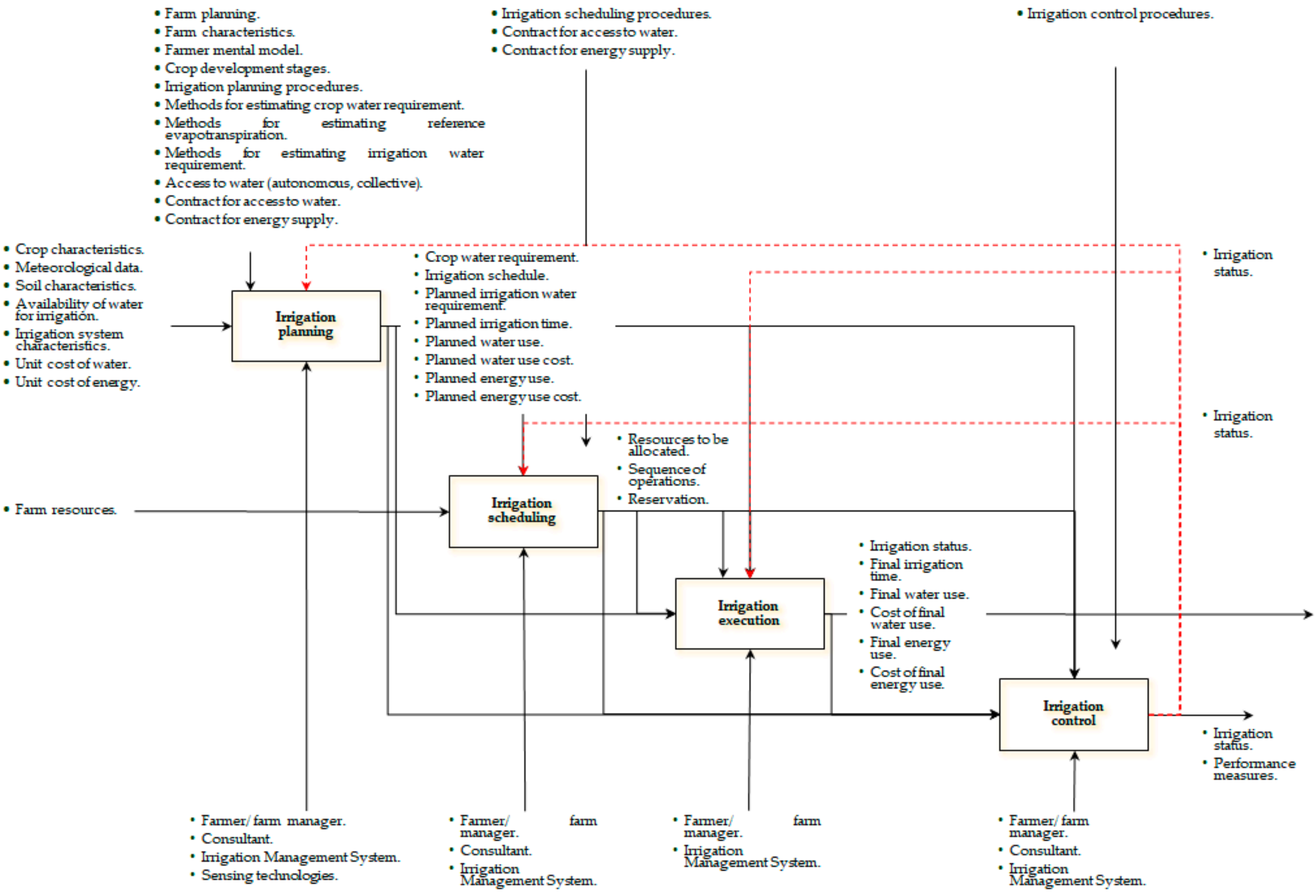

Figure 3. Model of irrigation Operations Management (IDEF0 diagram).

Irrigation planning emphasizes the dimension "planned" to the output factors: irrigation water requirement, irrigation time, water and energy use, and water and energy use cost. Irrigation planning can be referred to as a timescale of the harvest or within the harvest, according to experts 16 and 20.

To plan the crop water requirement, data from three pillars are essential: crop, soil, and climate (factors related to theoretical propositions 2b and 2c), as reported by experts 11, 15, 16, and 23. The irrigation schedule establishes irrigation days based on irrigation planning procedures, such as minimizing the cost of energy use, taking advantage of irrigation at night time, given the energy supply contract and the relative unit cost of energy at different times during the day, as reported by the two farm managers and expert 2. The factors mentioned are addressed in theoretical propositions 2e and 2g.

Irrigation time can be planned in relation to nightly, daytime, and peak operating times (factors related to theoretical propositions 2e and 2g), according to the two farm managers and experts 10, 14, and 25. Water use, water use cost, energy use, and energy use cost can be planned based on different operating times. Energy use and energy use cost can be planned depending on the irrigation equipment like pumps and motors, as reported by the two farm managers (factors related to theoretical propositions 2e, 2g, 2h, 8a, and 8b). The pumps and motors can be powered by diesel oil, renewables, or electrical energy, according to [116] and expert 27. Irrigation planning can be conducted at the level of the farm and field.

The controls facilitating the execution of the function consist of the same factors as in the context diagram, except for irrigation scheduling and control procedures, based on farm manager interviews and experts 1, 11, 15, 16, 17, and 23. The contract for access to water is essential to know the availability of water for irrigation, as reported by experts 16, 25, 26, and 27 (factors addressed in theoretical propositions 2b, 2c, 2g, 2h, and 10).

Water can be unlimited or limited, according to experts 14, 16, 25, 26, and 27. Water availability for irrigation is also influenced by collective access to water resources, which poses challenges for irrigation planning based on factors, such as water demand, water supply, available water volume, farm location, priority in access, and the economic sector (human activity, animal breeding, irrigation, industry) in the case of conflicts over water use, according to experts 9, 14, 15, 17, 18, 24, 26, and 27 (factors related to theoretical propositions 2h and 10).

The energy supply contract can contribute to establishing the planning procedures since the cost of electrical energy can vary based on the hours during the day and can impact the definition of irrigation time, as reported by the MATOPIBA pilot farm manager: "*Nightly irrigation is what makes the business viable*". The manager of "Farm Bahia" said the following: "*The priority is to take advantage of the time reserved for irrigation, which is 9 h a night. But irrigation is carried out during the day too, almost all pivots are off by 11:00*". Experts 2 and 14 agreed with this (factors addressed in theoretical propositions 2a, 2e and 2g).

Farm planning involves distinct factors affecting seasonal decisions the farmer must make, like crops to cultivate [81,117]. Expert 1 highlighted the strategic nature of this planning, which involves long-term decisions (factor related to theoretical proposition 6). Farm planning also involves economic factors the farmer needs to consider. Experts 3, 4, 16, 24, 25, and 26 cite input price and availability, production cost, product prices, and market trends. As highlighted by the results of the two case studies, the cost of the electrical energy plays a fundamental role because it can influence the use of electrical energy and the planning of the operating time (factors mentioned in theoretical propositions 2e and 2g).

Experts 1, 9, 15, 20, 22, 24, 25, 26, and 27 cite another characteristic of agriculture, which is the uncertainty related to climatic factors, such as precipitation, water availability, and air temperature (related to theoretical propositions 2b). Expert 18 added the volatility of rainfall and drought due to the extension of Brazilian territory, while expert 26 stated that the explored adoption can contribute to reduce the risk related to these factors: "*The more the farmer invests in Precision Agriculture in the context of Agriculture 4.0, the greater the information base and knowledge of these factors he has. Therefore, the greater the control of his business*" (factors related to theoretical proposition 2b). Experts 13 and 31 added that the availability of more information leads to reducing the risks in agricultural production, for example, with climate change, which has increasingly prolonged effects. According to expert 34, the risk, linked, for example, to a possible period of drought, which may be critical based on the type of crop that the farmer plans to cultivate, can be reduced if information is made available to the farmer in real time. Expert 10 highlighted that: "*In the manufacturing industry the production process is somehow dominated, particularly inside a factory or warehouse, it is a well-known process. In agriculture, it rains, it rains more, it rains less, there it's hail, there is a problem with an epidemic of foot and mouth disease, fruit flies, rust in soybeans. This is why the planning and control of agricultural operations are very critical and challenging. The adoption of innovative technologies and models of OM poses a challenge to the farmer aimed at reducing the risks of seasonality on production management*". Expert 25 added that due to climate changes, the statistics used for planning increase their uncertainty and, for this reason, the adoption of PA would provide access to more reliable and complete data and, therefore, it could reduce the risk in irrigation OM.

Irrigation planning processes the following inputs: crop characteristics, meteorological data, soil characteristics [58,118,119], the availability of water for irrigation, as reported by experts 17 and 27, the characteristics of the irrigation system (like minimum depth of water to apply, water flow, irrigated area), the unit cost of water, and the unit cost of energy according to the two farm managers (factors covered by the theoretical propositions 2b, 2e, 2g, and 2h).

The mechanisms used in the planning of irrigation are considered in terms of the farmer or farm manager, the consultant, the IMS, and the sensing technologies [118,120] (factors related to theoretical propositions 8, 8b, 8d). The farmer oversees irrigation management. Farms such as the MATOPIBA pilot and "Farm Bahia" use an IMS to assist the manager in planning. Sensing technologies support planning thanks to the collection of field data and access to more correct data, as reported by expert 5 (factors related to theoretical propositions 2, 2b, 8b, and 8c). Experts 2, 3, 10, and 23 highlighted the role of the consultant (addressed in theoretical proposition 8d) as an opportunity to support the farmer.

Key outputs of irrigation scheduling are the allocation of agricultural resources: people, machines [77], irrigation technique [121–123], irrigation resources, and water sources, according to the two farm managers (factors related to theoretical propositions 8 and 10).

In the case of shared water sources, such as a collective irrigation canal or watershed, the access to water and its use depend on the water access contract, as highlighted by experts 2, 8, 14, 16, 17, 25, 26, and 27. Expert 9 added that farmer location also affects irrigation scheduling, for example, in an irrigated perimeter. The contract can regulate the use of resources for measuring the water use, which farmers must install to measure the water flow, according to expert 2 (factors analyzed in theoretical propositions 1, 2h, and 10).

Irrigation scheduling produces a reservation and an operation sequence to execute. An example is described in the case of "Farm Bahia", in which the operation "*execution of irrigation with the application of irrigation water requirement equal to 9.4 mm in 50% of the irrigated area*", using the resource "*center pivot 4*", is scheduled on "*day 1*" (factors related to theoretical propositions 2, 2e, and 6). Irrigation scheduling procedures involves priority rules such as the minimization of the cost of electrical energy use relative to the use of water. This rule defines the priority for executing the irrigation in the night period in the two case studies (factors addressed in Theoretical propositions 1, 2g, and 6).

According to the proposal to adopt a management model inspired by the industry (factor related to theoretical proposition 6), irrigation scheduling can be considered planning at the operational level, as reported by expert 1: "*The farmer has a planning that is more strategic, long, and medium term. And then there is a more operational planning, for defining the planning of the machines, irrigation, spraying, harvesting, post-harvesting*".

The execution of irrigation affects the performance of the scheduled operations [124]. Scheduled resources are expected to be activated automatically in the context of Agriculture 4.0, as stated by expert 26. Experts 1 and 22 highlighted the benefits that automation can bring in relation to switching on and off the irrigation equipment (factors concerning theoretical propositions 1 and 8).

However, experts 1 and 2 added a challenge related to the quality of electrical energy (factor addressed in theoretical proposition 2g) for performing irrigation with an automated system: "*The farmer cannot install an automation system to turn the pump on and off and the control systems because the energy quality will burn this equipment more quickly, due to the overload*", expert 2. Expert 17 also cited the challenge of Internet coverage on the farm location (factor related to theoretical proposition 10) to enable the execution of irrigation with an automated system, while expert 18 highlighted the challenge of training the workforce (factor addressed in theoretical proposition 4d) to execute a system based on automation. The challenges of electrical energy quality and Internet coverage are also confirmed by the manager of "Farm Bahia": "*Despite having installed 17 center pivots, our system is all manual, because the electrical energy quality is very bad. The less the system is automated, the lower the risk that equipment can burn out. If all the center pivots are turned on at the same time, the power drops, so each center pivot has a different starting time by one minute*".

Outputs of the execution of irrigation result in status and some performance indicators: final irrigation time, final water use, final energy use, final water use cost, and final energy use cost, based on irrigation planning and scheduling outputs. The explored adoption allows us to achieve measurable benefits, according to experts 2, 11, 14, and 25 (factors analyzed in theoretical propositions 1, 2, and 2a).

The control of irrigation receives other function outputs to monitor the irrigation system and its resources [122,125]. In the case of irrigation equipment, for example, this function controls the input application, as reported by experts 2, 15, and 16 (factors related to theoretical propositions 2e, 6, 8, and 8b). Expert 2 highlighted that: "*The great advantage of adoption is that the farmer controls the application of water, energy, fertilizers. So, when he gains precision in applications, he controls the level of energy use, which has an extremely high cost*". Experts 9, 16, and 23 added other benefits, such as localized water application, application uniformity, equipment efficiency, and pressure control (factors analyzed in theoretical propositions 1, 2, and 2a). This control helps the farmer in relation to the risks of insufficient and excessive irrigation [118] (factors related to theoretical propositions 1 and 2a).

Through resources such as sensing technologies, the three agronomic pillars are also monitored, according to experts 2, 14, 15, 16, and 23. Expert 23 stated: "*It is important to evaluate the result of the irrigation by looking at the plant, using satellite and drone. And controlling how the plant is responding*" (factors dealt with in theoretical propositions 1, 2b, 2f, 8b, and 8c). Therefore, controlling irrigation operations through sensing technologies can affect the adoption of PA. Expert 23 emphasized the large volume of data available and accessible thanks to these technologies, whose utilization can improve the visual inspection. The adoption also helps the control of irrigation machines, according to experts 20 and 25 (factors related to theoretical propositions 1, 2, 2d, 8b, and 8c).

Irrigation control also provides information for the next harvest, as stated by expert 35: "The farmer will use the information from the current or next harvest for the next one. How did the model respond? Did the gain of efficiency meet the expectations?" (factors analyzed in theoretical propositions 2 and 6).

The results of irrigation control are the irrigation status and some other performance measures, such as production efficiency, as well as the measures related to water and energy use [126] (factors addressed in theoretical proposition 1). In the two case studies, the IMS produces performance measures by center pivots, such as production, revenue, and cost. Resource control is also emphasized by experts 2 and 4 as an advantage of adoption (factors related to theoretical propositions 1, 2, 2a, 2f and 8b). As in the industry, the farms can adopt measures to monitor and review performance [127], with a focus on OM, benefits highlighted by experts 10 and 27 (factors concerning theoretical propositions 1, 1a, and 6).

Irrigation control procedures refer to information to perform irrigation operations (factors related to theoretical proposition 6). Regarding the electrical energy use, the operating time of a center pivot must be planned and executed to avoid periods of higher costs of energy [128]. According to expert 8, in collective water use, the farmer receives a volume of water for a specific time, which must be controlled during the execution.

4. Discussion

In this section, the results and their contributions are discussed to answer the research questions and verify that the research objectives are achieved, beginning with the factors that can affect the explored adoption. Then, the irrigation OM model and the relationships between some factors identified in the case studies are discussed.

4.1. Factors That Can Affect the Explored Adoption

This work contributes to the current knowledge on PA adoption with a set of categories and factors that can affect the adoption, which complements previous studies [12–14,60] and allows us to overcome the identified gaps. The performance measures related to attitude are grouped into quantitative and qualitative benefits that can be achieved with the adoption. Quantitative performance measurements are integrated with crop water requirement, variable rate water use, production yield, profit, revenue, and production cost. The category "Access to data" is divided into access to agronomic data and access to operational data to differentiate the data sources (agronomic pillars and irrigation operations). The category "Changes" is organized into changes for the farmer and changes for the farm to highlight the challenges and barriers that the farmer and the farm must face and overcome to successfully adopt.

Empirical results add to [69] the following factors: technical training, managerial training, mental model, irrigation management, data-based management, and farm management as a business. Regarding the farmer mental model, the main barrier to the adoption is cultural, which depends mainly on farmer age and experience. According to experts 8, 9, and 20, younger farmers are more likely to be successful in adoption due to their familiarity with innovative technologies, which involve experience and knowledge of computer science and mathematics. For older farmers and those with low educational levels, adoption can represent a cultural shock, which is also linked to their conservatism. The case studies highlighted other significant beliefs, since the mental model of the two farm managers is aimed at minimizing the energy use cost due to the lack of definition of water use cost. The cost of water use is not a priority factor in irrigation OM of the two farms evaluated, even though the two farm managers are young and graduates. At the same time, the farmer mindset is involved in other factors, such the scarcity of water, the need to change the belief that irrigating is different from applying water and to move from experience-based management to data-based management, which the farmer can adopt through sensing technologies and OM models inspired by the industry. As for the changes for the farm, the empirical results emphasize that the OM has not evolved at the same speed as agronomic management in Brazil. OM is undervalued by the farmer due to little knowledge and skills in the OM subject. The previous category "Operations planning and control" is more generically named "Operations Management models inspired by the industry", thanks to the contribution of several experts. This category introduces a new factor: collaborative management models.

The identified categories and factors, shown in Tables 2 and 3, like electrical energy supply contract, and planned irrigation water requirement, can influence the perception of the farmer, affecting the intention of adoption. According to [129,130], the greater the benefits perceived from sensing technology adoption (like decrease in use of water and relative cost), the more likely their intention to adopt it. In addition, the less the farmer perceives the obstacles, such as training in irrigation OM, and the more resources he believes are available, such as training, the greater the perceived control and the more likely the intention of adopting.

The identified factors also provide progress in knowledge as they allow us to overcome the gaps in the literature related to the factors concerning irrigation OM and farmer behavior, themes little explored to explain PA adoption. These factors contribute to explain the potential of PA for irrigation operations, considering the applications available, adopting the proposed model for irrigation planning, scheduling, executing, and controlling, such as planning water use and energy use costs, measuring final irrigation time, and water use.

This work contributes to previous studies, complementing the factors specific to the studied domain, relevant for a comprehensive understanding of the adoption explored [21]. Examples of these factors are as follows: agronomic data access and operational data access (water access contract, electrical energy supply contract).

4.2. Model of Irrigation OM

As PPC is one of the core functions of OM, which aids in planning and utilizing resources [75], and as experts 1 and 6 suggested the adoption of planning and control models of operations such as PPC, these theoretical perspectives inspired the building of the model of irrigation OM, through the foundation of theoretical proposition 6.

The organization of the factors in a model contributes to representing the irrigation OM and the relationships between the factors in a structured way. Considering the gap in the literature relative to the factors concerning the OM, this model contributes to the understanding of PA adoption by theoretical propositions about the relationships between these factors to explain the adoption. These relationships are represented in the model, which is broken down into four functions in Figure 3.

This model complements the irrigation OM model shown in Figures 4 and 5 [69] with the factors presented in Sections 3.1 and 3.2. The context diagram of irrigation OM, shown in Figure 2, highlights the complementing factors. In relation to the controls, the following factors are added in this work: farm characteristics, farmer mental model, access to water (autonomous, collective), contract for access to water, and contract for energy supply. In relation to the inputs, the factor "characteristics of the irrigation system" is integrated, while regarding the mechanisms, the factors "consultant" and "Irrigation Management System" are added. As for the outputs, irrigation status, water and energy use, cost of water, and energy use complement the previous diagrams published in [69]. These factors are significant for the completeness of the proposed model and for the progress of knowledge on PA adoption.

In the model, irrigation planning differs from scheduling, based on inspiration from the planning and control models of operations (factor related to theoretical proposition 6) and from experts 1 and 6. The model contributes to the research of [28], in which irrigation is not the focus.

4.3. Results of Case Studies: Relationships between Some Factors in the Model

The case study findings complement the categories and factors in the literature that can affect the adoption of PA, allowing one to explore the relationships between factors. In this section, the relationships between the adoption and the factors "educational level", "training", "access to data" and "resources (people—consultants)" are discussed.

The experts interviewed highlight the importance and role of "training" and "consultants" factors. Farmer training has a crucial role in spreading PA technologies [61] and in the explored adoption, according to theoretical proposition 3a. The farmer can also hire consultant services as an opportunity to support his OM, according to theoretical proposition 8d.

Using the factors "educational level", "training", "access to data", and "resources (people—consultants)" in relation to the adoption (factors addressed in theoretical propositions 2, 3a, 8d, and 9), the empirical results allow us to study the relationships between these factors in the MATOPIBA pilot and "Farm Bahia".

Regarding technical training, the two managers have skills and knowledge of irrigation and PA technologies, as they graduated in Agronomic Engineering and take part in training courses. However, at "Farm Bahia", the planning of irrigation water requirement is carried out with the service of consultants, who define the crop water requirement and the planned irrigation water requirement. In the MATOPIBA pilot, the farm manager plans these two factors. Therefore, the manager of "Farm Bahia" proved less knowledgeable about agronomic data. The data collection to conduct the case study was completed thanks to the support of the consultants, while the MATOPIBA pilot manager had complete knowledge on the agronomic data.

As reported by expert 2 and observed in "Farm Bahia", the outsourcing of irrigation operations can lead to a loss of control by the farmer. Still, expert 3 highlighted that outsourcing is growing significantly in agriculture. Therefore, the farmer can lose control over some operations and the related data [131,132].

The two farm managers have low managerial skills in irrigation OM, since they did not take courses in this area at the universities where they studied. Furthermore, on the two farms, mapping of irrigation OM is not available, and irrigation planning and control models are not adopted. Access to data is hampered by the lack of integration between agronomic databases in the IMS and operational databases, in particular the cost of water use and cost of electrical energy use. Both farm managers are supported by consultants to manage the relationship with the companies that supply the two inputs. Furthermore, the two managers do not differentiate between irrigation planning and scheduling terms and operations.

Concerning the educational market for training future farmers in Brazil, it is important to note that in relation to the National Curriculum Guidelines for the undergraduate course in Agronomic Engineering or Agronomy, a discipline of agricultural OM is not included in the core of essential professional content. This core can be complemented by specific content inserted in the pedagogical project of a course [133]. As for the Agricultural Economics community, a discipline concerning the irrigation OM can be included in the curricula of undergraduate courses.

The experts interviewed also highlight that the irrigation OM is a gap in the training and knowledge of farmers in Brazil, as reported by experts 1, 6, and 11.

Therefore, the results of the case studies allow us to identify two training models: in relation to technical training, "Farm Bahia" adopts an outsourcing model through the support of consultants, while the MATOPIBA pilot manager administers all irrigation operations. As for managerial training, the two farm managers have low training in irrigation OM. These preliminary findings must be analyzed in relation to the need for changes for both the farmer and farm in order to adopt PA, with the objective of exploring the farmer empowerment model and the farm organizational model to support the adoption. However, these empirical results cannot be generalized, due to the scope and the limitations of this work. Future research is proposed to explore the farmer training model and the farm organizational model for the explored adoption.

5. Limitations and Research Agenda

Based on the results achieved and discussed, the theoretical propositions, the limitations relative to the scope of work, and the data collected in the interviews with the experts and the two farm managers, a future research agenda is formulated (shown in Table 4). For each study, the level influencing the farmer decision-making process on the adoption is indicated: micro—farm, medium—farm ecosystem, macro—watershed or irrigated perimeter.

Future research 1: The irrigation OM model shown in Figure 3 is proposed as a theoretical framework to direct future studies to investigate the relationships between the factors involved in the explored adoption. According to [28], in this model, "Irrigation planning" plays a central role in OM. "Irrigation planning" may be decomposed in lower-level child diagrams based on the IDEF0 technique [41], which can be used in combination with simulation models for the support it provides in model documentation and data collection [134]. Therefore, future research is proposed to study the relationships between the factors related to the decomposition of "Irrigation planning" and the adoption of sensing technologies, such as satellites and drones, using simulation techniques.

Table 4. Future research agenda.

Components	Factors	Decision Making Level	Future Research
Model of irrigation OM	Factors related to the decomposition of the "Irrigation planning" and the adoption of sensing technologies	Micro	Future research 1. Study of the relationships between the factors related to the decomposition of the "Irrigation planning" and the adoption of sensing technologies, using simulation techniques.
Unit of analysis	Farm size—industrial farm, educational level, training, access to data, resources (people—consultants)	Micro	Future research 2. Study of the training model and organizational model of industrial farms for the explored adoption with focus on OM.
	Farm size—family farm	Micro	Future research 3. Study of the relationship between the adoption and the factor "farm size—family farm" in the irrigation OM model.
	Factors related to other agricultural operations	Micro, medium, macro	Future research 4. Study of the explored adoption with focus on extending the irrigation OM model to other agricultural operations.
Constructs of TPB	Factors related to the Subjective Norm construct	Medium	Future research 5. Exploring the relevant factors for the explored adoption, in relation to the farm ecosystem.
Behavior	Factors related to decision making in irrigation OM	Micro, medium	Future research 6. Study of the explored adoption with focus on decision making in OM of irrigation.
	Factors related to the diffusion of PA in the context of Agriculture 4.0	Macro	Future research 7. Study of the factors affecting the diffusion of PA in the context of Agriculture 4.0 with focus on farmer behavior and irrigation OM.
Determining factors of adoption	Factors related to collaborative management models inspired by the industry	Macro	Future research 8. Study of the application of the irrigation OM model to the management of watersheds and irrigated perimeters, using collaborative management models.

Future research 2: Regarding the unit of analysis and the factor "farm size—industrial farm" (addressed in theoretical proposition 10), this work involved the MATOPIBA pilot and "Farm Bahia". According to [42], two in-depth case studies were conducted. This choice is a limitation of this research in terms of the replication of the results [42,101], especially concerning the relationships between the adoption and the factors: educational level, training, access to data, and resources (people—consultants). Considering the factor "farm size" of the farms involved in the cases, future research is suggested to study whether the results can be replicated and generalized and to investigate the farmer training model and the organizational model of industrial farms for adoption in the state of Bahia and in other Brazilian states. Considering that training and educational level are key factors in empirical findings, this research analyzes how the results will be communicated to farmers and how the extent of changes in farm management will be communicated to scientists.

Future research 3: According to previous studies on PA adoption [135] and as reported by experts 1 and 8, farm characteristics, such as farm size (family farm), affect technology adoption. Future research is suggested to study the interconnection between the adoption and the size of the family farm in the model of irrigation OM.

Future research 4: The case studies and the expert interviews highlight the connections between irrigation and other agricultural operations. Some experts, like expert 15, emphasize that the adoption for irrigation should be seen as complementary and integrated with other agricultural operations.

The literature on irrigation also underlines the integration between agricultural operations. For example, center pivots provide an excellent vehicle to apply some fertilizers to meet the exact crop requirements [116]. The farmer must consider that some operations and decisions are interlinked. For example, irrigation for competing crops is an important agricultural planning issue when water is scarce [79]. Furthermore, each operation has several agronomic conditions that must be satisfied in the field before the operation can be performed efficiently and effectively. The assessment of these conditions is included in the field preparation operation [83].

Therefore, with inspiration from [27] (p. 71), this work proposes an integrated model of agricultural Operations Management, shown in the graphical abstract, that expands the field of study of irrigation, involving the factors addressed in theoretical propositions 4c and 6. This integrated management model offers a holistic view of the agricultural OM based on the three agronomic pillars of a farm production system. This model includes the corn development stages [136] and emphasizes the integration between the agronomic pillars, the irrigation operations, and the other agricultural operations, as highlighted by experts 2, 11, 12, 15, and 16. Future research is proposed to study the explored adoption with a focus on extending the model of irrigation OM to other agricultural operations.

Future research 5: By exploring the factors relevant for the adoption of PA in the context of Agriculture 4.0, the TPB construct “Subjective Norm” was considered out of scope. Future research is suggested to include the “Subjective Norm” and to investigate the relationships between the farmer and the actors operating on the farm ecosystem, including extension professionals [34], governments, and technology companies [36]. This proposal is focused on the analysis of the factors out of the scope of this research (related to theoretical propositions 3f, 9, 10, and 11) and their impacts on the adoption.

Future research 6: In the literature [28,137,138] and in the results of expert interviews and case studies, common factors can be found between adoption and decision making in irrigation OM. For example, the relationship between the planned irrigation water requirement and water use can affect decision making in irrigation management. Another example is cited by expert 5: “*The farmer can make a more accurate decision regarding irrigation time and water flow of the center pivot, because he can work with sensors that provide precision in information. He can plan the operations so that irrigation is more effective*”. Since the farm managers in the two case studies do not manage the irrigation planning operations, including the planned cost of water use and the planned cost of electrical energy use, except that at farm planning level, following the explored adoption, the proposed model can be useful to support decision making. Future research is suggested to study the adoption with a focus on decision making in irrigation OM.

Future research 7: Regarding the behavior “diffusion” (i.e., the process by which an innovation is disseminated among several individuals [139]), it was considered out of scope in exploring the relevant factors for the adoption studied, such as extension professionals who can help effectively facilitate the diffusion of PA technologies and bridge the gap in PA information dissemination channels [34]. Future research is needed to investigate the factors that can affect the diffusion of PA in the context of Agriculture 4.0, with a focus on irrigation OM and farmer behavior. According to [36], considering the overemphasis placed on high-tech solutions in the literature, special attention is needed for the inclusion and exclusion effects of the new technologies. The research should consider at what scale to spread innovations to investigate whether this would create more losers than winners.

Future research 8: Regarding the opportunities for the farmer following the explored adoption related to irrigation planning and control, experts 16, 22, 25, and 27 mention the collaborative management models (factor related to theoretical proposition 7). The adoption of these models allows us to overcome some challenges inherent in irrigation OM in the case of shared management of water resources, such as ensuring the availability of water during the harvest. The suggestion of experts 1 and 6 of adopting a management model inspired by the industry (factor addressed in theoretical proposition 6) for irrigation leads to the consideration of other models, such as Sales and Operations Planning (S&OP). S&OP is the long-term planning of sales-related production levels within the framework of a manufacturing planning and control system. The main objective is to balance aggregate supply and aggregate demand, through updates of the annual business plan [140,141]. The inspiration for the S&OP model suggests the idea of exploring the possibility of overcoming the challenges related to poor and ineffective communication between the demand and supply of water in a watershed. This idea involves factors that can be useful to overcome the challenge of balancing water supply (shared water managed by the water resource management agency) and water demand (water users, including farmers).

Furthermore, to help effectively facilitate the diffusion of PA technologies and bridge the gap in ineffective communication, extension professionals can play a key role [34]. Future research is proposed to study the application of the irrigation OM model to the management of watersheds and irrigated perimeters, using collaborative management models inspired by the industry.

6. Conclusions

The research objectives in this work were formulated to answer the research questions and overcome the gaps in the literature about the factors that can affect the adoption of PA in the context of Agriculture 4.0.

The identified categories and factors in this study contribute to broadening the understanding of the determinants of PA adoption in the 4.0 era, adding OM and the farmer mental model to the literature. The findings show the importance of sociological and psychological factors in the research on PA adoption. The central role of farmer behavior and perceptions expands the sensing technology applications in the domain of PA, according to the farmer needs and his mental model, in terms of beliefs about the perceived benefits and disadvantages in irrigation OM.

The categories and factors concerning the irrigation OM also suggest the establishment of operational solutions, thanks to the proposal of adopting the irrigation OM model. The irrigation OM model can be applied as a theoretical framework to direct future research to investigate the relationships between the factors identified in the explored adoption. This model provides applications, enabling one to manage decision making in irrigation OM.

The empirical results emphasize the role of farmer and workforce training, and the related gaps reported by the experts interviewed and the case studies, to success in the adoption. Therefore, this work suggests the inclusion of a discipline related to irrigation OM in courses of Agronomic Engineering and Agricultural Economics for training future farmers for the revolution in progress.

The results of the case studies allow one to study the relationship between the adoption and the factors “educational level”, “training”, “access to data”, and “resources (people—consultants)”. These findings highlight the adoption of an outsourcing model related to technical training in “Farm Bahia”, with the support of consultants.

In addition to the theoretical contributions, this work provides some practical contributions. The model of irrigation OM can be useful to support the farmer decision making in managing operations and for the development of an IMS integrating agronomic crop management and irrigation OM.

Considering the exploratory nature of this work, a future research agenda is formulated, addressing the factors and components considered out of scope and including an integrated model of agricultural OM based on the three agronomic pillars.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture14010134/s1. Supporting information can be found in Supplementary Material A, Supplementary Material B, Supplementary Material C, and Supplementary Material D.

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