sustainability

MDPI

Article

Design and Evaluation of a Precision Irrigation Tool's Human–Machine Interaction to Bring Water- and Energy-Efficient Irrigation to Resource-Constrained Farmers [†]

Georgia D. Van de Zande *, **Fiona Grant**, **Carolyn Sheline**, **Susan Amrose**, **Jeffery Costello**, **Aditya Ghodgaonkar** and **Amos G. Winter V**

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; fionag@mit.edu (F.G.); csheline@mit.edu (C.S.); samrose@mit.edu (S.A.); jcostllo@mit.edu (J.C.); adighod@mit.edu (A.G.); awinter@mit.edu (A.G.W.V.)

* Correspondence: gdvdz@mit.edu

[†] This article is a revised and expanded version of two conferences papers entitled Evaluating the Potential for a Novel Irrigation System Controller to Be Adopted by Medium-Scale Contract Farmers in East Africa. In Proceedings of the ASME International International Design Engineering Technical Conferences, St. Louis, MO, USA, 14–17 August 2022; and Design and Evaluation of an Automatic Scheduling-Manual Operation Tool to Bring Precision Irrigation to Resource-Constrained Farmers. In Proceedings of the ASME International International Design Engineering Technical Conferences, Boston, MA, USA, 20–23 August 2023.

Abstract: As freshwater supplies decrease, adopting sustainable practices like water- and energy-efficient irrigation is crucial, particularly in resource-constrained regions. Here, farmers often cannot purchase precision irrigation equipment, which achieves high water and energy efficiencies via full automation. Currently, no irrigation methods exist that combine automatic scheduling of events with manual operation of valves, familiar hardware on low-income farms. This work synthesizes functional requirements for a tool that could address efficiency needs while integrating into current manual practices. Then, a design concept for an automatic scheduling and manual operation (AS-MO) human–machine interaction (HMI) that meets these requirements is proposed. Two design stages of the AS-MO HMI were evaluated by farmers and market stakeholders in three countries. Results show that farmers in Kenya and Jordan valued the proposed AS-MO HMI because they could increase efficiency on their farms without the cost or complexity of automatic valves. In Morocco, a possible market was found, but a majority of participants preferred full automation. Interviewees provided feedback on how to improve the tool's design in future iterations. If adopted at scale, the proposed AS-MO tool could increase efficiency on farms that otherwise cannot afford current precision irrigation technology, improving sustainable agriculture worldwide.

Keywords: sustainable design; water efficiency; energy efficiency; human–machine interaction; human–machine information transfer; user interaction; user experience; irrigation; agriculture; automation; precision irrigation; decision support systems

Citation: Van de Zande, G.D.; Grant, F.; Sheline, C.; Amrose, S.; Costello, J.; Ghodgaonkar, A.; Winter V, A.G. Design and Evaluation of a Precision Irrigation Tool's Human–Machine Interaction to Bring Water- and Energy-Efficient Irrigation to Resource-Constrained Farmers. *Sustainability* **2024**, *16*, 8402. https://doi.org/10.3390/su16198402

Academic Editors: Elio Romano, Carlo Bisaglia, Andrea Bragaglio, Giampaolo Schillaci and Sabina Iole Giuseppina Failla

Received: 19 August 2024
Revised: 20 September 2024
Accepted: 25 September 2024
Published: 27 September 2024

1. Introduction

The United Nations' second Sustainable Development Goal (SDG 2) calls for food security by 2030 [1], an aim particularly imperative in low- and middle-income regions like East Africa (EA) and the Middle East and North Africa (MENA). Here, over 33% and 10% of the population, respectively, is projected to be undernourished in 2030 [2]. Numerous studies have shown that increasing irrigation access is an effective path towards food security [3–5]. However, irrigation is water- and energy-intensive, countering the second aim of SDG 2: sustainable agriculture. The high water use of irrigation is especially concerning in the arid and semi-arid regions, like MENA and EA. Here, there are growing numbers of small and medium farms. In EA, medium-scale farms, generally sized 5–15 acres, rely on hired manual labor to feed growing city centers [6]. In MENA, farm sizes are country-dependent, with small farms ranging 5–25 acres and medium farms ranging 50–120 acres [7]. Both small and medium farms typically rely on hired manual labor, but medium farms may also have specialized workers, like managers or agronomists. Due to their prevalence, these small- to medium-scale farms have the promise to increase food security, but doing so sustainably remains challenging [8,9].

Solar-powered drip irrigation (SPDI) has been proposed for EA and MENA as a means to increase yields while reducing water and fossil fuel use [10–12]. Drip irrigation uses a network of pipes and emitters to deliver water directly to crops, saving up to 50% of water compared to commonly-used flood irrigation [13]. Solar power is especially applicable in rural EA where access to grid electricity can be uncommon [14] and in arid regions, like MENA, that have high solar irradiance [15,16]. However, solar systems have high investment costs, posing a significant barrier to farmer adoption [6]. System energy use is critical in off-grid irrigation because it dictates solar array and energy-storage costs.

Prior work suggests that water- and energy-saving technologies could particularly benefit medium-scale farms in EA and small- to medium-scale farms in MENA, many of which have access to capital to pay for some of this technology [6,7]. However, irrigation systems can only conserve resources when they are properly operated by farmers. Research shows that farmers do not necessarily practice ideal irrigation, partly due to insufficient technical training and partly due to farmers, understandably, prioritizing risk mitigation over introducing sustainability measures [17,18].

The 2022 State of Food and Agriculture (SOFA) report from the United Nations Food and Agriculture Organization (FAO) focuses on the potential of precision agriculture technology to improve sustainability and resilience to climate change [19]. However, the report emphasizes that these benefits can only be realized if precision technologies are designed to be inclusive of small-scale producers, particularly in low- and middle-income countries (LMICs). Precision irrigation (PI), the practice of calculating and delivering the correct amount of water to crops at the correct time, could help resource-constrained farmers realize the water and energy savings of SPDI [20,21]. PI technologies measure farm and weather conditions and calculate ideal irrigation schedules, often using automated valves to carry out these schedules [22]. Despite its benefits, PI technologies are not widely adopted by small- and medium-scale farmers in LMICs because existing technologies are not designed to meet the specific needs of this target user group [19].

Existing PI solutions are largely inaccessible to small- and medium-scale farmers in EA and MENA due to their costs and complexities. Many existing precision irrigation controllers use sensor arrays, solenoid valves, and proprietary hardware and software [20,21,23–26], which cost up to USD 10,000 to equip a medium-scale EA farm [27]. Instead, farmers in the target user group often employ local laborers to both monitor and carry out irrigation tasks using manual valves [6]. These laborers use inexpensive but time-consuming and often imprecise manual methods for determining when to irrigate, like “stick” tests [27]. In this test, a laborer inserts a stick 10 cm into the soil. If it comes out with dirt attached, the soil is moist enough. The irrigation experience of hired laborers varies widely, so farmers cannot rely on these binary tests to deliver the most water- and energy-efficient irrigation. While human laborers can observe current weather and crop conditions, their forecasts are less accurate than PI forecasts. Forecasting becomes only more difficult for humans as climate change worsens [28].

Some existing products attempt to bridge the gap between fully automated PI and fully manual methods [29]. However, these timer-based products fall short of delivering the efficiency and prediction benefits of PI. For example, the Pro-C irrigation controller (Hunter Industries, California) and the SST1200OUT irrigation timer (Rain Bird Corporation, California) are low-cost products—in the USD 100–300 range—that control several solenoid valves to carry out irrigation schedules entered by the user. While these products are affordable, they still rely on humans to determine the irrigation schedule. Even for experienced farmers, it is challenging to determine an irrigation schedule that concurrently optimizes water and energy use.

Precision irrigation control for SPDI systems is an active area of research. Previous studies have proposed ways to adjust irrigation in real-time [30,31], optimize irrigation schedules for minimal water use [32], and match the irrigation power requirement to the available solar power profile as a way to reduce power system size and cost [24,25]. Although these studies demonstrate increased operational efficiency and cost reduction, the proposed PI solutions are tailored to individual cases, and the studies do not address farm heterogeneity or solution scalability. As such, the practical implementation and feasibility of these PI solutions for the target user group is yet to be explored.

A technology's potential impact relies on its adoption among target users, and adoption of irrigation technologies is historically challenging in resource-constrained regions [19,33–35]. Farmers' desire to adopt a PI tool is unknown but critical to its potential impact. Therefore, there is a need to understand the functional requirements (FRs) of a PI tool for resource-constrained farmers and to understand an associated human–machine interaction (HMI) that would satisfy farmers' needs. In this case, farmers would be the primary humans interacting with the technology, and we define the machine as any physical equipment or digital tool that is part of the engineering system aiding the farmer and their irrigation efforts. This work aims to propose and evaluate a means of bringing the sustainability benefits of precision irrigation to resource-constrained farms without the high costs and complexities of existing methods. We do this by assessing the potential viability of a PI tool in EA and MENA and understanding how farmers might value and interact with such a tool in practice. Specifically, we:

1. Define the FRs and design specifications of a PI tool for SPDI systems in resource-constrained markets that integrates with the current practices and capabilities of target farms;
2. Characterize a human–machine interaction (HMI) that meets these FRs;
3. Substantiate the value of the HMI among lead users and early adopters, assess these potential users' desires to adopt such a tool, and iterate the HMI concept based on findings;
4. And assess target farmers' satisfaction with the proposed PI tool and HMI and identify avenues for improvement.

These four research objectives were met through a multi-stage design process in which two iterations of a PI tool concept were conducted. Section 2 synthesizes findings from the literature into a set of FRs. These FRs are then revisited and formed into design specifications using findings from the two design iterations (Section 5.3.4). Articulating the tool's FRs and design specifications demonstrates the potential of PI tools—and precision agriculture tools at large—in historically underserved markets. Section 3 proposes an AS-MO tool and HMI concept that could meet the FRs, addressing the second research objective. To improve this initial concept and address the third research objective, two design iterations were conducted and are detailed in Sections 4 and 5, respectively. The results from the first iteration are presented in Sections 4.2.1 and 4.2.2. Findings from this first design iteration were incorporated into a second, the results of which are presented in Section 5.3. The second design iteration was also used to assess farmer satisfaction with the tool, addressing the fourth objective. Finally, Section 6 discusses the study's limitations and potential implications on the fields of precision irrigation, sustainable agriculture, and beyond. The validation of the utility, ease of use, and value proposition of the HMI in this work facilitates the creation of tools that bring the benefits of PI to resource-constrained farms.

2. Functional Requirements of a PI Tool in Target Markets

Functional requirements (FRs) describe the functions a device or system must be able to perform to produce a desired outcome [36]. FRs are gathered during the preliminary design stage and refined through interactions with potential users, stakeholders, and expert professionals. Like in all new product development processes, identifying FRs is an essential step in developing a PI tool that meets the needs of resource-constrained farmers in LMICs. For this study, the FRs are primarily gathered from the literature and previously published stakeholder interviews [6]. The corresponding design specifications for the tool are refined from the interviews and focus groups presented in subsequent sections. Together, the FRs and design specifications provide guidelines for designers to create PI tools for the target user group, whose needs remain unmet by existing technologies.

The 2022 SOFA report articulates how to expand the adoption of precision agriculture technologies to meet the SDGs. The report finds that the primary barriers to adoption in LMICs are a lack of digital literacy and technology extension services in rural areas, limited internet connectivity and access to electricity, and the high cost of existing products [19]. As described in the Introduction, existing and proposed PI technologies often require technical expertise to operate. These solutions assume that network connectivity, sensing and electronics hardware, and computing power are all accessible to the farmer, which is not always the case in resource-constrained contexts. Although the literature provides numerous ways to design irrigation control schemes, the underlying assumption is that instrumentation complexity and cost are minor constraints to the end user. Conversely, in resource-constrained markets, complexity and cost become key constraints [6].

Table 1 lists the functional requirements (FRs) for the proposed PI tool. To meet the needs of target users, the tool must deliver similar performance to existing PI technologies designed for resource-plentiful markets (FR1); this includes at least partial automation of the irrigation decision-making process by creating an irrigation schedule for the user (FR3). As specified by the 2022 SOFA report, the technology must be scale-neutral (FR2), meaning it works for any farm scale, accessible to users with a range of technical knowledge and access to training (FR3), easily adaptable to the local context to account for farm heterogeneity (FR2, FR5), and affordable to the target user group (FR6) [19]. As small- and medium-scale farmers tend to be highly risk averse [6], the tool must also consistently compute an accurate irrigation amount and operate reliably in any given context (FR4, FR5). Currently, there is not a widely available PI technology that meets all of these requirements.

Table 1. FRs for a PI tool that meets the needs of small- and medium-scale farmers in resource-constrained markets.

No.	Requirement	Justification
FR1	Improve system efficiency	Deliver similar performance as existing PI tools, conserve resources, reduce costs
FR2	Case-specific	Account for case-specific parameters (heterogeneity) on farms and varying levels of user agronomy experience
FR3	Create irrigation schedule and communicate with user	Eliminate the need for expert technical knowledge, while building user proficiency by keeping them in the irrigation control loop
FR4	Accurate irrigation amount	Mitigate risk to crop yield
FR5	Reliable operation	Mitigate risk to crop yield, make tool easy to maintain, promote adoption by building users' trust
FR6	Affordable	Make tool financially and locally accessible to facilitate adoption

FR3, which specifies creating an irrigation schedule and communicating it to the farmer, is a critical feature that could determine the tool's success among resource-constrained farmers. This study primarily focuses on characterizing an HMI that enables FR3, with a particular focus on advancing transferring information between the machine and the user.

FR3 is a departure from the design ideologies of existing PI technologies, which aim to fully automate the decision-making and execution steps of irrigation using a suite of sensors and actuators. In resource-constrained markets, however, it is beneficial to keep the user in the control loop due to large variations in user technical experience and farm heterogeneity [19]. Keeping the user in the loop may trade greater precision for less technical complexity, but this design decision allows the tool to leverage users' agricultural expertise and real-time human observation, as well as build users' trust in the technology.

3. Characterization of a Proposed AS-MO Tool and HMI

A PI tool for EA and MENA farms was conceptualized to meet FR3 and the other FRs described in Section 2. Figure 1 characterizes the two critical actions of irrigation system control. First is determining a schedule of irrigation events (i.e., "Scheduling"). The second is operating valves in a hydraulic network (i.e., "Operation"). Each action can be done either manually by a farmer or automatically by the system, resulting in four distinct design spaces. Fully manual methods, like stick tests paired with manual valves, are in the upper left. Fully automated PI solutions are in the lower right quadrant. Existing irrigation timers fall into the manual scheduling and automatic operation quadrant. To the authors' knowledge, no commercial technologies exist that deliver the automatic scheduling benefits of PI while primarily relying on manual operation, a practice common on EA and MENA farms. The lower left quadrant of Figure 1 highlights this gap. We hypothesize that a technology in the automatic scheduling and manual operation (AS-MO) design space is well-suited for the small- and medium-scale farms found in EA and MENA.

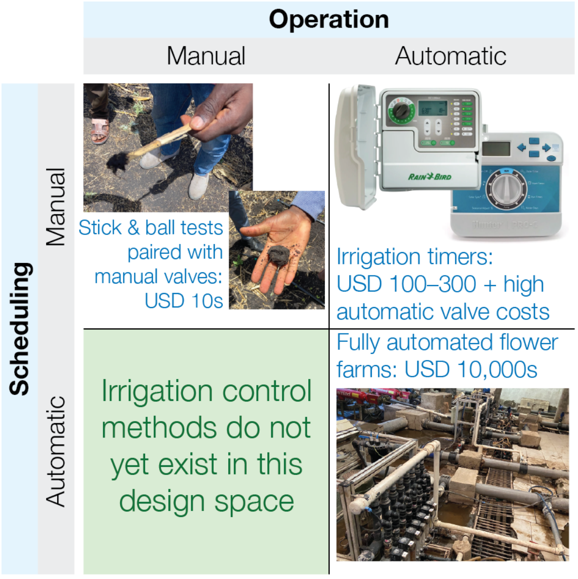

Figure 1. Visualization of the design spaces of irrigation system control methods with regard to two key actions: scheduling and operating. Existing methods fill three of the four spaces. This work proposes a tool within the automatic scheduling and manual operation space and evaluates this concept's fitness for medium-scale farmers in EA and MENA.

To facilitate automatic scheduling, this tool could incorporate many of the proposed techniques from the literature that improve energy use efficiency, reduce water use, increase crop production, or minimize irrigation system costs. While many existing and under-development solutions can automatically generate irrigation schedules, the proposed tool incorporates one that was developed in parallel with the HMI solution explored in this study [37]. This theory is particularly well-suited for this context because it addresses several of the identified FRs outlined in Table 1. It targets optimal water and energy use efficiency in SPDI systems (FR1) and takes in site-specific details for calibration (FR2). Cloud computing and predictive modeling ensure that the tool reliably delivers the appropriate water volume (FR4, FR5). Leveraging computation to minimize the number of on-field sensors ensures that the hardware is affordable and easy to maintain, and implementing solar profile-matching schedules enables smaller, less expensive power systems (FR6).

However, this scheduling theory alone, as well as many others, does not address FR3, which is necessary to ensure a feasible, adoptable solution for resource-constrained farmers. The right of Figure 2 shows how the AS-MO tool's HMI communicates an easy-to-follow schedule. In this initial conceptualization, it sends Short Message Service (SMS) reminders throughout the day to farmers' cell phones, products which are increasingly more common in low-resource countries [38]. SMS-based instructions, which could address FR3, have proven successful in resource-constrained medical interventions [39,40], so that model was adopted for irrigation instruction. At the beginning of each day, the tool sends the redetermined irrigation schedule to the farmer. The farmer can accept or slightly modify this preliminary schedule. Once the accepted schedule begins, the tool sends messages to the farmer's phone, reminding them to manually open or close valves (lower right of Figure 2). The farmer would then manually open or close valves as directed, sending an SMS to confirm completed actions. Because farmers might not open or close valves on time, a confirmation allows the tool to measure how long each irrigation event was in practice without needing to use sensors throughout the field. This measurement is important, so the scheduling theory's algorithm can accurately calculate the duration of future irrigation events. This interaction process is repeated throughout the day, according to the predetermined irrigation schedule.

By utilizing existing scheduling theory, leveraging farmer expertise, and integrating into existing labor practices, this proposed AS-MO HMI is designed specifically for target farmers.

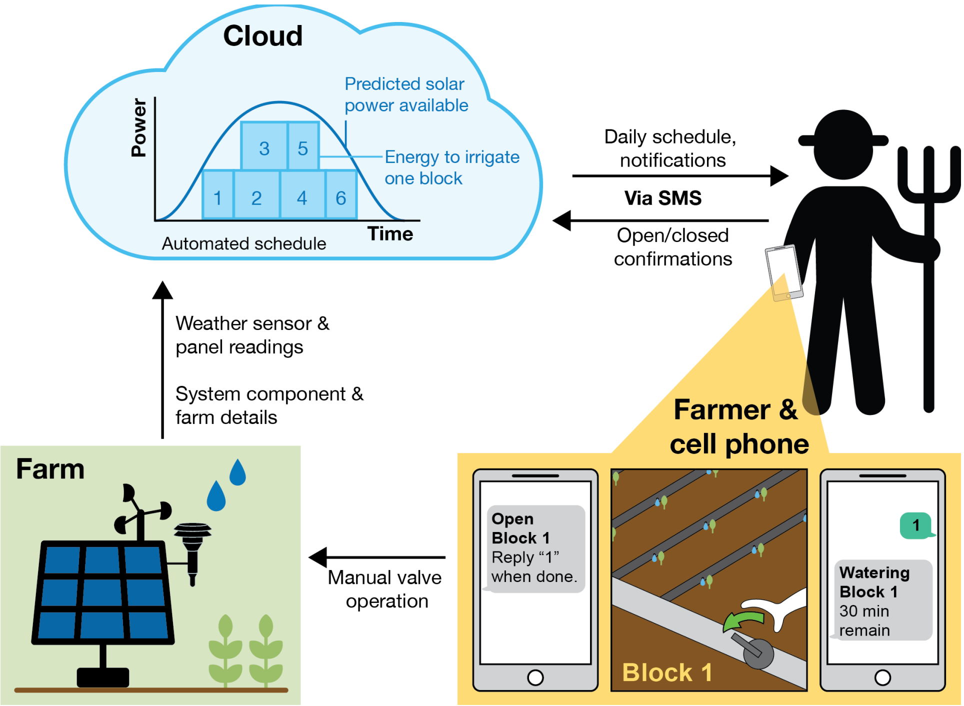

Figure 2. Depiction of the proposed AS-MO tool and HMI. On the left, details about the farm and irrigation system are fed into an algorithm that leverages cloud computing and predictive modeling to automatically generate efficient irrigation schedules. On the right, this schedule is communicated to farmers for manual operation via SMS messages at the beginning of the day and at the start and end of each irrigation event. These messages instruct farmers to carry out the generated schedule by manually operating valves. When farmers confirm completed actions, they inform the algorithm how closely the schedule was followed so the next day's schedule can be generated accordingly.

4. First Design Iteration of the AS-MO HMI: Storyboard-Based Assessment in Kenya

To assess the proposed AS-MO tool and HMI, an approach originally introduced in prior work [27] and inspired by Lean Startup methodologies [41] was followed. In particular, the early steps of the Lean Design for Developing World (LDW) Method [42] served as an example for this work, as they have for other design engineers working in LMICs [43,44]. This method recognizes the unique challenges—like access to users and logistics of travel—and pitfalls facing those who engage in engineering for global development [45]. In the LDW method, designers first conduct market and field research, develop an initial product concept, and create a hypothesis regarding the product's potential value. The previous sections of this paper summarize these efforts. The LDW method continues with designers aggregating customer needs, generating engineering specifications, and creating a minimum viable product. The LDW method assumes an existing customer base, so modifications to these steps were made to assess the initial concept with potential users and market stakeholders. Sections 4 and 5 detail these efforts in two design iterations.

4.1. Materials and Methods for Storyboard-Based Interviews and Focus Groups

To understand how medium-scale EA farmers might value the proposed AS-MO HMI, tours of 11 medium-scale farms were conducted in Kenya in October 2021. Tours, given by managers or employees, included observations of existing SPDI systems and crop production techniques. Accompanying the tours, 35 individual interviews and small focus groups were held with farm owners, managers, employees, and key market stakeholders, all of whom provided different perspectives on the AS-MO HMI. These interviews were facilitated using storyboards, tools that help engineers elicit user feedback on early-stage concepts [46]. The low-fidelity nature of storyboards is appropriate for early design stages when the concept can change easily [47]. The four storyboards used in this study visually depicted:

1. How the proposed AS-MO tool might integrate into standard SPDI systems;
2. The anticipated value the tool might deliver farmers, including energy, water, and cost savings;
3. How the tool integrates weather and agronomy details to build a schedule;
4. How farmers interact with the tool on a daily basis.

The storyboards were shown in the above order, introducing more detail about the tool's features and potential benefits as the interview progressed. Visuals of the storyboards are provided in Supplemental Information (SI).

The storyboards were used alongside open-ended questions, also provided in SI, designed to understand the key benefits and costs the tool might have to the participant. Participants were asked to give both positive and negative feedback on the concept. It was stated that the tool and HMI features had not been solidified, stressing that the participants' honest feedback would be critical to designing the most beneficial tool and HMI. To learn if farmers might adopt this technology, they were asked if they would consider installing it on their farm, and why or why not. If they answered "no," participants were asked if they would recommend the tool to a neighbor who was installing a new SPDI system, and why or why not. To continue developing the AS-MO concept, farmers were asked if they had ideas for improving the tool or HMI.

Interviews were conducted with 16 farm owners, managers, and employees, all selected for the study because they were early adopters of SPDI or potential lead users for the AS-MO tool. While lead users and early adopters may represent a small number of users, they often provide valuable insights on novel technology [48].

To complement farmers' responses and to learn if the proposed tool and HMI could become a viable product in the region, 19 market stakeholders were also interviewed. Stakeholders were broadly familiar with irrigation in EA and represented professional viewpoints of different sectors of EA agriculture markets. These individuals have collectively helped thousands of farmers improve their farms, so they could provide perspectives on a large population of farmers in ways that individual farmers could not. Stakeholders with diverse perspectives of the irrigation market were recruited. Their roles, affiliations, and rationales for selecting these individuals are given in SI.

Questions asked of stakeholder interviewees were designed to address the following topics: design changes necessary to develop the proposed AS-MO tool into a commercial product, and whether their price range expectations met what the research team estimated to be possible. An estimated range of USD 300–500 was based on the price point of products in the manual scheduling-automatic operation design space [49,50]. The cost of the proposed tool is expected to be slightly higher because several weather sensors, expected to be USD 100–200 [51], are also needed for the tool to function. Like the farmers, the stakeholders were also encouraged to ask questions about and suggest changes to the tool and HMI.

4.2. Results of the Storyboard-Based Assessment

This section is separated into two subsections, which both address the third research objective. Findings from these two sections inform the second design iteration.

4.2.1. Substantiation and Elucidation of Value and Adoption Desire in Kenya

Fourteen of 16 interviewed farmers claimed they would be willing to adopt the proposed AS-MO tool, signaling a high value might be placed on the proposed HMI. They valued it for three key reasons: it could increase the reliability of their irrigation, increase their confidence while making irrigation decisions, and enable more energy-efficient irrigation. These values are elucidated further in the following three paragraphs.

First, managers, owners, and employees claimed that an automatic scheduling tool could increase the reliability of their irrigation. Thirteen farmers reported challenges scheduling irrigation events during unpredictable weather conditions, like cloudy periods. During these days, farmers said their systems had trouble pumping at desired rates. A majority of participants decided when to schedule irrigation events based on experience and observations at single points in time, not accounting for future events. A majority of participants were interested in the proposed tool's ability to predict the available solar power and water demand, claiming this feature could distribute and store water in ways to reduce the risk to crops.

The second reason participants valued the proposed AS-MO tool is that they claimed an automatic scheduling tool could increase their confidence while making irrigation decisions, saving them time and effort. Multiple farmers demonstrated manual tests, like the stick test, that they currently use to plan irrigation events. Multiple farmers noted these methods were cumbersome because they needed to check multiple places in each irrigation block to assess water demand. Further, an agronomist noted these binary tests cannot account for the variation of soil textures and crop water requirements commonly seen between farms. This stakeholder claimed the proposed tool could increase users' confidence in their irrigation schedules because it accounts for these variations. Several farmers noted they hire an agronomist to visit their farm biweekly to provide irrigation scheduling advice. They claimed the tool could provide more frequent irrigation direction, further increasing their confidence.

The third value farmers saw in the proposed AS-MO tool and HMI was that it could enable more energy-efficient irrigation for a small investment and minimal hardware change. During eight of 11 farm tours, energy inefficiencies in system operations were observed or noted by the farmers (e.g., a solar pump not running despite high solar irradiance). Farm owners recognized that pumping downtime either meant their solar system was oversized or that they were not irrigating to the farm's full potential, introducing costly inefficiencies. Participants claimed that automatically-generated schedules could avoid these losses, and a majority preferred to realize this benefit while continuing to use manual valves. Managers and employees claimed they wanted to continue visually checking blocks at the end of irrigation events, suggesting a distrust in full automation. They also wanted to continue using the familiar hardware they currently use. Owners wanted to minimize the additional investment needed on the farm to gain several key benefits of automatic scheduling, so they preferred the less expensive option: manual valves.

Farm owners and key stakeholders claimed the proposed price point was appropriate for the anticipated efficiency benefits, suggesting market viability in Kenya. Owners said the estimated USD 300–500 price point for the AS-MO tool matched their expectations. Several reported paying an agronomist approximately USD 14/visit for biweekly farm evaluations, further suggesting farmers' willingness to invest in irrigation advice. In all stakeholder interviews with equipment distributors, the price estimate for the tool matched expectations. The interviewed stakeholders expressed their support for the AS-MO tool concept to become a product in the EA market. At Davis & Shirtliff, an irrigation equipment distribution company serving EA, all eight interviewed engineers and managers believed it was viable. A former director of this company said he was "convinced [this concept] is feasible and can be implemented". At Xylem, Inc., a global water solutions company, all three interviewed managers agreed. They further claimed this tool and HMI could provide value to many of the resource-constrained regions they serve.

All other stakeholders expressed belief in the AS-MO tool's value to their customer base, further substantiating its potential value. Government officials mentioned that the demand for SPDI is expanding and an AS-MO tool could help farmers adopt good irrigation practices with their new systems. A borehole driller said a tool that monitors irrigation events could help him advise clients who are expanding irrigation on their farms. These preliminary results show that farmers in Kenya and stakeholders in EA value the combination of automatic scheduling with manual operation in the proposed tool and HMI.

4.2.2. Improvements Based on Findings from First Design Iteration

Interviews with farmers and stakeholders highlighted two key design changes to the proposed AS-MO concept:

1. The updated tool should send messages using data rather than SMS. Several participants claimed SMS rates were higher than data rates in Kenya, so it was preferred that the tool use data. The second iteration of this concept used data-based messaging instead.
2. The updated HMI should include the ability for farmers to slightly adjust the irrigation schedule during the day. Farmers claimed they would trust the tool to automatically calculate the correct amount of water most of the time, but not in all cases. For example, if they recently installed the tool, they would want to monitor how it differs from their typical schedules for a few weeks. This response highlights the importance of keeping the user in the control loop to build trust and promote adoption. Farmers may also want to skip irrigation events if they were harvesting earlier than expected or if the system needed maintenance. In these cases, participants said they would like to adjust the schedule as desired after visual inspections at the end of irrigation events. In the second iteration of this concept, farmers were given the ability to skip irrigation events or to add time to irrigation events if they observed insufficient water delivery. The order and duration of irrigation events were still automatically scheduled and communicated to farmers to enable manual valve operation.

5. Second Design Iteration of the AS-MO HMI: Prototype-Based Assessment in Kenya, Jordan, and Morocco

5.1. Materials for Prototype-Based Interviews and Focus Groups: Design of a Physical HMI Prototype

The design improvements listed in Section 4.2.2 were incorporated into a physical prototype of the AS-MO tool and HMI that simulated a farmer's daily interaction [52]. The LDW-inspired approach introduced in Section 4.1 was continued with this prototype serving as a minimum viable product. Prototypes increase the quality of feedback given by interview participants because they allow a potential user to imagine interacting with the proposed device [53]. This mechanism was used to evaluate how farmers and stakeholders respond to the basic elements of the AS-MO HMI. The prototype consisted of three components: a mobile phone, a control box, and a weather station (Figure 3).

GEAR Lab Irrigation Controller
Section 2: 45 minutes left

Open Section 3 and
confirm on your phone.

GEAR Lab Irrigation Controller - K...

Skip Section 1.

Irrigating Section 1 for 30 minutes. Next event is at 8:30am. 4:16 PM

Please close Section 1 and confirm. 4:16 PM

Section 1 is closed.

Add 10 minutes to Section 1.

You have added 10 minutes to Section 1. 4:17 PM

Please close Section 1 and confirm. 4:17 PM

Figure 3. The three components of the physical prototype used to facilitate interviews. The phone (**A**) was equipped with a Telegram bot that stepped farmers through a set of key interactions. The control box (**B**) displayed the status of these interactions and directed farmers to interact on the phone. The low-cost weather station (**C**) showed farmers what data the tool might collect.

The phone was equipped with Telegram, a data-based messaging app (Telegram FZ-LLC, Dubai, United Arab Emirates, 2023). Telegram users can have conversations with bots that deliver preprogrammed messages and can ask users short answer questions to determine the messaging path. For this study, a Telegram bot was built to walk participants through the following set of simulated AS-MO HMI interactions:

- Provide farmers with a daily irrigation schedule, simulating the first message received each morning;
- Ask farmers if they approved that initial schedule;
- Send a message prompting farmers to manually open or close valves when irrigation events start or end, respectively;
- Allow farmers to add 10 min when an irrigation block is scheduled to end; and
- Enable farmers to skip events before they begin.

These interactions aimed to bring farmers the scheduling flexibility that was shown as valuable in Section 4.2.2.

The prototype control box consisted of an e-Ink (Adafruit, New York, NY, USA) screen mounted on a box of similar proportions to the anticipated design. Inside the box was a Raspberry Pi microprocessor (Raspberry Pi, Cambridge, UK) that executed the Telegram bot's script. The box did not have any physical modes of interaction (e.g., buttons or dials), but it was designed to:

- Display the open/closed status of irrigation blocks based on confirmations participants made in Telegram;
- Display a countdown telling the user when the next irrigation event was scheduled;
- Demonstrate to participants the anticipated size of a permanently-mounted control box.

The prototype weather station included the type of weather sensors that would be required to generate optimized irrigation schedules: wind speed, wind direction, ambient light, solar irradiance, precipitation, temperature, and humidity. This allowed the research team to elicit feedback on the weather information participants found valuable.

5.2. Methods for Prototype-Based Interviews and Focus Groups

The physical prototype was designed to help participants describe what would be valuable or frustrating about the HMI. Interviews and small focus groups were conducted with potential users and market stakeholders in Kenya, Jordan, and Morocco, expanding coverage into two MENA countries. Participants were first introduced to the updated tool concept with a set of storyboards using the protocol described in Section 4.1. This set of storyboards reflected the two design improvements described in Section 4.2.2.

Participants were then given the physical prototype and guided to answer questions relating to the value and daily use of the proposed HMI. Semi-structured interview questions targeted three broader research questions: (1) What is the most useful information the tool could provide? (2) How would farmers use or not use the tool daily? (3) What drawbacks would farmers encounter with the tool's HMI?

As the prototype was intended to assess user interactions rather than the water and energy savings one could realize with automatic schedule determination, a mock irrigation schedule was presented to the user. The durations of irrigation events were also shortened for the study, and participants were advised of these adjustments.

The research goals sought to understand farmers' general satisfaction with the proposed HMI, so several less common interactions were not simulated:

- Significantly changing irrigation schedules (e.g., shortening or canceling irrigation events, or lengthening irrigation events before they began);
- Inputting farm details into the tool for calibration (e.g., field layout, crop types, and growth stages of crops);
- Providing farmers with forecasts greater than one day out.

In total, 22 prototype-based interviews and focus groups with farmers were conducted (seven in Kenya, five in Morocco, and 10 in Jordan), involving a total of 36 farmers (13 in Kenya, 11 in Morocco, and 12 in Jordan). Farmers were associated with 22 farms, ranging from 3–10 acres in Kenya, 5–120 acres in Morocco, and 4–120 acres in Jordan. Farm sizes were representative of the ranges in their respective countries for which SPDI is most feasible [6,7]. Due to travel complications, three interviews in Morocco were conducted without the prototype. These protocols involved only the storyboards.

Prototype-based interviews were also conducted with 21 market stakeholders (seven in Kenya, four in Jordan, and 10 in Morocco) whose backgrounds are summarized in SI. Interviews with stakeholders followed a similar protocol as interviews with farmers and sought to assess the tool's potential as a viable product in respective markets. On larger farms, particularly in Jordan and Morocco, the anticipated price point range was increased from USD 300–500 to USD 700–1000 because large farms often experience microclimates, so they may need several weather stations to provide accurate forecasts. All interviews took place in March 2022.

5.3. Results of the Prototype-Based Assessment

This section is separated into four subsections. Section 5.3.1 addresses the third research objective. Section 5.3.2 addresses the fourth research objective. Findings from those two sections are synthesized into a set of further design changes in Section 5.3.3. Finally, given all prior findings, the FRs are revisited and translated into design specifications in Section 5.3.4.

5.3.1. Further Substantiation of the HMI's Value

In 23 of 36 interviews (nine in Kenya, seven in Morocco, and seven in Jordan), farmers asserted the AS-MO tool would likely be adopted by farmers in the target user group. This result is consistent with preliminary results and suggests the tool and HMI may be valuable to MENA farmers as well as EA farmers.

The most valuable benefits of the tool according to participants were alleviating water scarcity concerns and preventing over-irrigation. Farmers and stakeholders alike noted climate change has made seasonal rains unpredictable. Farmers can no longer reliably anticipate water availability based on historical trends. Participants claimed an automatic scheduling tool could help them plan irrigation events. The AS-MO tool would act as an interactive dashboard that simplifies farmers' decision making for a complex system. As one Jordanian engineer explained, "If you provide a tool that will enable farmers to regulate the way they apply water the same way you regulate your car acceleration, you will get really impressive results".

Farmers in particular noted the tool could save them effort, money, and time, echoing results in Section 4. MENA farmers who used grid-based systems frequently cited high electricity costs, observing that by reducing power system costs, the tool could allow them to adopt SPDI. Professionals in this region also claimed the tool could reduce system energy consumption and cost by encouraging farmers to reduce over-watering and over-pressurizing the system. This is why, as multiple stakeholders observed, a key aspect of the tool's value proposition is that it accounts for both water and energy use concurrently.

In 11 interviews, farm owners and stakeholders agreed that the estimated price points were reasonable for the target users. No other participants asserted that the proposed price point was too high, suggesting that there may be promising markets in both EA and MENA for the proposed AS-MO tool.

5.3.2. Participants' Adoption Desires and Preferences for Scheduling and Operation

Figure 4 summarizes the scheduling and operation preferences noted from the 36 farmer and stakeholder interviews. These preferences indicate that an AS-MO HMI may be most likely to be adopted in EA and certain MENA submarkets.

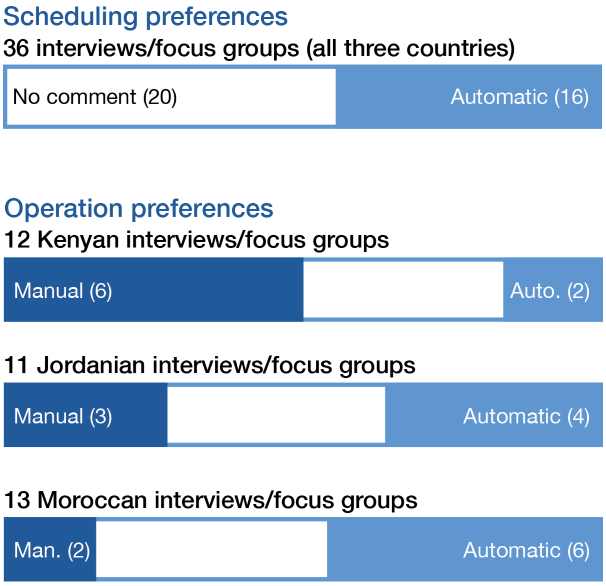

Figure 4. A summary of both farmer and stakeholder preferences for scheduling and operation. Automatic scheduling was preferred over manual scheduling by all participants who had a preference. Preference for manual operation over automatic operation differed by country. Not all participants indicated a preference, so they are visualized with white space.

In 13 of 22 farmer interviews, participants noted they appreciated the automatic scheduling aspect of the AS-MO HMI. This result, consistent with Section 4, suggests this is an important feature for Jordanian and Moroccan farmers in addition to Kenyan farmers. Participants noted an automatically-determined schedule specific to their farm and weather conditions could improve yields.

There was disagreement among farmers on their preferences for manual versus automatic valves. In 12 interviews (two in Kenya, four in Jordan, and six in Morocco), farmer or stakeholder participants preferred automatic valves, while in 11 interviews (six in Kenya, three in Jordan, and two in Morocco), manual valves were preferred. The preference for automatic operation was particularly driven by MENA participants who operated or worked on larger farms. On larger farms, participants claimed automatic operation was worth the investment because laborers would otherwise walk long distances to manually operate valves, potentially increasing labor costs. Several of these farms had already installed solenoid valves and asked if the tool could also operate those valves.

Kenyan farmers in particular favored manual valve operation over automatic operation, with only two of seven farmers claiming an automatic valve preference. Consistent with preliminary results reported in Section 4, manual valves were heavily preferred due to low costs. Study participants also noted the reliability and familiarity with manual valves in the region could benefit Kenyan farmers more than solenoid valves. Several participants in Jordan also had a preference for manual valves, suggesting that an AS-MO HMI could have promise in these markets.

5.3.3. Improvements Based on Findings from Second Design Iteration

The two design changes and updates to the AS-MO tool and HMI described in Section 4.2.2 were valued by participants in all three countries. The majority of farmers interviewed liked the ability to add time or skip irrigation events. This suggests that farmers value a degree of manual control, a finding consistent with Figure 4. Farmers also liked that the prototype used data rather than SMS because local SMS rates were higher than local data rates.

In this design iteration, study participants suggested two key features to add to future iterations of the AS-MO tool and HMI:

1. While most farmers preferred for the main interaction to be through their phones, 11 participants suggested that farmers should have the ability to interact with the control box without a phone. Numerous reasons were cited as to why a phone might not be available. For example, the phone could be broken, the battery could be dead, someone else could be using the phone, or the cellular service could be poor. This result suggests that critical interactions with the AS-MO HMI should be integrated into a control box design, so that farmers who need it have consistent access.
2. Farmers and stakeholders alike expressed a preference for a custom app as opposed to using a messaging app like Telegram. Participants claimed a custom app would increase functionality, citing three key benefits and one potential drawback:
    (a) Participants noted inputting the farm details needed for automatic scheduling could be easier with a custom app. Farmers and agronomists agreed that they would happily update farm details when they change crops, as long as it were an easy process. This suggests that particular consideration should be put into this interface for the tool. A custom app would allow for the greatest flexibility when inputting these details.
    (b) A custom app would allow different users to visualize their farm data in different ways, reflecting differences in the types of information that various participants reported finding the most valuable. Managers and employees reported that detailed data on crop irrigation needs and weather forecasts would be most valuable. Owners said they were less concerned with daily operations and more concerned with the overall status (e.g., if their system was working well or the crops were healthy). These results demonstrate a variety of interfaces highlighting different information might be needed to account for a diversity of users. A custom app could provide this flexibility.
    (c) Several participants were concerned a messaging-based interaction could be difficult for illiterate laborers to use. An app enables the use of more symbols or voiced instructions, increasing the tool's accessibility.
    (d) While a custom app was strongly suggested by a majority of study participants, it was also noted that a custom app could not be used by farmers who have feature phones. However, studies have projected that by 2025, 84% and 61% of

all cellular connections in MENA and Sub-Saharan Africa, respectively, will be smartphone connections [54,55].

5.3.4. Target Specifications to Meet When Designing an AS-MO Tool and HMI

The findings of the two design iterations were synthesized into specifications for a PI tool that could address the needs of farmers in EA and MENA. Table 2 lists the design features and target specifications that align with the FRs first defined in Table 1, showing how to design a high-performance, low-cost AS-MO tool and HMI for resource-constrained markets.

Table 2. Key features and design specifications with target values for a PI tool that meets the needs of small- and medium-scale farmers in resource-constrained markets.

No.	Requirement	Elements	Design Specification or Proposed Feature
FR1	Improve system efficiency	Increase water use efficiency Increase energy efficiency (solar)	10–50% water savings, comparable to sensor-based methods [56] 10% increase in energy efficiency (solar profile-matching) [25] 20% power system cost reduction [6]
FR2	Case-specific	Scalable calibration procedure Easy-to-use data entry interface	Input crop type, soil composition, field layout, GPS Characterize hydraulic system operation on-site
FR3	Create irrigation schedule and communicate with user	Intuitive user interface Non-disruptive communication frequency Compatible with local operating system	Keep user in the control loop with AS-MO Update irrigation schedule daily Allow user to adjust or skip events App-based interface, using data (not SMS) iOS and Andriod compatible
FR4	Accurate irrigation amount	Accurate soil moisture estimation Accurate weather data/forecast	±10% water demand accuracy, according to interviewed stakeholders Daily, site-specific weather forecast Real-time weather and hydraulic measurements
FR5	Reliable operation	Reliable on-site connectivity Robust energy management/storage Robust calibration Simple maintenance Weatherproof	WiFi or local network (e.g., LoRa) Power always available for scheduled irrigation One-time calibration, accurate throughout season Locally-available or standard hardware IP68 enclosure (weatherproof)
FR6	Affordable	Low-cost compared to existing tools Minimal specialized hardware	USD 300–500 (EA) USD 500–700 (MENA) Locally-available or standard hardware Cloud-based computation

Similar to existing PI technologies, the tool must improve the water and energy use efficiency of an irrigation system (FR1). Numerical targets for water and energy savings were identified from the literature on existing PI tools [56] and scheduling with solar-powered irrigation [25]. Previous stakeholder interviews were used to identify the associated power system cost savings that would be valuable to the target users [6]. For the remaining FRs, the key elements and their respective specification(s) or features were distilled from the storyboard- and prototype-based interviews and focus groups conducted in this study. Conversations with farmers and irrigation engineers provided insight on the inputs and calibration methods that could make the tool case-specific (FR2) as well as technically accessible to the user (FR3). Prototype feedback from potential users and PI industry professionals informed the specifications for irrigation accuracy (FR4), reliability in the farm environment (FR5), and the tool's price and maintenance (FR6). Together, the design specifications and features proposed for the AS-MO tool can serve as a guide for designing PI technologies that could meet the needs of a broader population of users.

6. Discussion

This work demonstrated that the proposed AS-MO tool and HMI has the potential to bring the efficiency benefits of PI to medium-scale farms in Kenya and small- and medium-scale farms in Jordan and Morocco. It could do this by bridging the gap between existing, expensive PI technologies and affordable, easy-to-adopt irrigation methods.

Data from the study validated the assumptions made in Section 3 about the potential benefits of an AS-MO irrigation control method over the other methods in Figure 1. First, compared to both manual scheduling methods (top half of Figure 1), an AS-MO HMI was hypothesized to address problems that are hard for humans to solve alone, such as creating efficient, reliable irrigation schedules. Discussions with farmers confirmed that doing so was difficult, time-consuming, and sometimes not possible without the use of sensors and calculations. The increase in efficiency and reliability provided by automatic scheduling was found valuable by most farmers, confirming initial hypotheses.

Second, compared to full automation (lower right of Figure 1), an AS-MO tool was predicted to be more familiar and affordable to farmers. Some participants preferred manual valves over automatic ones because they were concerned about the reliability of solenoid valves, a technology with which they had little familiarity. Several farmers also valued the ability to continue visually inspecting each block after each irrigation event. Farmers' preferences to continue these current practices suggest equipment familiarity is a priority. Farmers, particularly owners, expressed interest in the AS-MO tool because it was lower cost than a fully-automated system, confirming that affordability is also a priority for the targeted farms.

Results from Kenya, Jordan, and Morocco are anticipated to be applicable to the larger regions of EA and MENA, so differences seen between the three countries could predict differences in the two regions. One key difference between the regions was that it appeared that several interviewed Jordanian and Moroccan participants were more familiar with current PI techniques than Kenyan farmers. Perhaps MENA participants were more excited about fully-automated systems because they already trusted solenoid valves while Kenyan participants more frequently expressed skepticism about automated valves. This could explain the mixed preferences for manual valve operation over automatic in Jordan and Morocco compared to strong preferences for manual operation in Kenya. While there was a slight preference for full automation in the Jordanian and Moroccan markets, this does not necessarily mean that an AS-MO tool could not provide value in the MENA region. There was strong interest in manual valves among the smaller farms in Jordan and Morocco which appeared to have less access to capital than medium-scale farms. This suggests there is likely a MENA market sector that would find an AS-MO tool valuable, similar to Kenyan farmers. Future exploration of the EA and MENA markets could confirm if the differences seen in Kenya, Jordan, and Morocco reflect the differences between EA and MENA as whole regions.

This study revealed insights about which features farmers prioritize when interacting with an AS-MO HMI, notably flexibility and low operating costs. Design updates to the proposed HMI allowed farmers to slightly adjust auto-generated schedules, a feature valued by participants in all countries. This suggests farmers who do not already use automation may not trust full automation. If so, it is important to put final control in farmers' hands, giving them the flexibility to take as much or as little automated advice as they like. A second design update was the choice to use lower-cost, data-based messages over SMS to communicate with users. The strong preference for data-based messages demonstrates that users are sensitive to operational costs in addition to capital costs. Future design decisions should consider this user need and address any other ways lower operating costs.

The proposed AS-MO tool and HMI could potentially be a segue product for farmers who are transitioning from fully manual to fully automated. Several study participants pointed out that it would be beneficial for the tool to be adapted to include automatic valve operation, especially on larger or wealthier farms. This result suggests the participants saw the potential for the AS-MO tool to be "upgraded" from a semi-manual/semi-automatic tool to a fully automatic tool according to users' needs.

The FRs and design specifications identified in this study outline how designers could proceed in creating this technology. The lack of existing technologies in the design space where automatic scheduling combines with manual operation for low-cost precision irrigation control (lower left of Figure 1). This gap implies that practitioners have not yet identified this space as a viable place for design innovation. Documenting the FRs and participants' responses to critical design features is valuable for engineers who design technologies for farmers in resource-constrained contexts.

Participants in all countries commented on the importance of demonstrating the tool and HMI to farmers before they would be likely to adopt the technology, a result consistent with the literature [17,57]. Nine farmers claimed they would need to closely monitor the tool for a period of time before trusting the automatic schedules were sufficient. Farmers and professionals expressed concern about the accuracy of the crop water demand estimation; engineers from Hunter Industries noted that the accuracy of this estimation would have to be within at least 10%, based on their experience designing irrigation controllers, to avoid negatively impacting crop yield. These results stress the importance of demonstrating the tool and HMI before farmers can realize its full benefits.

The results suggest that an AS-MO HMI could enable the implementation of various PI scheduling algorithms on resource-constrained farms, extending beyond the specific algorithm used in this study [37]. Many scheduling algorithms, including those mentioned in the Introduction [20,21,23–26,30–32], often rely on complex, expensive equipment to execute optimized irrigation schedules. They do so by relying on inputs and outputs from sensors and actuators installed throughout a field. The results from this study imply that the necessary hardware components—and not the scheduling algorithms themselves—drive the high adoption barrier to PI solutions documented in the literature [19]. This work suggests that existing PI algorithms and how they are realized on farms could be redesigned to meet the specifications outlined in Table 2. For example, instead of relying on soil moisture sensors and solenoid valves, PI solutions could use farmers as their primary sensors and actuators, as is described in the AS-MO HMI. With the primary barriers removed, resource-constrained farmers could have improved access to many more PI innovations and the sustainability benefits they bring.

The strategy of pairing automated actions with manual actions could open new areas for innovation in precision agriculture and sustainable development to serve a broader range of users. This work demonstrates the successful use of a design process in which the research team identified opportunities to automate complex tasks while designing ways for users to complete these tasks in simpler, manual ways. This approach allows a technology to realize certain benefits of automation while also incorporating the benefits of manual actions. The potential impact is overall lower product costs and higher user satisfaction. Interviewees suggested this semi-automatic/semi-manual product architecture could be valuable if applied to fertigation, suggesting that this approach could have implications past the specific example of irrigation in the MENA and EA markets. Additional opportunities could include fertigation, harvesting, or other agricultural challenges outlined by the 2022 SOFA report [19]. Further opportunities exist beyond agriculture. To apply a semi-automatic/semi-manual architecture to a new area, the framework in Figure 1 can be referenced. When doing so, researchers and designers should break down a problem into the necessary actions (e.g., scheduling and operation, in the case of irrigation). They can then understand which actions are simpler to perform manually and which would be more difficult. For the difficult actions only, researchers and designers would then identify ways in which technology could improve those actions. New technology may need to be invented to communicate complex operations to users who are carrying out manual actions. This strategy is particularly appropriate for resource-constrained contexts. In these settings, the value of a product can be increased by selectively introducing automation while costs are minimized by continuing manual labor otherwise.

Several limitations existed in this study. The small number of farmer interviews does not necessarily give a generalized opinion of all potential users in EA and MENA. To attempt to mitigate this limitation, lead users, early adopters, and market stakeholders were recruited for the study. To address this gap, future work could conduct a full market assessment of the proposed AS-MO tool and HMI to estimate the adoption potential within the EA and MENA markets.

A second limitation is that users did not interact with a fully functioning prototype for an extended period. The prototype performed basic interactions, not infrequent interactions like inputting details of a farm or managing a failure in the system. These interactions might be tedious or particularly valuable to farmers, but without simulating them, it remains unknown.

The LDW-inspired approach taken has limitations in that potential users were not involved in the co-development of the initial AS-MO concept, only its evaluation. To mitigate this limitation, the concept development relied extensively on findings from prior market and field research that actively sought open-ended perspectives from farmers and market stakeholders. Further, this approach carried the risk that participants may have limited their negative feedback to not offend the research team. To mitigate this, participants were shown low-fidelity representations of the concept, and the research team communicated that participants' feedback was crucial in developing the next iteration of the concept. The interview protocol was designed to elicit both positive and negative feedback, and the majority of participants did provide both. This validates that the study successfully prompted at least a degree of critical response from participants.

Finally, this work aims to assess the human-centered value of the proposed AS-MO HMI but does not detail the technical feasibility of the concept. Work conducted in parallel to this study addressed this aspect [37]. Preliminary results on technical feasibility informed how the concept was presented to participants in this study. Both human-centered and technical perspectives were developed concurrently to ensure that the AS-MO tool is valuable and tractable to farmers.

Despite these limitations, the assessment methods used serve as a model for other researchers of how designers can approach interdisciplinary research in global, resource-constrained settings. The process taken allowed the research team to discern user preferences about detailed features of the AS-MO concept without investing in a fully functional prototype. Such a prototype is not always feasible or possible for design teams, especially those working under lean startup conditions or in resource-constrained settings. After participating in this study, one stakeholder interviewee who was designing a payment service for farmers mentioned he would like to follow a similar process to evaluate his concepts. The storyboard- and prototype-based assessment described here is a case study of how he and others might approach concept evaluation in global markets.

Both EA and MENA farmers claimed full demonstrations were important for them to evaluate their trust in a device. We believe the prototype fidelity was sufficient given the early design stage, but they did give interviewees limited amounts of information about the AS-MO tool and HMI. As the concept develops, further testing should include long-term use of a working prototype.

7. Conclusions

The work aimed to propose and evaluate a potential means of bringing the sustainable water and energy efficiency benefits of PI to resource-constrained, small- to medium-scale farmers in EA and MENA. This was accomplished by pursuing four research objectives and two design iterations of an initial tool concept.

Research objective 1: Define the FRs and design specifications of a PI tool for SPDI systems in resource-constrained markets that integrates with the current practices and capabilities of target farms. Before a concept was proposed, an initial set of FRs was synthesized using findings from the literature. These FRs guided an initial concept of a tool, and feedback about this concept was solicited from potential users and market stakeholders. Their feedback was used to translate the FRs into design specifications, which can aid engineers, designers, and researchers who aim to serve the farmers studied in this work.

Research objective 2: Characterize a human–machine interaction (HMI) that meets these FRs. An initial concept for an AS-MO tool and HMI that could communicate complex, but efficient irrigation schedules to farmers was characterized. This concept merged the water- and energy-efficiency benefits of auto-generated irrigation schedules with the manually-operated equipment familiar to the studied population of farmers.

Research objective 3: Substantiate the value of the HMI among lead users and early adopters, assess these potential users' desires to adopt such a tool, and iterate the HMI concept based on findings. To evaluate the value of the proposed AS-MO concept, a two-part development process was implemented. First, storyboards of the concept were shown to Kenyan farmers and market stakeholders to elicit feedback that was used to update the concept. Second, a physical prototype of the tool's HMI was used in Kenya, Jordan, and Morocco to facilitate further interviews and focus groups with farmers and stakeholders. The results demonstrated that the proposed AS-MO tool has the potential to enable target farmers to realize the energy- and water-saving benefits of PI with lower-cost infrastructure. The majority of all interviewed farmers were interested in the automatic scheduling aspect of the AS-MO tool, recognizing it could save them time, effort, and money. Kenyan farmers and small-scale farmers in Jordan and Morocco liked the manual valve operation that an AS-MO HMI affords, citing preferences to adopt inexpensive, familiar hardware like manual valves over solenoid valves. These results indicate a potential market for PI technology designed specifically for resource-constrained farmers.

Research objective 4: Assess target farmers' satisfaction with the proposed PI tool and HMI and identify avenues for improvement. Interviews with farmers and stakeholders provided insights on how farmers might best interact with the AS-MO HMI. Results suggested that a smartphone app should be designed to enable user interactions with the tool. A data-based solution, like an app, would have lower operating costs than an SMS-based solution. Results showed farmers appreciated the flexibility to slightly change the predetermined schedule by adding time to the end of irrigation events or skipping the event if needed. Phones may occasionally be unavailable, so the permanently mounted control box should enable a limited set of critical interactions. A status screen and several buttons could meet this requirement. Stakeholders and farm owners suggested the tool has the potential to become a viable commercial product in the studied countries. All participants who commented on the estimated price of the tool claimed it would be affordable to target users.

To bring the AS-MO tool concept to fruition and realize its potential for increasing the adoption of sustainable agriculture, further research is needed to learn how farmers interact with a functioning AS-MO tool for an extended period of time. This study only addressed the core interactions of the proposed AS-MO HMI. Other interactions—like allowing farmers or agronomists to input farm details—need to be prototyped and tested. It is also necessary to study the AS-MO HMI over the course of a season to understand how to improve it for future users. Farmers in both regions claimed they would need to see the AS-MO tool installed and functioning on a farm to fully evaluate its potential benefit to them. This tool must be demonstrated under these conditions to gain further user feedback. The study also assumed that the perspectives of Kenyan farmers and Jordanian and Moroccan farmers would represent the perspectives of EA and MENA farmers, respectively. Future work should expand regional coverage to confirm or deny this assumption. If denied, learnings from other countries should be integrated into the tool to increase the likelihood of its adoption throughout the regions. Finally, a full market assessment should be conducted to estimate the tool's adoption potential in EA and MENA markets. With these next steps, future development on an AS-MO tool and HMI could help bring water- and energy-efficient irrigation to resource-constrained regions like EA and MENA, increasing sustainable agriculture worldwide.

8. Patents

The work described in this paper, along with other related efforts, has led to an international patent application (International Application No. PCT/US2023/072178), filed on 14 August 2023.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16198402/s1, Figure S1: The first storyboard shown to participants in EA depicts what a solar-powered drip irrigation system with an AS-MO tool might look like on a farm. Systems could have a pump that feeds from a water source. Water can be stored in a raised tank and drained to a network of pipes and drip lines, or it can pump directly to the drip network. Drip lines have emitters that deliver water directly to the root zones of crops. Solar panels could power the system, and energy could be stored in batteries and/or the raised tank. The scheduling tool could be mounted somewhere central, like under the panels. Sensors are also mounted centrally, and they record weather data. This storyboard was important to show farmers so they could imagine using the tool on their farms. Figure S2: An alternate version of Figure S1 that was shown to participants in MENA. This version depicts a reservoir as the water source and storage, which is most common in the MENA region. Figure S3: The second storyboard shown to farmers gives an overview of the predicted value that the scheduling tool could bring to farmers, comparing a system without the tool (top row) to one with it (bottom row). While maintaining water used, the tool allows for smaller power system sizes, less energy storage, and an increase in crop production. These savings manifest in an estimated 20% profit. A similar storyboard was shown to farmers who needed to save water. This alternate storyboard instead showed that the scheduling tool could grow the same amount of crops with a reduced volume of water and a smaller power system. This visual was important to show to farmers because it allowed them to see what might change if they used the AS-MO tool. Figure S4: The third storyboard shown to farmers provides an overview of how the scheduling tool works. It takes in sensed and historical weather information, such as precipitation and solar irradiance, to calculate evapotranspiration. The tool also factors in key farm details—including the crops that are grown on the field and the drip irrigation layout—that are input by the farmer. With these inputs, the scheduling tool can make short term weather predictions and can calculate the soil water balance to determine the optimal irrigation schedule from agronomy and system energy management standpoints. This schedule can instruct farmers how to operate their pump and manage the available power. Showing this storyboard gave farmers a sense of how the tool worked could allow them to trust the automatic scheduling determination or say if a key input was missing. Figure S5: The fourth storyboard provides a depiction of how farmers might interact with the proposed AS-MO tool using SMS reminders. At the beginning of the day, the tool tells the farmer their irrigation schedule. The farmer has the option to accept the schedule or make modifications. Once the approved schedule starts, the tool sends an SMS to the farmer's cell phone with the first instruction (e.g., "Open Block 1. Reply '1' when done"). The farmer follows these instructions, confirming when they have completed the task(s). After the appropriate amount of irrigation time, another SMS is sent to the farmer, telling them the next direction (e.g., "Close Block 1. Reply '1' when done. Open Blocks 2 & 3. Reply '23' when done"). This interaction cycle continues throughout the day until the irrigation schedule is finished. Table S1: Roles and affiliations of the 19 market stakeholders interviewed in the initial portion of this study, as described in Section 4; Table S2: Roles and affiliations of the 21 market stakeholders interviewed in the second portion of this study, as described in Section 5.

Author Contributions: Conceptualization, G.D.V.d.Z., F.G. and A.G.W.V.; methodology, G.D.V.d.Z.; software, J.C.; formal analysis, G.D.V.d.Z. and F.G.; investigation, G.D.V.d.Z., F.G., C.S. and A.G.; data curation, G.D.V.d.Z.; writing—original draft preparation, G.D.V.d.Z., F.G. and C.S.; writing—review and editing, G.D.V.d.Z., F.G., S.A., A.G. and A.G.W.V.; visualization, G.D.V.d.Z.; funding acquisition, S.A. and A.G.W.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by a gift from the Julia Burke Foundation and by the United States Agency for International Development (Cooperative Agreement Number AID-OAA-A-16-00058).

Institutional Review Board Statement: All interview protocols were approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects (Protocols #E3596 and #E4098).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to this set of human subject data is not publicly shareable.

Acknowledgments: The authors thank our field partners—Davis & Shirtliff, Puma Springs Farm, MIRRA Jordan, ICARDA Morocco, and INRA Morocco—for connecting us with participants and the participants themselves for sharing their perspectives. Thank you to Glen Urban and Maria Yang for providing guidance.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AS-MO	Automatic scheduling-manual operation
EA	East Africa
FAO	Food and Agriculture Organization
FRs	Functional requirements
HMI	Human–machine interaction
LDW	Lean design for developing world
LMICs	Low- and middle-income countries
MENA	Middle East and North Africa
PI	Precision irrigation
SDG	Sustainable Development Goal
SMS	Short message service
SPDI	Solar-powered drip irrigation

References

1. United Nations. *The Sustainable Development Goals Report*; United Nations: New York, NY, USA, 2020.
2. FAO, IFAD, UNICEF, WFP and WHO. *The State of Food Security and Nutrition in the World 2020*; FAO, IFAD, UNICEF, WFP and WHO: Rome, Italy, 2020. [CrossRef]
3. Amede, T. Technical and institutional attributes constraining the performance of small-scale irrigation in Ethiopia. *Water Resour. Rural. Dev.* **2015**, *6*, 78–91. [CrossRef]
4. Shah, T.; Verma, S.; Pavelic, P. Understanding smallholder irrigation in Sub-Saharan Africa: Results of a sample survey from nine countries. *Water Int.* **2013**, *38*, 809–826. [CrossRef]
5. Ngigi, S.N.; Thome, J.N.; Waweru, D.W.; Blank, H.G. *Low-Cost Irrigation for Poverty Reduction: An Evaluation of Low-Head Drip Irrigation Technologies in Kenya*; Annual Report; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2001.
6. Van De Zande, G.D.; Amrose, S.; Donlon, E.; Shamshery, P.; Winter V, A.G. Identifying Opportunities for Irrigation Systems to Meet the Specific Needs of Farmers in East Africa. *Water* **2023**, *16*, 75. [CrossRef]
7. Grant, F.; Amrose, S.; Talozi, S.; Nangia, V.; Winter V, A.G. Evaluating the potential for sustainable, user-centered PV-powered drip irrigation (PVDI) systems in the Middle East and North Africa. 2023, *Manuscript in preparation*.
8. Jobbins, G.; Kalpakian, J.; Chriyaa, A.; Legrouri, A.; El Mzouri, E.H. To what end? Drip irrigation and the water-energy-food nexus in Morocco. *Int. J. Water Resour. Dev.* **2015**, *31*, 393–406. [CrossRef]
9. Ward, F.A.; Pulido-Velazquez, M. Water conservation in irrigation can increase water use. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 18215–18220. [CrossRef]
10. Schmitter, P.; Kibret, K.S.; Lefore, N.; Barron, J. Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa. *Appl. Geogr.* **2018**, *94*, 41–57. [CrossRef]
11. Hrayshat, E.S.; Al-Soud, M.S. Potential of solar energy development for water pumping in Jordan. *Renew. Energy* **2004**, *29*, 1393–1399. [CrossRef]
12. Aliyu, M.; Hassan, G.; Said, S.A.; Siddiqui, M.U.; Alawami, A.T.; Elamin, I.M. A review of solar-powered water pumping systems. *Renew. Sustain. Energy Rev.* **2018**, *87*, 61–76. [CrossRef]
13. Allen, R.; Pereira, L.S.; Raes, D.; Smith, M. *FAO Irrigation and Drainage Paper No. 56*; Technical Report; FAO: Rome, Italy, 1998.
14. Blimpo, M.P.; Cosgrove-Davies, M. *Electricity Access in Sub-Saharan Africa*; World Bank: Washington, DC, USA, 2019; p. 167.
15. World Resources Institute. Aqueduct. Available online: https://www.wri.org/aqueduct (accessed on 5 June 2023).
16. Global Solar Atlas. Global Solar Atlas v2.8. Available online: www.globalsolaratlas.info/ (accessed on 15 May 2023).
17. Benouniche, M.; Kuper, M.; Hammani, A.; Boesveld, H. Making the user visible: Analysing irrigation practices and farmer's logic to explain actual drip irrigation performance. *Irrig. Sci.* **2014**, *32*, 405–420. [CrossRef]

18. Grant, F.; Sheline, C.; Sokol, J.; Amrose, S.; Brownell, E.; Nangia, V.; Winter, A.G. Creating a Solar-Powered Drip Irrigation Optimal Performance model (SDrOP) to lower the cost of drip irrigation systems for smallholder farmers. *Appl. Energy* **2022**, *323*, 119563. [CrossRef]
19. Food and Agriculture Organization of the United Nations. *The State of Food and Agriculture 2022*; FAO: Rome, Italy, 2022. [CrossRef]
20. Lakhiar, I.A.; Yan, H.; Zhang, C.; Wang, G.; He, B.; Hao, B.; Han, Y.; Wang, B.; Bao, R.; Syed, T.N.; et al. A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints. *Agriculture* **2024**, *14*, 1141. [CrossRef]
21. Liang, Z.; Liu, X.; Xiong, J.; Xiao, J. Water Allocation and Integrative Management of Precision Irrigation: A Systematic Review. *Water* **2020**, *12*, 3135. [CrossRef]
22. Abioye, E.A.; Abidin, M.S.Z.; Mahmud, M.S.A.; Buyamin, S.; Ishak, M.H.I.; Rahman, M.K.I.A.; Otuoze, A.O.; Onotu, P.; Ramli, M.S.A. A review on monitoring and advanced control strategies for precision irrigation. *Comput. Electron. Agric.* **2020**, *173*, 105441. [CrossRef]
23. Yahyaoui, I.; Tadeo, F.; Segatto, M.V. Energy and water management for drip-irrigation of tomatoes in a semi- arid district. *Agric. Water Manag.* **2017**, *183*, 4–15. [CrossRef]
24. Merida Garcia, A.; Fernandez Garcia, I.; Camacho Poyato, E.; Montesinos Barrios, P.; Rodriguez Diaz, J. Coupling irrigation scheduling with solar energy production in a smart irrigation management system. *J. Clean. Prod.* **2018**, *175*, 670–682. [CrossRef]
25. Zavala, V.; López-Luque, R.; Reca, J.; MartÃnez, J.; Lao, M. Optimal management of a multisector standalone direct pumping photovoltaic irrigation system. *Appl. Energy* **2020**, *260*, 114261. [CrossRef]
26. Adeyemi, O.; Grove, I.; Peets, S.; Norton, T. Advanced Monitoring and Management Systems for Improving Sustainability in Precision Irrigation. *Sustainability* **2017**, *9*, 353. [CrossRef]
27. Van de Zande, G.D.; Sheline, C.; Winter, A.G. Evaluating the Potential for a Novel Irrigation System Controller to Be Adopted by Medium-Scale Contract Farmers in East Africa. In Proceedings of the Volume 6: 34th International Conference on Design Theory and Methodology (DTM), St. Louis, MI, USA, 14–17 August 2022; p. V006T06A037. [CrossRef]
28. Sheshadri, A.; Borrus, M.; Yoder, M.; Robinson, T. Midlatitude Error Growth in Atmospheric GCMs: The Role of Eddy Growth Rate. *Geophys. Res. Lett.* **2021**, *48*, e2021GL096126. [CrossRef]
29. Sudarmaji, A.; Sahirman, S.; Saparso; Ramadhani, Y. Time based automatic system of drip and sprinkler irrigation for horticulture cultivation on coastal area. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *250*, 012074. [CrossRef]
30. Abioye, E.A.; Abidin, M.S.Z.; Aman, M.N.; Mahmud, M.S.A.; Buyamin, S. A model predictive controller for precision irrigation using discrete lagurre networks. *Comput. Electron. Agric.* **2021**, *181*, 105953. [CrossRef]
31. Delgoda, D.; Malano, H.; Saleem, S.K.; Halgamuge, M.N. Irrigation control based on model predictive control (MPC): Formulation of theory and validation using weather forecast data and AQUACROP model. *Environ. Model. Softw.* **2016**, *78*, 40–53. [CrossRef]
32. Lozoya, C.; Mendoza, C.; Aguilar, A.; Román, A.; Castelló, R. Sensor-Based Model Driven Control Strategy for Precision Irrigation. *J. Sens.* **2016**, *2016*, 1–12. [CrossRef]
33. Wainaina, G.K. Challenges in adoption of water-saving practices: Perspective from drip irrigation adoption in Kenya. *World Water Policy* **2021**, *7*, 74–87. [CrossRef]
34. Tesfaye, M.Z.; Balana, B.B.; Bizimana, J.C. Assessment of smallholder farmer's demand for and adoption constraints to small-scale irrigation technologies: Evidence from Ethiopia. *Agric. Water Manag.* **2021**, *250*, 106855. [CrossRef]
35. Kulecho, I.K.; Weatherhead, E.K. Reasons for smallholder farmers discontinuing with low-cost micro-irrigation: A case study from Kenya. *Irrig. Drain. Syst.* **2005**, *19*, 179–188. [CrossRef]
36. Robertson, S.; Robertson, J. *Mastering the Requirements Process: Getting Requirements Right*, 3rd ed.; Addison-Wesley Educational: Upper Saddle River, NJ, USA, 2012.
37. Sheline, C.; Grant, F.; Gelmini, S.; Pratt, S.; Winter V.A.G. Designing a predictive optimal water and energy irrigation (POWEIr) controller for solar-powered drip irrigation systems in resource-constrained contexts. *Appl. Energy* **2025**, *377*, 124107. [CrossRef]
38. Deloitte. *Sub-Saharan Africa Mobile Observatory*; Technical Report; Deloitte: London, UK, 2012.
39. Gibson, D.G.; Ochieng, B.; Kagucia, E.W.; Were, J.; Hayford, K.; Moulton, L.H.; Levine, O.S.; Odhiambo, F.; O'Brien, K.L.; Feikin, D.R. Mobile phone-delivered reminders and incentives to improve childhood immunisation coverage and timeliness in Kenya (M-SIMU): A cluster randomised controlled trial. *Lancet Glob. Health* **2017**, *5*, e428–e438. [CrossRef]
40. Pop-Eleches, C.; Thirumurthy, H.; Habyarimana, J.P.; Zivin, J.G.; Goldstein, M.P.; de Walque, D.; MacKeen, L.; Haberer, J.; Kimaiyo, S.; Sidle, J.; et al. Mobile phone technologies improve adherence to antiretroviral treatment in a resource-limited setting: A randomized controlled trial of text message reminders. *AIDS* **2011**, *25*, 825–834. [CrossRef]
41. Silva, D.S.; Ghezzi, A.; Aguiar, R.B.d.; Cortimiglia, M.N.; ten Caten, C.S. Lean Startup, Agile Methodologies and Customer Development for business model innovation: A systematic review and research agenda. *Int. J. Entrep. Behav. Res.* **2020**, *26*, 595–628. [CrossRef]
42. Pease, J.F.; Dean, J.H.; Van Bossuyt, D.L. Toward a Market-Based Lean Startup Product Design Method for the Developing World. In Proceedings of the Volume 2A: 40th Design Automation Conference, Buffalo, NY, USA, 17–20 August 2014; p. V02AT03A045. [CrossRef]
43. Reddie, M.; Frey, D. Development of a Novel Diabetic Foot Risk Assessment For Low-Resource Healthcare Settings: A Case Study of Lean Design. *Proc. Des. Soc.* **2023**, *3*, 1465–1474. [CrossRef]

44. Igleski, J.R.; Van Bossuyt, D.L.; Reid, T. The Application of Retrospective Customer Needs Cultural Risk Indicator Method to Soap Dispenser Design for Children in Ethiopia. In Proceedings of the Volume 2A: 42nd Design Automation Conference, Charlotte, NC, USA, 21–24 August 2016; p. V02AT03A058. [CrossRef]
45. Wood, A.E.; Mattson, C.A. Design for the Developing World: Common Pitfalls and How to Avoid Them. *J. Mech. Des.* **2016**, *138*, 031101. [CrossRef]
46. van der Lelie, C. The value of storyboards in the product design process. *Pers. Ubiquitous Comput.* **2006**, *10*, 159–162. [CrossRef]
47. Ulrich, K.T.; Eppinger, S.D.; Yang, M.C. *Product Design and Development*, 7th ed.; McGraw-Hill Education: New York, NY, USA, 2020.
48. Urban, G.L.; von Hippel, E. Lead User Analyses for the Development of New Industrial Products. *Manag. Sci.* **1988**, *34*, 569–582. [CrossRef]
49. Hunter Industries. Pro-C Product Page. 2022. Available online: www.hunterindustries.com/irrigation-product/controllers/pro-cr (accessed on 18 August 2024).
50. Rain Bird. SST1200OUT Irrigation Controller Product Page. 2022. Available online: https://store.rainbird.com/ (accessed on 18 August 2024).
51. CCL ELECTRONICS LIMITED. Alibaba.com. Available online: https://www.alibaba.com/product-detail/WI-FI-Professional-Weather-Station-with_62587658697.html (accessed on 18 August 2024).
52. Van De Zande, G.D.; Sheline, C.; Amrose, S.; Costello, J.; Ghodgaonkar, A.; Grant, F.; Winter, A.G. Design and Evaluation of an Automatic Scheduling-Manual Operation Tool to Bring Precision Irrigation to Resource-Constrained Farmers. In Proceedings of the Volume 3B: 49th Design Automation Conference (DAC), Boston, MA, USA, 20–23 August 2023; p. V03BT03A016. [CrossRef]
53. Lauff, C.A.; Knight, D.; Kotys-Schwartz, D.; Rentschler, M.E. The role of prototypes in communication between stakeholders. *Des. Stud.* **2020**, *66*, 1–34. [CrossRef]
54. GSM Association. *The Mobile Economy: Middle East & North Africa*; Technical Report; GSM Association: London, UK, 2022.
55. GSM Association. *The Mobile Economy: Sub-Saharan Africa*; Technical Report; GSM Association: London, UK, 2022.
56. Touil, S.; Richa, A.; Fizir, M.; Argente García, J.E.; Skarmeta Gómez, A.F. A review on smart irrigation management strategies and their effect on water savings and crop yield. *Irrig. Drain.* **2022**, *71*, 1396–1416. [CrossRef]
57. Mgendi, B.G.; Mao, S.; Qiao, F. Does agricultural training and demonstration matter in technology adoption? The empirical evidence from small rice farmers in Tanzania. *Technol. Soc.* **2022**, *70*, 102024. [CrossRef]