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The object of the study is the manual wheeled furrowing implement (IMRS), a human-powered tool used by smallholder farmers in the Tiabaya district (Arequipa, Peru) to form furrows and hill crops of onion and garlic requiring 45 cm spacing, operated for up to 227 furrows per plot in 10–12 hour shifts. The unvarying height of the handle compels taller individuals to maintain prolonged trunk bending and wrist extension, while shorter users manage the excess force with their arms, structurally excluding women who lack a fitting handle height. Four approaches were employed: design thinking and quality function deployment (QFD) to translate farmer needs into key engineering goals; VDI 2221/2225 to evaluate design alternatives; the McKyes & Ali equation for modeling soil resistance in sandy loam found in Tiabaya; and Digital Human Models within CATIA V5 for biomechanical validation at female P5 and male P95 percentiles before physical prototyping. The refined design incorporates a Ø2" SCH10 tube frame with a quick-release height adjustment limited to between 900 and 1,200 mm based on QFD priorities, a Ø600 mm spoked wheel, an AISI 1045 heat-treated furrower, and handles made from AISI 304 steel, minimizing push force by 8%. This reduction occurs because the larger wheel distributes soil reaction over a broader area, lowering rolling resistance per the McKyes & Ali model. The adjustable height eliminates the postures causing a score of 5 on the rapid upper limb assessment (RULA), reducing it to 4 for users at both measurement extremes. While unit cost is higher ( $\approx S/680$  vs.  $S/300-400$ ), a lifespan exceeding 12 years yields break-even within 3–4 years, aligning with sustainable development goals (SDGs) 2, 5, and 8

**Keywords:** furrowing implement, rapid upper limb assessment, quality function deployment, digital human modeling, smallholder agriculture, artisanal manufacturing

# ERGONOMIC OPTIMIZATION OF A MANUAL WHEELED FURROWING IMPLEMENT (IMRS) USING USER-CENTERED DESIGN METHODOLOGIES: A CASE STUDY IN PERUVIAN SMALLHOLDER AGRICULTURE

**Cesar Augusto Castillo Roque**

*Corresponding author*

Bachelor in Mechanical Engineering

Mechanical Engineering Professional School\*

E-mail: ccastilloro@unsa.edu.pe

ORCID: <https://orcid.org/0009-0002-5110-4080>

**Wendy Carolina Yupanqui Leon**

Bachelor in Industrial Engineering

Industrial Engineering Professional School\*

ORCID: <https://orcid.org/0009-0006-6524-194X>

**Trunks Giorgio Vasquez Llave**

Mechanical Engineer

Mechanical Engineering Professional School\*

ORCID: <https://orcid.org/0000-0001-7741-9043>

**Jose Carlos Canazas Rodriguez**

Master of Science

Mechanical Engineering Professional School\*

ORCID: <https://orcid.org/0000-0003-2236-7869>

**Yuri Lester Silva Vidal**

Doctor of Science with a Mention in Mechatronic Engineering

Mechanical Engineering Professional School\*

ORCID: <https://orcid.org/0000-0002-0461-470X>

**Jose Fernando Garate Delgado**

Master of Science

Food Industries Engineering Professional School\*

ORCID: <https://orcid.org/0000-0002-2218-0554>

\*Universidad Nacional de San Agustin de Arequipa

Santa Catalina, 117, Arequipa, Peru, 04001

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## 1. Introduction

The pressure caused by global population growth and the need to increase food production is felt most acutely in the agricultural resources of Africa, Asia, and Latin America [1]. In this context, small-scale farmers are essential to food se-

curity [2–4]. However, this group ranks among the least productive and is characterized by the absence of adequate and appropriate tools, greater physical effort, and injury risk [5, 6], which in turn undermines the occupational safety and health conditions promoted by SDG 8 [7]. The situation is compounded by the fact that most traditional tools are designed

without consideration of the female body, creating functional barriers to the full participation of rural women [8]. Addressing this problem is imperative for innovative engineering design and represents a direct path toward meeting SDG 5 on gender equality [9, 10].

The field of occupational ergonomics uses a variety of methods to assess posture and objectively identify ergonomic risks associated with manual tool use. The rapid upper limb assessment (RULA) method is an internationally validated and widely recognized instrument for rapidly evaluating biomechanical load on the upper limbs, neck, trunk, and legs during repetitive tasks. The RULA index categorizes the level of musculoskeletal risk associated with an activity on a scale from 1 to 7: scores of 1–2 indicate an acceptable posture requiring no change; 3–4 suggest the need for further investigation and possible modification; 5–6 signal that a postural change is required in the short term due to moderate-to-high risk; and 7 demands immediate ergonomic intervention. This method is particularly suited to identifying problems with manual agricultural tools, as these tasks involve extreme postures, sustained loads, and repetitive movements across long workdays – a combination of risk factors that accumulates rapidly [11].

Within the structural context of Peru, family farming faces specific obstacles including poor agricultural mechanization and inadequate farming technologies [12–14]. This scenario calls for solutions that are contextually relevant, cost-effective, sustainable, and above all ergonomic. Such study is directly pertinent to SDGs 5, 8, and most critically SDG 2, since improving mechanical efficiency is an unambiguous precondition for raising productivity in smallholder agriculture [15]. Therefore, study dedicated to the ergonomic optimization of manual agricultural implements for high-demand tasks in the Peruvian Andes is relevant and justified.

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## 2. Literature review and problem statement

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The paper [16] characterizes the biomechanical overload affecting farmers engaged in repetitive manual activities, and the risks this extends to their musculoskeletal system, can be defined and assessed using the methods described in ISO 11226 and ISO 11228. When workers are required to perform field tasks involving repetitive and sustained postures, the levels of load and stress imposed on their upper limbs and trunks exceed established limits – and this remains the case in the absence of any ergonomic mitigation. However, while this study characterized the problems related to risk estimation and assessment, it did not provide answers on how revised design criteria for low-cost agricultural tools could be developed. There appears to be an interdisciplinary divide between occupational ergonomics, where the emphasis lies in risk estimation, and mechanical engineering design, where the emphasis lies in delivering practical, physical solutions for tool development; this divide is most visible in the context of agricultural design.

A way to overcome these difficulties can be the application of regionally validated ergonomic studies using standardized methods. The paper [17] applied ISO 11228-3 to characterize repetitive movement risks associated with hand-held agricultural tools in an Andean zone context agronomically comparable to the Peruvian highlands, confirming that smallholder farming conditions generate musculoskeletal risk levels equivalent to those observed in industrial environments. This approach was relevant in establishing that the ergonomic problem is quantifiable and not exclusive to a particular geography,

however the study remained confined to assessment: no redesigned implement was proposed, and the manufacturing and economic constraints specific to artisanal workshops were not addressed.

The paper [18] extended this line of work by integrating sensor-based measurement with standardized postural scoring to quantify musculoskeletal risk in real time during repetitive standing occupational tasks. It is shown that this combination improves evaluation accuracy beyond what observational methods alone can achieve. However, the unresolved issue is one of practical feasibility: instrumented approaches require controlled conditions and equipment that are inaccessible to smallholder farmers and local workshops, making this methodology impractical as a direct design input in informal agricultural manufacturing settings.

Regarding proactive design approaches, the paper [11] presents the results of the study on digital human modeling (DHM) techniques applied within CATIA V5 during the preliminary design phase to predict ergonomic performance of manual workplaces before physical prototyping. It is shown that virtual mannequins representing anthropometric boundary cases – such as female P5 and male P95 percentiles – allow biomechanical load to be evaluated early in the design process, significantly reducing iteration cost. However, there were unresolved issues related to the input data required by DHM simulation: push and pull force boundary conditions must be supplied from a validated physical model of the task, a dependency that the study does not resolve for soil-engaging agricultural implements where interaction forces are governed by complex soil mechanics.

With respect to user-centered design, the paper [19] established Design Thinking as a structured iterative methodology for translating tacit, poorly articulated user needs into actionable engineering problem statements through empathize-define-ideate-prototype-test cycles. It is shown that this approach is particularly effective in contexts where end-user requirements are culturally embedded and difficult to formalize – precisely the situation of smallholder farmers. However, Design Thinking alone provides no quantitative mechanism for prioritizing technical requirements or evaluating design alternatives against measurable engineering criteria, limiting its use as a standalone engineering design tool.

The paper [20] and subsequent applied implementations [21] address this limitation through quality function deployment (QFD), a matrix-based methodology that converts qualitative customer requirements into prioritized, measurable technical specifications. It is shown that QFD systematically establishes the relative importance of user needs and links them to engineering targets, enabling objective comparison of design decisions. However, QFD defines what the design must achieve but does not govern how candidate solutions are generated or selected – the conceptual synthesis process remains unstructured.

For conceptual synthesis and technical-economic evaluation, references [22–24] present applications of the VDI 2221/2225 framework, which provides standardized procedures for functional decomposition, morphological analysis, and weighted multi-criteria evaluation of design alternatives. It is shown that VDI methods enable rigorous, reproducible selection of optimal configurations before committing to detailed design. This approach was applied in the regional Peruvian context by [25] for the conceptual design of road infrastructure machinery, confirming its transferability to local manufacturing conditions. The technical knowledge required to populate the morphological analysis – materials, mechanisms, manufacturing

processes – is systematically codified in design catalogs and patent databases [26, 27], which provide an accessible, structured corpus of existing engineering solutions. However, none of these works integrates VDI evaluation with ergonomic simulation or soil-tool modeling within a unified design workflow for low-cost agricultural implements.

Regarding the supply context, the paper [28] documents that artisanal workshops in the Andean zone systematically employ low-grade structural steels without heat treatments for implement manufacturing, resulting in accelerated wear and early functional failure. The paper [29] further shows that metalworking small and medium enterprises in this region operate without standardized production criteria, constraining product quality and reproducibility. The reason this gap persists is primarily structural: adopting engineering-grade materials and manufacturing processes increases unit cost beyond the immediate purchasing capacity of smallholder farmers, creating a systemic disincentive for quality improvement within the informal supply chain.

The pattern emerging across these works reveals three structural barriers that collectively explain the absence of a comprehensive solution. First, ergonomic assessment disciplines and mechanical engineering design operate in parallel rather than in sequence: risk quantification studies [16–18] stop at diagnosis without prescribing a redesigned tool, while design-method studies [19–25] proceed without validated ergonomic inputs. Second, methodologies developed for high-technology industrial environments are not directly transferable to artisanal manufacturing contexts, where material availability, fabrication capability, and unit cost constraints invalidate standard design assumptions [28, 29]. Third, the soil-tool interaction forces that govern the physical load on the operator – and therefore the boundary conditions for any ergonomic simulation – have not been connected to a user-centered design process in any of the reviewed works [30, 31]. These three gaps are not independent: resolving the ergonomic simulation gap requires bridging the soil-tool modeling gap, which in turn requires a design framework that can operate under artisanal manufacturing constraints.

Therefore, the unresolved problem is the absence of a comprehensive design framework that simultaneously integrates user-centered methodologies (design thinking, QFD), systematic conceptual engineering evaluation (VDI 2221/2225), soil-tool mathematical modeling, and digital ergonomic simulation (DHM) within a single coherent workflow applicable to low-cost manual agricultural implements manufactured under artisanal conditions. Existing works address each of these components separately [11, 16–24], and none demonstrates their integrated application in a context that combines the ergonomic, economic, and manufacturing constraints characteristic of smallholder farming in the Peruvian Andes [28–31].

The reviewed literature confirms that ergonomic risk assessment standards [16, 17], sensor-based postural evaluation [18], and digital human modeling simulation [11] have individually demonstrated effectiveness in quantifying musculoskeletal load during repetitive manual agricultural tasks. User-centered design methodologies such as design thinking [19], quality function deployment [20, 21], and the VDI 2221/2225 systematic framework [22–25] have proven effective for translating qualitative user needs into prioritized, measurable engineering specifications. The technical knowledge base required to support conceptual synthesis is accessible through structured design catalogs and patent databases [26, 27]. However, the artisanal manufacturing context of the Peruvian Andes is characterized by the systematic use of low-grade materials, ab-

sence of heat treatments, and lack of standardized production criteria [28, 29], conditions that invalidate direct application of solutions developed for high-technology industrial environments. Soil-tool interaction modeling for Andean agricultural conditions provides the missing physical input required to connect ergonomic simulation with real field forces [30, 31], yet this link has not been established within any integrated design framework for manual implements. All this allows to conclude that it is expedient to conduct research devoted to the development and validation of an integrated engineering design methodology – combining design thinking, QFD, VDI 2221/2225, soil-tool mathematical modeling, and DHM ergonomic simulation in CATIA V5 – for the ergonomic optimization of the manual wheeled furrowing implement (IMRS) used by smallholder farmers in the Peruvian Andes, with simultaneous validation of manufacturing feasibility and economic viability under artisanal production constraints.

Concerning the quantification of soil-tool interaction forces. The paper [30] documented the physical and pedological characteristics of agricultural soils in Andean terrace systems of the western Peruvian highlands, establishing the regional edaphic context within which implements such as the IMRS operate. The paper [31] demonstrated that mathematical optimization of structural parameters of tillage tools – using validated force models as inputs – significantly improves operational stability under variable soil load conditions. Together, these works inform the soil-tool modeling required as input to DHM simulation; however, neither addresses the ergonomic dimension of implement design nor connects their findings to a user-centered design process.

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### 3. The aim and objectives of the study

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The aim of the study is to ergonomic optimization of the manual wheeled furrowing implement (IMRS) used by smallholder farmers in the Peruvian Andes. This will enable the transfer of optimized technical specifications to artisanal manufacturing workshops currently operating without standardized design criteria, reducing musculoskeletal risks for operators across the P5–P95 anthropometric range and improving the rapid upper limb assessment (RULA) index from the level requiring short-term intervention to the level requiring only further investigation.

To achieve this aim, the following objectives were accomplished:

- to translate farmers' qualitative requirements and artisanal manufacturing constraints into prioritized quantitative engineering specifications through the integrated application of design thinking and quality function deployment (QFD);
- to select the optimal implement configuration through weighted technical-economic comparison of conceptual alternatives using the VDI 2225 methodology, and to determine the push force boundary conditions for ergonomic simulation through application of the McKyes & Ali soil resistance model;
- to validate the biomechanical performance of the optimized configuration through ergonomic simulation in CATIA V5 with digital human models (P5 and P95 percentiles), integrating realistic push forces derived from the McKyes & Ali soil resistance equation to evaluate the RULA index;
- to assess manufacturing and economic feasibility by generating technical production documentation and performing a life-cycle unit cost analysis to confirm design transferability to local artisanal workshops.

## 4. Materials and methods

### 4.1. The object and hypothesis of the study

Object of the study is the manual wheeled furrowing implement (IMRS), a human-powered tool used by smallholder farmers in the Tiabaya district (Arequipa, Peru) to form furrows and hill crops of onion and garlic requiring 45 cm spacing, operated for up to 227 furrows per plot in 10–12 hour shifts.

The central hypothesis of this study is that combining user-focused design approaches (like design thinking and quality function deployment), methodical conceptual assessment (as outlined in VDI 2221/2225), soil-tool mathematical analysis (by McKyes and Ali), and digital ergonomic modeling (DHM in CATIA V5) into a cohesive design process will result in a manual furrowing tool configuration that meets three criteria: a RULA score that does not exceed 4 for users within the P5–P95 anthropometric spectrum, a pushing force of 200 N or less, and practical and financial viability based on the limits of artisanal workshops in the Peruvian Andes.

Assumptions: based on the field analysis conducted by the authors and interviews with farmers from the Bajo Cural Lateral 3 sector, the following working assumptions were established:

- 1) soil mechanical parameters remain constant within the sandy loam texture range, as confirmed by LABSAF laboratory analysis;
- 2) operators work predominantly on flat terrain with slopes less than 5%, a condition observed in the visited plots;
- 3) local artisanal workshops have basic equipment (SMAW welding, bench drill, grinder), verified through visits to three artisanal workshops in the area, but lack technical design and material selection criteria.

The following simplifications in modeling were implemented:

- 1) the mechanical characteristics of the soil, including cohesion, internal friction angle, and soil-metal friction coefficient, were taken from published data about sandy loam soils that align with the LABSAF classification instead of being directly measured in the field, because there was no laboratory triaxial testing equipment accessible at the research location;
- 2) the push force was determined as a static value utilizing the McKyes & Ali equation based on one representative working depth and speed, disregarding dynamic fluctuations in force along the furrow path or vibrations caused by the operator;
- 3) the digital human model simulation within CATIA V5 assessed the posture at one representative moment during the work cycle, without accounting for the gradual build-up of fatigue throughout a 10 to 12-hour shift or the variations in technique among different operators. These simplifications align with the initial design phase goals of the study, which aim to choose and verify a concept prior to advancing to physical prototyping.

### 4.2. Data collection and user requirements (empathize and define phases)

The study was developed under a design thinking approach [19] in the Tiabaya district (Arequipa, Peru), an area characterized by the coexistence of valley soils and terraced hillsides [30]. Through field visits to the Bajo Cural Lateral 3 sector (Fig. 1), the operational environment was characterized for implement validation.

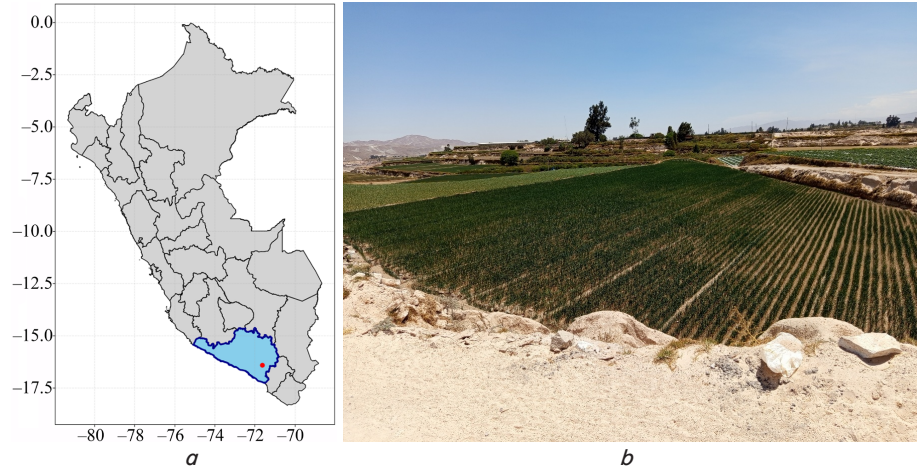


Fig. 1. Study area location: *a* – map of Peru indicating the location of Tiabaya district in the Arequipa region; *b* – panoramic view of the Bajo Cural Lateral 3 agricultural sector, showing terrace topography with onion and garlic crops

It was identified that the predominant crop (onion and garlic) is worked in furrows spaced 45 cm apart, requiring frequent furrowing and hilling tasks. To ensure design parameter accuracy, a physical-chemical soil analysis was performed at the "Lateral 3, Bajo Cural" sampling point. The results certified by LABSAF laboratory (Table 1) determined that the substrate has a Sandy Loam texture according to the USDA triangle classification (Fig. 2).

Table 1

Physical-chemical characteristics of soil  
(Bajo Cural Lateral 3 Sector)

Parameter	Value	Unit
Texture	Sandy loam	–
Sand	66	%
Silt	27	%
Clay	7	%
pH	7.9	–
Electrical conductivity	393	μS/cm
Organic matter	1.9	%
Calcium carbonate equiv.	2.5	%

Source: analysis certified by LABSAF Laboratory (Code SU1712-AQP-24), August 2024.

The physical-chemical soil analysis (Table 1) determined a sandy loam texture with 66% sand, which implies high abrasive capacity. The pH of 7.9 (slightly alkaline) and the presence of calcium carbonates (2.5%) generate a corrosive environment for metallic materials without surface protection. These soil characteristics constitute critical constraints for IMRS material selection.

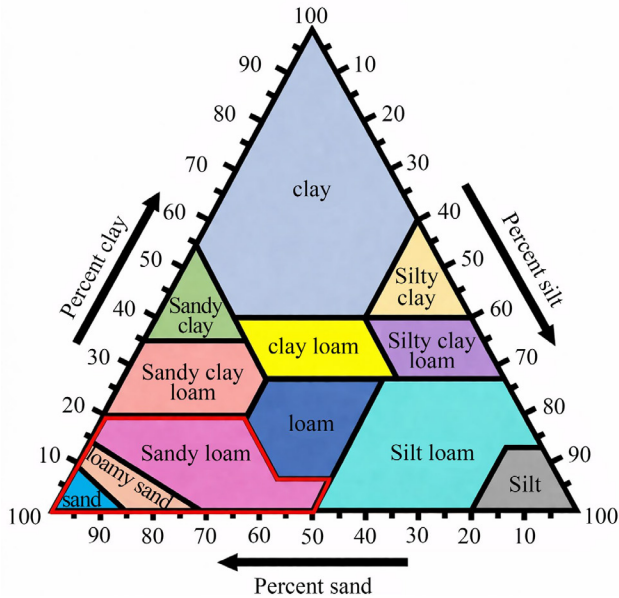


Fig. 2. Textural classification of the soil sample from the Bajo Cural Lateral 3 sector using the USDA triangle, indicating its location in the Sandy Loam zone with high penetration resistance and abrasive capacity

Structured surveys applied to local farmers revealed that producers use artisanal implements (cost ≈300–400 PEN)

with a rudimentary height adjustment system, limited to two discrete positions. Critically, modifying this height requires partial disassembly of the tool—an impractical and slow task during agricultural work. As a consequence, users give up adapting the tool to their height, opting to work with inadequate configurations. Visual inspection (Fig. 3) revealed accelerated material deterioration with generalized oxidation in manual contact zones and the active blade.

To validate the ergonomic limitations reported in surveys, the research team operated the tool under real use conditions (Fig. 4), experiencing firsthand the biomechanical load and maneuverability difficulty. This immersion confirmed that the tool forces maintaining uncomfortable postures during workdays of up to 12 hours.

Given the high operational efficiency (one person per hectare), the population available for field tests was limited. To ensure inclusivity and preserve anthropometric coverage, digital human models (DHM) were employed defining critical boundary cases: female 5<sup>th</sup> percentile (P5) and male 95<sup>th</sup> percentile (P95). This extremes validation strategy ensures that the tool is functional for the widest possible range of users [11, 16]. Fig. 5 shows an isometric view of the current implement, which weighs 6.68 kg according to SolidWorks software.

This baseline weight constitutes a critical reference value: it will be directly compared against the optimized solution in subsequent sections to quantify the mass impact of the proposed design changes.



Fig. 3. Conservation status of current artisanal furrowing implements, showing severe oxidation on handle and tool body due to the use of construction steels (ASTM A36 and ASTM A53) without surface treatment



Fig. 4. Empirical validation through participant observation of the artisanal plowing implement: a – male member of the research team operating the implement on sloping ground with vegetation; b – female member of the research team performing the plowing task in field conditions, illustrating the pushing posture and the height limitations of the handle; c – member of the research team performing a plow pass on a cultivated plot with established row spacing

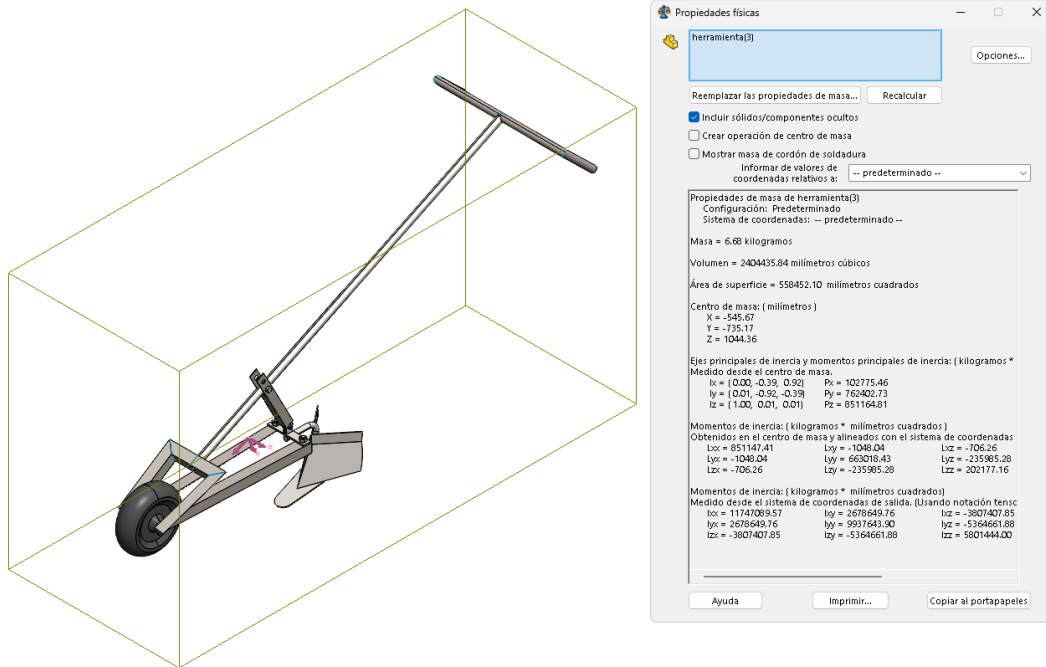


Fig. 5. Isometric view and mass data of the artisanal implement (6.68 kg)

**4. 3. Conceptual engineering and parameterization (ideate phase)**

Concept synthesis and maturation followed a systematic product development approach aligned with VDI 2221 standard [22], defining the functional structure and solution principles. To optimize the process, the product generation engineering (PGE) approach was incorporated, allowing iteration management on existing market references [23], and integrating agile practices to support short field validation cycles [24]. The functional decomposition of the implement establishes a single main function – forming furrows and hilling crops through human traction – which is broken down into subfunctions and elementary functions as detailed in Table 2.

The morphological matrix generated three conceptual solutions with different combinations of adjustment mechanisms (quick-release pin, rack-and-pinion, wing bolts), wheel types (pneumatic, metal spoked), and furrower materials (AISI 1045 with heat treatment, ASTM A-36). Fig. 6 shows the three conceptual solutions.

Solution 1 (Fig. 6, a) incorporates a quick-release pin mechanism located at the junction between the handle tube and main frame; the operator actuates the pin via a flexible cable from the handle, allowing handle height adjustment in a range of 800–1200 mm through discrete perforations every 50 mm, without leaving the working position. Solution 2 (Fig. 6, b) implements a rack-and-pinion system mounted laterally on the telescopic tube, actuated by manual crank; this mechanism

offers continuous and precise adjustment, but requires the operator to move to the mechanism location. Solution 3 (Fig. 6, c) uses concentric telescopic tubes fixed by wing bolts in aligned perforations; adjustment is made by loosening bolts, sliding the inner tube to the desired position, and hand-tightening, a process that demands more time but requires no specialized components.

Table 2

Subfunctions and elementary functions

Subfunction	Elementary function	Function carrier
SF1: Transmit energy	EF1.1: Couple operator hands	Ergonomic handles
	EF1.2: Conduct force to implement	Frame
	EF1.3: Allow height adjustment	Adjustment mechanism
SF2: Guide trajectory	EF2.1: Reduce advance friction	Wheel
	EF2.2: Stabilize direction	Fork geometry
SF3: Cut soil	EF3.1: Penetrate soil	Furrower central tip
	EF3.2: Resist abrasion	High hardness steel
SF4: Displace material	EF4.1: Deflect soil laterally	Furrower wings

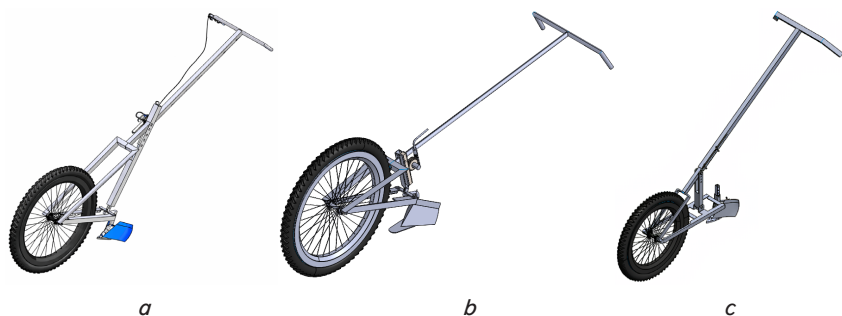


Fig. 6. Conceptual solution drawings for height adjustment mechanism: a – quick-release pin; b – rack-and-pinion; c – wing bolts

#### 4. 4. Conceptual variants evaluation (VDI 2225)

For the technical and economic evaluations of the IMRS conceptual solutions, the VDI 2225 comparative evaluation was employed, given that it is difficult to determine actual cost figures during the conceptual design phase, the experience of research team members was considered, in addition to criteria that are justified. Tables 3, 4 present the technical and economic evaluations, respectively. According to VDI 2225, each objective is scored between 0 and 4, where zero indicates that the solution is insufficient to meet the desired objective, and 4 indicates optimal compliance. The absolute value scale facilitates determining whether a particular variant is relatively close or far from the theoretical ideal, thus being more suitable for comparing design alternatives. Consequently, a score ( $p$ ) is assigned to each variant considering each criterion, as well as a weighted weight ( $g$ ) according to the relative importance of technical or economic criteria.

Technical criteria evaluated:

- a) push force reduction ( $g = 17\%$ );
- b) ergonomic adjustment and anthropometric inclusivity ( $g = 25\%$ );
- c) wear and corrosion resistance ( $g = 17\%$ );
- d) local manufacturability ( $g = 21\%$ );
- e) structural durability and service life ( $g = 21\%$ ).

The VDI 2225 comparative assessment was used for the economic and technical evaluations of the IMRS conceptual solutions. Given that it is difficult to establish actual cost figures during the conceptual design stage, the experience of the research team members was taken into account, as well as criteria that are justified. According to VDI 2225, each objective is rated between 0 and 4; zero means that the solution is insufficient to achieve the desired objective, while four indicates optimal compliance. The absolute value scale helps define whether a specific variant is relatively close to or far from the theoretical ideal, making it more appropriate for comparing design options. Therefore, each variant is assigned a score ( $p$ ) according to each criterion and a weighted value ( $g$ ) according to the relative importance of the technical or economic criteria. The prioritized technical criteria were reduction of thrust force, ergonomic fit, wear resistance, and local manufacturing capability. The economic criteria considered were material costs, ease of fabrication, and ease of sourcing components from the regional market. The best option is determined by the two quantities showing the greatest increase, prioritizing the one positioned in the upper right quadrant of the diagram. Solution 3 takes approximately 9 hours and preserves the current artisanal process, requiring only a simple modification using screws and clamps with repetitive workshop assembly. Solution 2 is the most time-consuming (approximately 12–14 hours): the rack-and-pinion mechanism demands elaborate and precise machining, may require fine adjustment to avoid increasing defect rates, and creates a need for tooling not available in local workshops. Compared to the current artisanal IMRS, which takes 6–8 hours to fabricate in local workshops, Solution 3 scores 3 because it works within local capabilities without compromising quality. Solution 1 also scores 3 because it preserves traditional manufacturing processes, while Solution 2 scores 1 because its complex mechanisms make artisanal fabrication significantly slower and harder to implement.

Regional material accessibility ( $g = 17\%$ ): this criterion analyzes the accessibility of materials and components from the regional Arequipa market – steel suppliers such as Aceros Arequipa and Otero Industrial, as well as local hardware

distributors. Regional market accessibility minimizes delays, eliminates transport and import costs, and reduces external sourcing dependency, allowing local workshops and small-holder farmers to adopt the product more rapidly. Local workshops stock most components shared across the three variants – Ø2" SCH10 ASTM A53 tubing, reinforced Ø600 mm metal wheels, and AISI 304 handles – and can supply and deliver them the same day. Differences lie in the furrower material and adjustment mechanism. Solution 1 offers high adaptability, as AISI 1045 steel for the furrower component is readily available in standard bar and plate form from regional steel suppliers, and the quick-release pin mechanism is commercially accessible through industrial hardware distributors. Solution 3 also offers high adaptability due to its use of basic materials consistent with current artisanal practice. (A36 or generic equivalents). The disadvantage of Solution 2 is that the rack-and-pinion mechanism requires specific machined parts – pre-fabricated gears or racks – that may not be available locally, potentially leading to delays or the need for custom machining. Solution 3 scores 3 because it is straightforward to operate while incorporating useful technological improvements. Solution 1 scores 3 because it is comparable to the current standard. Solution 2 scores 2 because it relies on less common components that could increase procurement time and introduce logistical risks in regional artisanal workshop contexts.

Low maintenance cost ( $g = 17\%$ ): This criterion examines the anticipated cost of preventive and corrective maintenance over the tool's service life. Given that farmers typically do not perform repairs – a broken or worn tool is simply discarded – designs that demand less maintenance are inherently less costly. For family farms with limited financial resources, cost-saving designs require less lubrication, fewer repairs, fewer partial replacements, and less downtime, all of which carry real economic value. Components shared across the three solutions – Ø2" SCH10 tubular frame, Ø600 mm metal wheel, AISI 304 handles – require minimal upkeep, limited to cleaning and a visual weld inspection. Under normal conditions, this maintenance would cost approximately S/50–70 per year, representing around 3–4% of the average monthly income generated by a family farm in the region. Differences in maintenance cost arise from the adjustment mechanism and its associated wear and corrosion. Solution 1 (quick-release pin) is the least maintenance-demanding option, as its components are robust and at most accumulate dirt rather than requiring repair or replacement. Solution 3 (wing bolt) is also a low-cost option – adjustable to compensate for play and repairable with basic tools.

Solution 2 (rack-and-pinion) is the most costly to maintain, as its constituent gears require lubrication, periodic servicing, and eventual replacement, leading to increased dirt accumulation, wear, and a higher likelihood of malfunction under frequent use. Solution 1 was assigned 3 points for being a low-maintenance system that reduces repair burden and improves product longevity. Solution 3 was also assigned 3 points for its simplicity, placing it on par with the existing standard. Solution 2 was assigned 1 point because its greater complexity and overengineered nature will result in higher indirect costs and repair work in local workshops.

Minimum maintenance viability ( $g = 22\%$ ): This criterion assesses the design's ability to function with minimal interventions during its operational lifespan, taking into account the observed tendency among farmers to forgo preventive and corrective maintenance in favor of premature disposal when failures occur. A good design in this area cuts down on the need for lubrication, cleaning, or repairs, which cuts down on

downtime, hidden costs, and barriers for users with limited resources. This helps with durability and sustainability. The parts that are the same in all three solutions (frame in Ø2" SCH10 tube, Ø600 mm metal wheel, AISI 304 handles) don't need much maintenance (just cleaning off dirt and checking for damage), so they can be used in farming without any special tools. The differences are in the way the adjustment works and how well it holds up to dirt and wear. Solution 1 (quick-release pin mechanism) is the most viable option because it has strong parts that don't get dirty very often, no complicated moving parts that can get stuck, and only needs to be cleaned and lubricated once a year. This fits in perfectly with non-maintenance habits and extends the service life without any extra work. Solution 3 (wing bolt mechanism) is still a good option, just like the current artisanal method. It may come loose, but it can be fixed by hand and is still usable for heavy use. Solution 2 (rack-and-pinion mechanism) is less viable because gears collect dirt quickly in abrasive soil conditions, which means they need to be cleaned and lubricated often and are more likely to break down, which speeds up disposal. Compared to the current artisanal IMRS (which has low viability because it needs to be thrown away often because it rusts or wears out), Solution 1 gets a score of 3 because it is naturally strong and doesn't need much maintenance without losing functionality. Solution 3 gets a score of 3 because it is the same as the locally accepted standard, and Solution 2 gets a score of 2 because it is more vulnerable, which means more implicit interventions and a higher chance of being abandoned too soon in real life. The complete technical and economic evaluations under the VDI 2225 methodology are presented in Tables 5, 6 respectively.

The location of Solution 1 in the upper right quadrant confirms that the tubular frame with quick-release pin mechanism achieves the best balance between technical performance and economic viability among the alternatives evaluated. This result is consistent with the functional requirements established in the QFD matrix, in particular the priority criteria of ease of height adjustment, simplicity of manufacture in local craft workshops, and reduction of unit cost. Consequently, Solution 1 was selected as the basis for detailed design and subsequent ergonomic validation.

**4. 5. Mathematical model (prototype phase)**

The soil-tool interaction was modeled using the universal earthmoving equation extended for narrow blades [32, 33]. The model predicts total push force as the sum of cutting components, lateral friction, and rolling resistance

$$F_{push} = F_H + F_{lat} + F_{roll}$$

Values reported in literature indicate that the soil-metal friction coefficient in sandy soils typically varies between 0.06 and 0.5, depending on moisture, compaction, texture, and implement type [34, 35]. The mechanical input parameters were established from values reported in the literature for sandy loam soils consistent with the textural classification of the study area, and are summarized in Table 3.

The mechanical parameters of the sandy loam soil were established from typical values reported in literature. The bulk density of 1.5 g/cm<sup>3</sup> corresponds to non-compacted sandy loam soils [36]. Cohesion  $c = 3$  kPa is within the 1–5 kPa range for moist sandy loam soils. The internal friction angle  $\phi = 32^\circ$  is consistent with experimental results from [37]. The soil-metal friction coefficient  $\mu_{sm} = 0.5$  represents a conser-

vative value for the higher surface roughness of artisanal manufacture IMRS [38].

Table 3

Model input parameters (Tiabaya sandy loam soil)

Parameter	Symbol	Value	Unit
Soil specific weight	$\gamma$	14,700	N/m <sup>3</sup>
Cohesion	$c$	3,000	Pa
Internal friction angle	$\phi$	32	°
Soil-metal friction coef.	$\mu_{sm}$	0.5	–
Working depth	$d$	0.05	m
Blade width	$w$	0.15	m
Attack angle	$\alpha$	30	°

**4. 6. Virtual validation (evaluate phase)**

The optimal design was subjected to biomechanical evaluation in CATIA V5, applying the calculated push force ( $F_{push} = 11.36$  kg for artisanal; 10.52 kg for optimal model) as a horizontal vector on P5 and P95 mannequins. The rapid upper limb assessment (RULA) index was evaluated under dynamic working conditions, comparing performance against the artisanal IMRS baseline.

**5. Results of ergonomic optimization of the manual wheeled furrowing implement**

**5. 1. User requirements analysis through quality function deployment**

The QFD matrix [20, 21] systematized qualitative needs expressed by farmers during the empathy and definition phases (design thinking), prioritizing user requirements through pairwise comparison.

Pairwise comparison revealed that direct ergonomic requirements (N1 – reduce back pain, N2 – adjustable to height, N3 – less push effort) obtained maximum prioritization (11 points each), followed by quick adjustment and compatibility (6 points), durability (3 points), and price (1 point). The resulting prioritization was translated into seven quantifiable technical specifications, presented in Table 4, which constitute the measurable engineering targets governing all subsequent design decisions.

Table 4

Technical specifications derived from QFD analysis

ID	Technical requirement	Unit	Target value	Direction
RT1	Adjustable handle height	mm	900–1200	Target
RT2	Maximum push force	N	≤ 200	↓ Minimize
RT3	RULA index	points	≤ 4	↓ Minimize
RT4	Field adjustment time	s	< 30	↓ Minimize
RT5	Working width	mm	450	Target
RT6	Material hardness	HBW	≥ 450	↑ Maximize
RT7	Unit manufacturing cost	PEN	≤ 700	↓ Minimize

The QFD analysis confirms that ergonomic requirements dominate design priorities (N1–N3 and N4 collectively represent >70% of weighted importance).

**5.2. Optimized configuration selection through VDI 2225**

The VDI 2225 evaluation identified Solution 1 (circular tubular frame with quick-release pin, metal spoked wheel Ø600 mm, double-wing furrower in AISI 1045 steel, and stainless steel AISI 304 handles) as optimal, as shown in the technical and economic evaluations presented in Tables 5 and 6, respectively. The weighted average valuation for Solution 1 reached 75% (technical value  $X_i = 0.70$ , economic value  $Y_i = 0.75$ ), positioning it in the upper right quadrant of the technical-economic diagram, closer to the theoretical ideal.

The VDI 2225 standard allows representing results in a technical-economic diagram (Fig. 7), where the theoretical ideal point is shown in blue, the red point corresponds to Solution 1 (circular frame with quick-release pin), yellow to Solution 2 (rack-and-pinion mechanism), and green to Solution 3 (wing bolts mechanism). It is observed that Solution 1 is positioned in the upper right quadrant, closer to the ideal than the other evaluated alternatives. The weighted average valuation for Solution 1 reached 75%, making it the best solution within the set of assumptions and constraints considered.

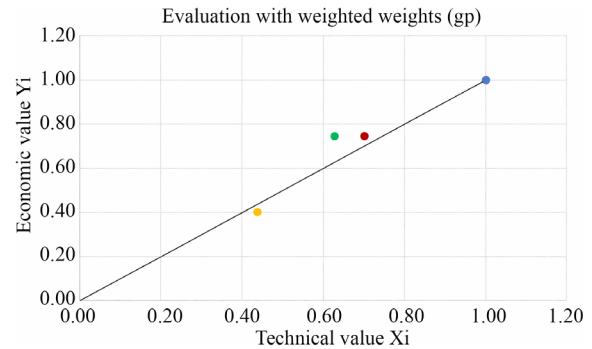


Fig. 7. VDI 2225 Technical-economic diagram with weighted values

**5.3. Biomechanical validation through rapid upper limb assessment analysis**

The ergonomic evaluation of the artisanal and optimized IMRS configurations was performed using the rapid upper limb assessment (RULA) method implemented in CATIA V5, applying the push force calculated from the McKyes & Ali soil resistance model to both the P95 male and P5 female digital human models under dynamic working conditions. The results of this comparative evaluation for both the artisanal and optimized configurations, across both anthropometric boundary cases, are presented in Table 7.

The artisanal IMRS yielded a RULA score of 5 ("Investigate and change soon"), indicating that the current configuration requires short-term ergonomic modifications. This result is mainly attributed to the fixed handle height: for tall male users (P95) it forces adopting postures with trunk flexion and sustained wrist extension; for shorter female users (P5), although trunk posture is more comfortable, push force generates direct load and musculoskeletal risks in arms and wrists. The postural analysis for both anthropometric boundary cases is illustrated in Fig. 8.

The optimized IMRS achieved a rapid upper limb assessment (RULA) score of 4 ("Investigate further") in both anthropometric percentiles, thanks to the quick height adjustment mechanism (without disassembly) and ≈8% reduction in push force.

Technical evaluation (VDI 2225)

Evaluation criteria for designs in concept or project phase										
Concept/ Solutions			S1		S2		S3		Ideal solution	
N°	Evaluation criteria	g	p	gp	p	gp	p	gp	p	gp
1	Push force reduction	17%	3	0.50	3	0.50	3	0.50	4	0.67
2	Ergonomic adjustment and anthropometric inclusivity	25%	3	0.75	2	0.50	1	0.25	4	1.00
3	Wear and corrosion resistance	17%	3	0.50	2	0.33	3	0.50	4	0.67
4	Local manufacturability	21%	2	0.42	1	0.21	3	0.63	4	0.83
5	Durability and service life	21%	3	0.63	1	0.21	3	0.63	4	0.83
Maximum score $\sum p \cdot \sum gp$		100%	14	2.79	9	1.75	13	2.50	20	4,00
Technical value $X_i$			0.70	0.70	0.45	0.44	0.65	0.63	1.00	1.00

Table 5

Economic evaluation (VDI 2225)

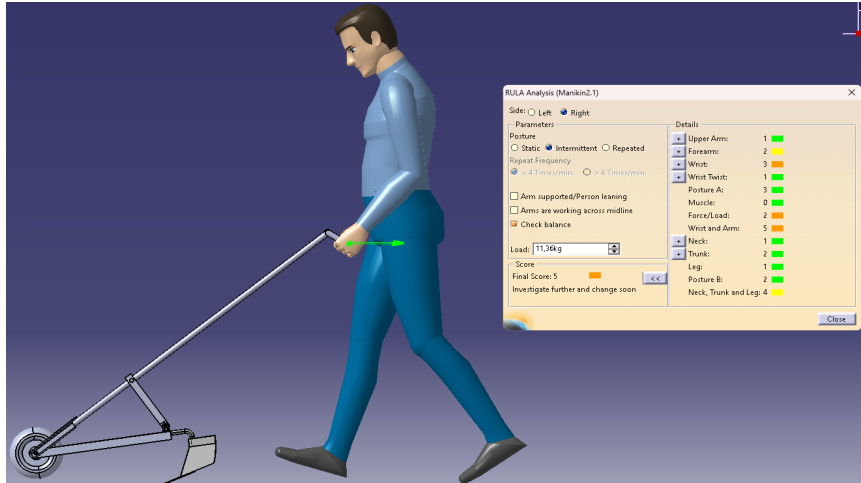
Evaluation criteria for designs in concept or project phase										
Concept/Solutions			S1		S2		S3		Ideal solution	
N°	Evaluation criteria	g	p	gp	p	gp	p	gp	p	gp
1	Low material cost	22%	3	0.65	2	0.43	3	0.65	4	0.87
2	Ease of artisanal fabrication	22%	3	0.65	1	0.22	3	0.65	4	0.87
3	Local material availability	17%	3	0.52	2	0.35	3	0.52	4	0.70
4	Low maintenance cost	17%	3	0.52	1	0.17	3	0.52	4	0.70
5	Minimum maintenance viability	22%	3	0.65	2	0.43	3	0.65	4	0.87
Maximum score $\sum p \cdot \sum gp$		100%	15	3.00	8	1.61	15	3.00	20	4,00
Economic value $Y_i$			0.75	0.75	0.4	0.40	0.75	0.75	1.00	1.00

Table 6

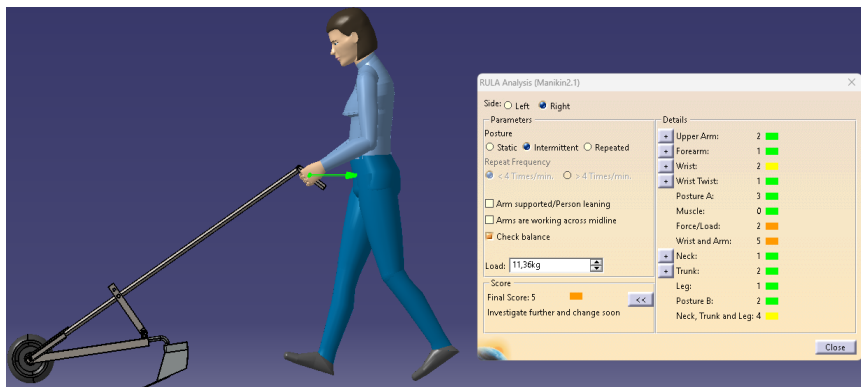
Rapid upper limb assessment evaluation comparison: artisanal vs. optimized IMRS

Parameter	Artisanal IMRS	Optimized IMRS	Δ
Mass [kg]	6.68	11.91	+78%
Push force $F_{push}$ [kg]	11.36	10.52	-8%
Handle height Z [m]	0.85 (fixed)	0.80–1.20 (adj.)	✓
Wheel diameter [m]	0.10	0.60	+500%
RULA Score	5	4	-1
Action level	Investigate soon	Investigate further	✓

Table 7

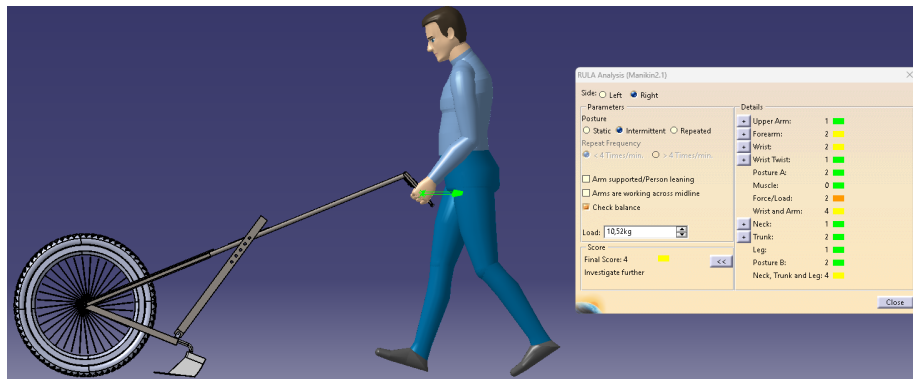


a

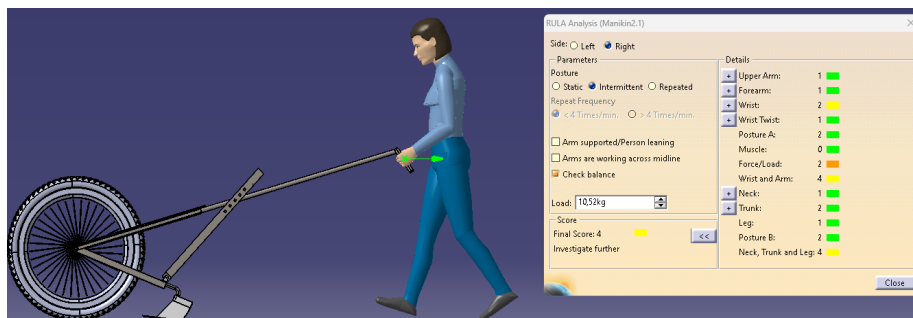


b

Fig. 8. Rapid upper limb assessment analysis in CATIA V5 of the artisanal implement: a – P95 male mannequin operating posture with score 5; b – P5 female mannequin operating posture with score 5



a



b

Fig. 9. Rapid upper limb assessment analysis in CATIA V5 of the optimized implement: a – P95 male mannequin operating posture with score 4; b – P5 female mannequin operating posture with score 4

This one-level reduction in the RULA index is particularly impactful given the extreme repetitiveness observed: in typical plots ( $\approx 102 \times 102$  m), a 10–12 hour workday generates  $\approx 227$  furrows (45 cm spacing), implying thousands of weekly repetitions with constant posture. The lower accumulated bio-mechanical load mitigates back/wrist pain reported at day’s end, chronic fatigue, and musculoskeletal risks, improving long-term productivity and occupational health.

**5. 4. Economic analysis and industrial feasibility**

The economic analysis was performed following industrial engineering principles for manual agricultural tool evaluation, adapting the hourly cost method covering depreciation, investment interest, and maintenance. The unit cost of the optimized IMRS was estimated through a detailed bill of materials breakdown based on real Peruvian market prices from suppliers including Mercado Libre Peru, Otero Industrial, Aceros Arequipa, and Grupo Marcela, updated to 2025–2026, as presented in Table 8. The general input parameters used for the cost analysis are summarized in Table 9, and the resulting annual fixed charges and lifecycle cost comparison between the artisanal and optimized configurations are presented in Table 10.

Unit cost estimation (BOM-bill of materials)

Description	Quantity	Unit price (S/)	Subtotal (S/)
Circular steel tube Ø2" ASTM A53 (6 m)	~5–6m	160–220	180
AISI 1045 steel (double-wing furrower)	~2–3 kg	12–18/kg	45
Metal spoked wheel Ø600 mm	1	250–300	280
Quick adjustment mechanism (pin)	lot	50–80	70
AISI 304 handles (with rubber)	lot	100–150	130
Auxiliaries (welding, paint)	lot	-	50
Labor (cutting, welding, assembly)	1 unit	100–150	130
Other (transport, margin ~10%)	-	-	50
Total			$\approx 680$

Although Solution 1’s direct hourly cost is slightly higher, actual artisanal practice (frequent disposal + multiple purchases due to adjustment rigidity) raises its effective annual cost to S/175–350 (considering 2–4 units per family in 10 years). Farmers expressed willingness to pay more for comfort/safety improvements. Over a 10-year horizon, life cycle cost (LCC) analysis favors Solution 1 ( $\approx S/120$  + minimal maintenance) vs. artisanal ( $\approx S/175$ –350 for replacements). Payback of initial cost premium  $\approx 3$ –4 years, with additional benefits: RULA reduction from 5 to 4 (impactful at  $\approx 227$  furrows/plot and 10–12 hour workdays, mitigating reported pain) and +10–15% estimated productivity.

**6. Discussion of results of ergonomic optimization of the manual wheeled furrowing implement**

The 8% reduction in push force results from two geometric decisions working together. The larger wheel diameter (Ø600 mm) spreads the normal soil reaction across a wider contact arc, which directly lowers the rolling resistance term in the McKyes & Ali equation at the working depth and speed used in the field. At the same time, the height adjustment mechanism – constrained to  $Z = 900$ –1,200 mm as established in the quality function deployment matrix (Table 6) – eliminates the trunk flexion and sustained wrist extension that produced a rapid upper limb assessment score of 5 in the original artisanal tool (Fig. 8). Both corrections acted simultaneously across the full anthropometric range, which is why the improvement from score 5 to 4 (Fig. 9, Table 7) held equally for the P5 female and P95 male mannequins despite their different body dimensions. The adjustment mechanism was selected through the VDI 2225 technical-economic evaluation (Fig. 7), where Solution 1 – tubular frame with quick-release pin – earned a 75% weighted score by balancing ergonomic performance with the fabrication capabilities of local artisanal workshops. That result confirmed that the concept selection stage was the most consequential decision in the entire design process.

Table 8

Table 9

General data for cost analysis

Variable	Description	Unit	Artisanal IMRS	Optimized IMRS
$V_a$	Acquisition value	S/	350	680
$V_r$	Salvage value	% $V_a$	20%	20%
$V_e$	Financial useful life	Years	5	12
$i$	Annual investment rate	%	10	10
$H_a$	Effective hours per year	Hrs/year	400	400
$Q$	Maintenance	% $V_a$ /year	10	5

Table 10

Annual fixed charges and cost analysis

Concept	Formula	Artisanal (S/)	Optimized (S/)
Depreciation (D)	$(V_a - V_r) / V_e$	56	45
Investment (I)	$(V_a + V_r) / 2 \times i$	21	41
Maintenance (T)	$Q \times V_a$	35	34
Annual total	$D + I + T$	112	120
Direct cost per hour	$(D + I + T) / H_a$	0.28	0.30
Effective annual cost*	-	175–350	120

Note: \* – effective annual cost for artisanal includes frequent disposal and multiple purchases (2–4 units per family in 10 years).

Material selection reinforces these results on the durability side. AISI 304 stainless steel was chosen for the handles to resist the oxidation that builds up in grip zones exposed to sweat and alkaline soil (Table 1) during long workdays. These material decisions are what make the life-cycle cost analysis favor the optimized tool: the higher initial price ( $\approx S/680$  vs. S/300–400 artisanal) is offset by more than doubled service life and near-zero maintenance, producing a net economic advantage over the full lifespan. This confirms that in resource-limited contexts, durable ergonomic solutions outperform cheap ones over time [28, 29].

The findings of this study address each of the issues outlined in Section 2 through targeted design choices. Musculoskeletal hazards in agricultural workers were quantified [16, 17], but no redesigned implement was proposed; this

study bridges that gap by providing a detailed optimized design – including wheel size, range of handle height, furrower shape, and choice of materials – based on ergonomic risk information utilized as inputs in the QFD matrix. The value of digital human modeling for ergonomic validation was demonstrated [11], with the absence of verified force boundary conditions identified as an outstanding issue; the soil resistance model by McKyes and Ali used here offers those necessary boundary conditions, linking soil characteristics from the field (as seen in Table 1) with the push force metrics attributed to the P5 and P95 mannequins. The VDI 2221/2225 framework [22–25] along with the QFD [20, 21] approach had only been previously utilized in advanced industrial settings; this study illustrates their applicability to handcrafted manufacturing environments, with all three proposed solutions initially shaped by the production capabilities confirmed in local workshops in Arequipa. Lastly, both [28, 29] highlighted the discrepancies in material and production quality found in Andean artisanal workshops, yet did not relate these issues to an ergonomic design approach; the choices regarding materials in this study – the AISI 1045 heat-treated furrower and AISI 304 handles – were specifically influenced by soil corrosivity data (referenced in Table 1) and the limitations of workshop capabilities recorded during site visits.

The simultaneous consideration of female P5 and male P95 anthropometric extremes is another distinguishing feature of this framework, in contrast to comparable studies that validate design approaches against only a single representative user or male-only percentiles [17, 18]. This directly responds to the gender inclusivity gap identified in the introduction, producing a tool that ergonomically fits the full range of Peruvian smallholder farmers and contributes to the fulfillment of SDG 5.

The numerical results of this study – values for push force, expense estimates, and soil characteristics – are particular to the Tiabaya area, but the comprehensive design framework can be applied to any smallholder farming setting that produces manual tools in artisanal environments. Agricultural highlands in Bolivia, Ecuador, and Colombia possess similar soil compositions, population metrics, and limitations in workshop facilities, which makes the QFD-VDI-DHM method usable without requiring changes to the methodology. More generally, this framework fills a significant void – the gap between evaluating ergonomic risks and engineering design processes – which is not limited to Peru but is a common issue in smallholder farming across sub-Saharan Africa, regions of South and Southeast Asia, and other nations in the Andes. The component for modeling the interaction between soil and tools can be customized to suit various implement designs and soil types by adjusting the relevant mechanical factors, while the DHM simulation technique is relevant for any manual tool where push or pull forces present the main ergonomic danger.

The primary constraint of this study lies in not having a tangible prototype or firsthand assessment of tool specifications. All biomechanical assessments were carried out via digital human model simulations in CATIA V5, which only analyzes posture at a specific moment during the work cycle and fails to take into account the gradual fatigue build-up during 10–12 hour shifts, individual differences in operator methods, or variations in dynamic force throughout the furrow path. The soil mechanical parameters utilized as boundary conditions (Table 5) were obtained from existing literature on sandy loam soils instead of being gathered in situ, which

adds variability to the push force estimations attributed to the mannequins. Factors such as seasonal moisture levels, history of tillage, and local compaction could alter cohesion, the internal friction angle, and the soil-metal friction coefficient, resulting in higher actual force requirements. The economic evaluation references market prices in Arequipa and is not applicable to other regions without adjustment. Lastly, while the RULA method gives specific scores, it does not measure enhancements within those score ranges, which restricts the sensitivity of ergonomic evaluations.

The most immediate advancement of this study involves physical prototyping and field validation, which will encounter the practical challenge of coordinating trials during the furrowing season and obtaining a representative anthropometric sample from geographically dispersed rural communities. A logical next step is to use this integrated framework on other manual tools used in Peruvian smallholder agriculture. For example, aporcado and arado tools have similar biomechanical needs and are made in the same artisanal way. This would mean changing the soil-tool model to fit different blade shapes and ways of interacting. Substituting the analytical McKyes & Ali equation with discrete element method simulation [35] at the modeling level would yield a more accurate prediction of dynamic force variation along the furrow path. However, this approach encounters substantial challenges regarding computational costs and the necessity for direct laboratory measurement of soil microparameters for model calibration, with the required equipment currently unavailable in the study region. Finally, the transfer of the technical documentation produced in this study to local artisanal workshops – the practical objective outlined in the study’s aim – will face the organizational and financial challenges identified in [28, 29]. This necessitates supplementary technology transfer initiatives that surpass the confines of engineering design research, with their design and assessment forming a distinct research agenda.

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## 7. Conclusions

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1. The pairwise evaluation of the requirements expressed by farmers utilizing the QFD matrix indicated that ergonomic factors are the most significant design concerns: the ability to adjust handle height (N1), reduce push force (N2), and achieve a specific RULA score (N3) each garnered the highest possible score (11 points), together accounting for more than 70% of the total importance. This resulted in seven measurable engineering criteria, with RT1 (handle height adjustable between 900–1,200 mm), RT2 (push force not exceeding 200 N), and RT3 (RULA score of 4 or less) identified as key design objectives. Interestingly, farmers considered price to be the least limiting factor – this conclusion challenges the prevailing assumptions of supply-side development and supports the choice to use superior materials and mechanisms.

2. Among the three conceptual options assessed via VDI 2225, Option 1 – featuring a tubular structure with a quick-release mechanism, a spoked wheel measuring 600 mm in diameter, a heat-treated furrower made from AISI 1045, and handles crafted from AISI 304 – obtained a weighted average result of 75% ( $X_i = 0.70$ ,  $Y_i = 0.75$ ), which is nearest to the theoretical ideal. According to the McKyes & Ali framework, the optimized setup required a push force of 10.52 kg, compared to the traditional baseline figure of 11.36 kg, resulting in an 8% decrease mainly due to the larger wheel size that allowed for a broader distribution of soil reaction.

3. Virtual ergonomic simulations showed a rapid upper limb assessment score drop from 5 to 4 for both the smallest female and the largest male operator – substantially different body sizes, same result. Across roughly 227 furrows per plot in a 10–12 hour shift, a single-level score reduction is not trivial: lower load per cycle accumulates into measurably less fatigue and musculoskeletal strain by end of day. Evaluating both anthropometric extremes rather than one reference posture is what sets this framework apart from most ergonomic assessments conducted in the same regional context.

4. Although the initial unit cost is approximately S/680 compared to S/300–400 for artisanal counterparts, the economic break-even point falls within 3–4 years, determined by a service life exceeding 12 years against under 5 for current tools, and by eliminating the repeated purchases that artisanal practice requires. When indirect productivity gains and reductions in occupational injury exposure are also considered, the lifecycle balance further favors the optimized tool. This economic outcome was only achievable because the concept selection stage was constrained by local manufacturability – all components sourced from regional suppliers and all fabrication done with equipment available in Arequipa workshops – making technology transfer a concrete outcome of the design process rather than a stated aspiration.

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#### Conflict of interest

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The authors confirm that no conflicts of interest-financial, personal, authorship-related, or of any other nature-exist that could have influenced this study or the results reported herein.

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#### Financing

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The study was performed without financial support.

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#### Data availability

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Data will be made available on reasonable request.

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#### Use of artificial intelligence

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During the preparation and revision of this manuscript, the authors used Claude Sonnet (Anthropic, version accessible via claude.ai, 2024–2025) as a large language model

tool for English language editing and text coherence improvement.

The tool was applied in the following sections: Abstract and Keywords, Introduction (Section 1), Literature Review and Problem Statement (Section 2), Materials and Methods (Section 4), Results (Section 5), Discussion (Section 6), and Conclusions (Section 7).

The specific tasks delegated to the AI tool were limited to: reformulation of sentences for grammatical correctness and academic register in English, improvement of textual coherence and logical flow between paragraphs, compression and restructuring of existing text to comply with journal formatting requirements (abstract length, section structure), and translation support from Spanish to English for specific passages. The AI tool was not used to generate scientific content, produce or interpret experimental data, formulate hypotheses of the study, perform calculations, or derive conclusions.

All AI-assisted text was verified by the authors through manual paragraph-by-paragraph review against the original Spanish drafts, raw experimental data, CATIA V5 simulation outputs, and cited source materials. Any content that did not accurately reflect the authors' original findings or interpretations was corrected prior to submission.

The use of AI tools had no influence on the conclusions of the study. All results, interpretations, and conclusions are entirely the authors' own and are based exclusively on the experimental data, simulations, and analyses conducted by the research team.

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#### Authors' contributions

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**Cesar Augusto Castillo Roque:** Conceptualization, Methodology, Formal analysis, Software, Investigation, Validation, Writing – original draft, Writing – review & editing; **Wendy Carolina Yupanqui Leon:** Methodology, Formal analysis, Visualization; **Trunks Giorgio Vasquez Llave:** Investigation, Writing – original draft, Software, Visualization; **Jose Canazas Rodriguez:** Investigation, Data curation, Resources; **Yuri Lester Silva Vidal:** Project administration, Supervision; **Jose Fernando Gárate Delgado:** Conceptualization, Resources, Validation.

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