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Integration of maintenance criteria into the design process of agricultural equipment in Burkina Faso

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Abstract

Agricultural mechanization in Africa, and particularly in Burkina Faso, remains significantly constrained by the mismatch between the maintenance requirements of imported two-wheel tractors and local maintenance conditions. In this context, the present study addresses the integration of maintenance criteria into the design of a two-wheel tractor by relying on the Preliminary Analysis of Maintenance Criteria (APCMA) tool, developed for the design of equipment intended for small and medium-sized enterprises in developing countries.

APCMA is a graphical tool comparable to a *"maintenance wall"*, collaboratively constructed by the various stakeholders involved in maintenance. Through the identification of *"missing bricks"* and the overall wall profile, it highlights the key maintenance-related aspects that should be considered during the equipment design phase. The maintenance criteria, scored by stakeholders, are mathematically modeled within an evaluation space based on statistical medians. This approach made it possible to determine the ideal representative score for assessing a maintenance criterion from the perspective of multiple stakeholders.

To this end, a field survey was conducted involving 33 stakeholders from different categories, leading to the identification of 17 maintenance criteria for the two-wheel tractor to be incorporated into the co-construction of the initial wall. Based on this analysis, 11 context-oriented maintenance design solutions were proposed to fill the missing bricks and achieve the final/target wall, which enabled the design and development of a two-wheel tractor prototype. In addition, Python 3.12 application was developed and integrated into the automated design decision-making process.

The results demonstrated the transformation of the initially deficient wall into an optimal final projection, thereby validating the selected maintenance criteria while reducing the production cost by 40% compared with imported models. This prototype provides a sustainable alternative for both small-scale and large-scale farmers.

Keywords: Agricultural mechanization; APCMA; Two-wheel tractor; Equipment design; Maintenance criterion; Burkina Faso

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1. Introduction

Agriculture is one of the main pillars of the economy in Burkina Faso, engaging more than 82% of the working population (Food and Agriculture Organization of the United Nations [FAO], 2022). Despite its major socioeconomic importance, the sector remains characterized by low productivity, largely due to the arduous nature of manual labor and the low level of mechanization (Sims & Kienzle, 2017). In this context, the two-wheel tractor represents a relevant intermediate solution between animal traction and conventional tractors (Baudron et al., 2015).

However, the Burkinabe agricultural machinery fleet presents a paradox : many imported machines become inoperative after only a few years of use, or even after their first major failure. This premature failure is mainly explained by the mismatch between imported equipment and local operating conditions, particularly the lack of spare parts availability and design choices that do not sufficiently account for local maintenance constraints (Houmy et al., 2013 ; Binswanger et al., 1995). Users of imported two-wheel tractors frequently encounter difficulties related to the supply of specific spare parts and the limited local mastery of transmission technologies. In this regard, Mmari and Mpanduji (2023), as well as several authors working on context-adapted agricultural equipment design, have emphasized the importance of involving artisans and mechanics in the design process, progressively adapting imported models, and reusing components already available in local markets. According to FAO (2022), imported machines designed for intensive, highly mechanized, and capital-intensive farming systems are often incompatible with smallholder farms in developing countries because of spare-part shortages, limited local maintenance skills, and poor adaptation to local pedoclimatic conditions. Similarly, recent work by Chang (2023) highlights the over-engineering of imported agricultural equipment, the mismatch between perceived value and actual cost, and the dependence on proprietary technologies.

To address these challenges, the development of locally appropriate mechanization, the promotion of simple, modular, and multifunctional machines, and the integration of maintenance considerations from the design stage appear essential. In the life cycle of agricultural equipment, the design phase determines more than 70% of the future maintenance costs of the equipment (Bationo & Boujut, 2022 ; Dhillon, 2002).

In response to this issue, several authors have investigated the integration of maintenance into the design of agricultural equipment adapted to the context of developing countries. Sayed et al. (2022), for example, argued that designers and manufacturers of agricultural machinery should consider environmental and social implications, as well as technical support services, in order to provide mechanization solutions suited to smallholder farmers. Azouma et al. (2005, 2009) integrated manufacturing and maintenance through the concept of Design for Economic Manufacture (DEM), which relies on local know-how, and proposed tools such as the Availability Specification Sheet (CdCD), Distributed Maintenance for Africa (MDA), and Failure Modes, Effects, and Criticality Analysis (FMECA) to incorporate reliability and maintainability into equipment design. According to Nzie (2006), the Distributed Design Model (DDM) developed by Salaün (1995) can also be used to integrate maintenance considerations into design. Bationo et al. (2009) further argued that maintenance integration can be achieved through the consideration of sociotechnical maintenance network models, since modeling and analyzing these networks is a prerequisite for the design of appropriate equipment. They also proposed maintenance-oriented design rules and the Design for Maintenance Sociotechnical Network (DFMSN) approach, which belongs to the broader family of Design for X (DFX) tools (Kuo, 2001), as a framework for integrating maintenance into equipment design. Finally, frugal innovation, affordability-oriented design, targeted functional reduction (*just enough technology*), and the reuse of existing components have also been advocated as relevant design strategies.

Taken together, these studies highlight the need to account for major local constraints and maintenance practices, but they do not provide a systematic approach for integrating maintenance criteria into the design process. In contrast, the Preliminary Analysis of Maintenance Criteria (APCMA) tool proposed by Bationo and Boujut (2022) offers a means of identifying technical solutions to be incorporated into design based on an ex ante analysis of maintenance-related criteria associated with the risk of rejection of the equipment under development. These criteria reflect the major operational constraints and practices of the stakeholders involved and should therefore be incorporated into design in order to facilitate maintenance during the equipment's operational phase in a given locality. The APCMA method may thus constitute a strategic lever for aligning technical solutions with local sociotechnical maintenance realities (Bationo & Boujut, 2022 ; Bationo, 2007).

This tool follows a collaborative and continuous-improvement logic. It is conceptually similar to Failure Modes, Effects, and Criticality Analysis (FMECA) and Preliminary Risk Analysis (PRA) in its anticipatory role with respect to maintenance problems, many of which are strongly influenced by the operating environment. PAMC itself is derived from field studies based on equipment designed by manufacturers using maintenance-oriented design approaches. However, the current APCMA framework does not include a software-based automated implementation, nor does it include a simulation phase enabling the visualization of the final or target maintenance wall before prototype manufacturing, which would facilitate decision-making and deployment.

The scientific challenge addressed in this study lies first in the design of a two-wheel tractor prototype adapted to the Burkinabe context through the integration of maintenance criteria, and second in the need to quantify an initially qualitative process in order to automate it, while ensuring robust data aggregation and rapid iteration across multiple design scenarios. In practice, the manual processing of field-survey data (cross-tabulations, weighting, and satisfaction calculations) is often time-consuming and limits the responsiveness of design teams.

Accordingly, this study is structured around the following central research question :

How can maintenance criteria be effectively integrated into the adaptation and design of a two-wheel tractor for Burkina Faso ?

2. Materials and Methods

The adopted methodology is based on an integrated approach combining the following elements.

2.1. Identification of maintenance criteria by stakeholder category

A field survey was conducted using the "Japanese step" method (Shiba, 1995), which makes it possible to capture at least 70% of useful information from approximately ten interviewees. In this study, however, the sample consisted of 33 stakeholders, including 17 users, 6 maintenance technicians, 5 spare-parts traders, and 5 local manufacturers (welders/equipment builders), distributed across the rice-growing areas of Guiriko and Nando in Burkina Faso. This investigative approach made it possible to characterize interactions within the sociotechnical maintenance network and to structure questionnaires aimed at identifying the maintenance criteria specific to each stakeholder category.

To improve the robustness of stakeholder perception analysis, a dispersion analysis was conducted in addition to the median-based aggregation. The sole use of the median does not adequately reflect the degree of consensus among different stakeholder groups. Therefore, boxplots were generated and analyzed for each maintenance criterion in order to assess :

- The dispersion of assigned scores ;
- The possible presence of outliers ;
- The level of agreement among stakeholders.

2.2. Presentation of the Preliminary Analysis of Maintenance Criteria (APCMA)

APCMA is a design-support tool intended for local teams to integrate maintenance considerations into the design of equipment for small and medium-sized enterprises (Bationo, 2003 ; Bationo & Boujut, 2022). To implement this tool, a preliminary field survey based on the Japanese step method is required in order to identify the stakeholders involved in the equipment life cycle and the essential maintenance criteria needed to construct a "maintenance wall."

This initial wall is co-constructed in segments, with each stakeholder category assigning scores from 1 to 5 to each predefined and coded maintenance criterion. Through the identification of "missing bricks" and the overall wall profile, the method highlights maintenance-related deficiencies. Subsequently, stakeholders from each professional category propose technical solutions to fill the missing bricks. These solutions represent upstream knowledge and know-how that can be mobilized during design in order to address the most critical maintenance constraints.

The implementation of APCMA is organized into three phases :

- **Phase 1 :** selection of stakeholders, preparation, planning, and identification of coded maintenance criteria. These criteria are environment-dependent and are initially established through field investigation ; they may evolve as the context changes.
- **Phase 2 :** analysis of the equipment or product through joint construction of the maintenance wall and completion of the initial APCMA wall.
- **Phase 3 :** analysis of the overall wall profile and proposal of technical solutions.

At its current stage, and in the context of this study, the PAMC tool requires an additional simulation phase to visualize the effects of the proposed technical solutions through a final or target wall prior to prototype manufacturing. This simulation step makes it possible to validate the selected technical solutions based on the improvements observed in the final wall.

2.3. Automated PAMC tool

Software developed in **Python 3.12** was used to automate the entire APCMA process, from field-survey data processing to design-scenario simulation. The system architecture is organized into four functional modules

- **Input module:** A graphical user interface enabling the entry of stakeholder evaluations and verification of data consistency.
- **Statistical computation module:** Implementation of median-based aggregation algorithms for each maintenance criterion.
- **Simulation module:** A matrix-based computation engine that automatically generates the impact matrix from the selected solution vectors.
- **Visualization module:** Automatic production of graphical representations of the initial and final walls in the form of comparative histograms.

The overall process comprises three successive stages

- Generation of the initial wall from survey data;
- Selection of a solution vector and automatic construction of the associated impact matrix ; and
- Iterative computation of criterion evolution toward the final wall.

This architecture makes it possible to rapidly explore different design scenarios. The implementation of the new automated PAMC approach in this study follows an iterative loop, as presented below.

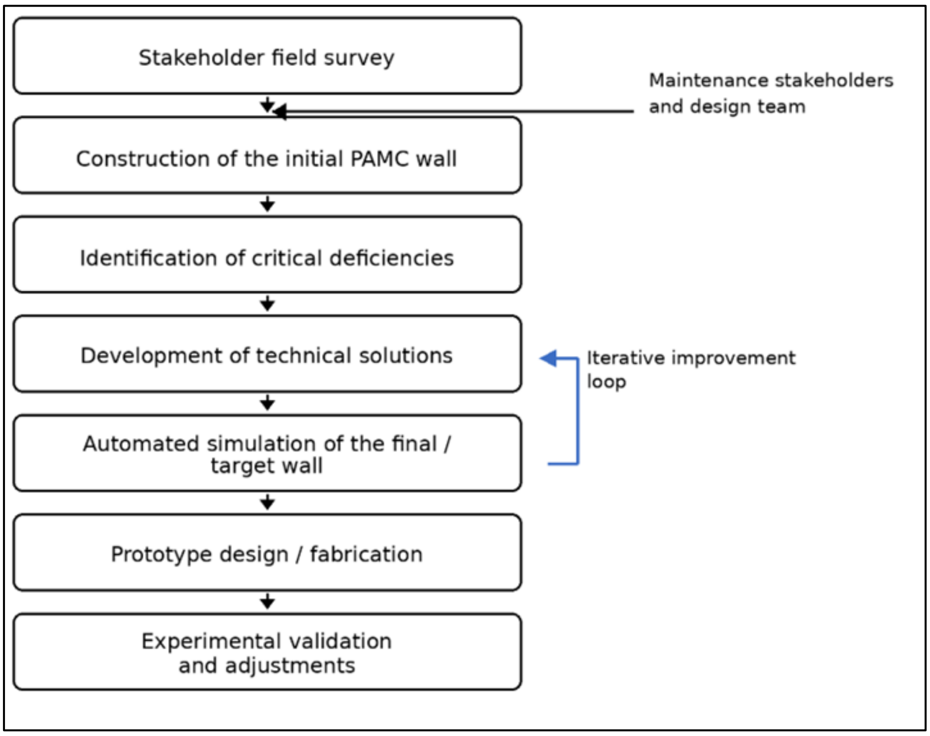


Figure 1 Iterative workflow of the automated Preliminary Analysis of Maintenance Criteria (APCMA) applied to two-wheel tractor design

This iterative loop ensures the gradual adaptation of the technology to the local context while fostering stakeholder appropriation throughout the design process (Bationo & Boujut, 2022 ; Ben-Daya et al., 2009).

Survey data were collected and assessed against predefined maintenance criteria using a five-point Likert scale, ranging from 1 (not satisfactory at all) to 5 (highly satisfactory), as shown in Table 1. This scale provided a structured framework (Table 2) for quantifying stakeholder perceptions, by category (zone), of the maintenance performance of existing two-wheel tractors (Grim, 1936 ; Jamieson, 2004 ; Pimentel, 2010). Stakeholders were identified according to their occupational roles, while each zone represented the corresponding segment of the maintenance wall. The field data were then processed using descriptive statistical frequency analysis in Microsoft Excel.

Table 1 Likert scale for assessing maintenance criteria

Brick level	Interpretation
5	Very satisfactory
4	Satisfactory
3	Moderately satisfactory
2	Insufficient
1	Not satisfied

Table 2 Definition of stakeholder categories

Acteur	Définition
Fabricants (Zone 1 ou portion 1 du mur)	Ils sont caractérisés principalement par leur capacité d'identifier des besoins de clients et de les matérialiser par une conception (innovante, copie, adaptation) et une fabrication.
Utilisateurs (Zone 2)	Ils désignent la catégorie d'acteurs qui exploite un équipement dans une entreprise
Commerçants /vendeurs de pièces (Zone 3)	Indépendamment des autres acteurs, ils vendent des pièces de rechange d'équipement.
Maintenanciers/réparateurs (Zone 4)	Ils désignent principalement ceux qui réparent les équipements. Ils peuvent reproduire la technologie et fabriquer des pièces de rechange.

2.4. Mathematical modeling of the transfer function and the system evolution equation toward the final (target) wall

The effect of the selected technical solutions on the maintenance criteria is represented by an impact matrix M of dimension (n×k) where each coefficient ω_{ij} denotes the influence of technical solution j on maintenance criterion iii. As illustrated below, the coefficients are assigned discrete values of +1 for a positive contribution (improvement), 0 for a neutral effect, and −1 for a negative contribution (degradation) (Saaty, 2008).

$$M = \begin{pmatrix} \omega_{1,1} & \omega_{1,2} & \cdots & \omega_{1,k} \\ \omega_{2,1} & \omega_{2,2} & \cdots & \omega_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_{n,1} & \omega_{n,2} & \cdots & \omega_{n,k} \end{pmatrix} \quad (1)$$

This impact matrix enables the simulation of the maintenance wall evolution during the pre-design stage through a transfer function inspired by models derived from Multi-Attribute Utility Theory (MAUT) (Larivet & Brouard, 2007 ; Saaty, 2008).

The transition from the initial maintenance wall to the final (target) wall is modeled using an evolution equation that integrates the cumulative effects of the selected technical solutions. This formulation ensures that the resulting values remain bounded within the interval [1, 5], which corresponds to the levels of the Likert scale adopted in this study.

$$v_i^{final} = min\left(5,\ max\left(1,\ v_i^{init} + \sum_{j=1}^{m} \omega_{i,j}\right)\right) \quad (2)$$

where :
v_i^{final} : final wall value ;
v_i^{init} : initial wall value ;
m : number of selected technical solutions ;
$\omega_{i,j}$: impact of solution j on criterion i.

2.5. Preliminary design and 3D modeling

The selected technical solutions were integrated into the overall architecture of the two-wheel tractor. A 3D model was developed using computer-aided design (CAD) software (SolidWorks) in order to verify

- Dimensional and functional compatibility;
- Accessibility to maintenance-related components;
- Disassemblability of subassemblies.

The design prioritizes a welded mechanical structure, commercially available components, and simple interfaces, in accordance with the principles of Design for Maintenance (DFM) (Dennis et al., 2014).

2.6. Prototyping and experimental validation

The three-dimensional modeling of the prototype was carried out using SolidWorks software. The two-wheel tractor prototype was manufactured in the workshops of the Centre Ecologique Albert Schweitzer Burkina (CEAS-Burkina) using conventional machine tools (lathe, welding station, and drill press).

The prototype was designed and built from the selected technical solutions using locally available production resources. Functional tests were conducted to verify compliance with the required traction capacity, tillage depth, and forward operating speed (Bell, 2010).

The maintainability assessment was based on feedback from users and maintenance technicians, allowing the design to be refined and adjusted.

In addition, the sizing of the two-wheel tractor was based on the use of a diesel engine (ZS1105NF, rated at 18 HP). The traction force was calculated to ensure that, for implement penetration depths ranging from 18 to 22 cm, the plowing width would remain between 60 and 80 cm in clayey soils. The target working speed was set at 4.5 km/h, which corresponds to the practical operating requirements of two-wheel tractors.

The prototype, coupled with a plowshare, was manufactured and tested for the plowing of a 1-hectare field in order to assess its technical performance. The soil moisture content prior to plowing ranged from 10% to 12%.

The parameters measured during the tests on the 1-ha experimental site located in Gomtoaga, Koubri Department, Kadiogo Province, Centre Region, Burkina Faso, were as follows :

- Working time (measured using a stopwatch with 1/100 s precision) ;
- Treated area (measured using a 10 m tape measure) ;
- Soil compaction (measured using a penetrometer, in mpa or kg/cm^2) ;
- Diesel fuel consumption (determined by level difference) ;
- Qualitative observations (machine behavior, ergonomics, and incidents).

3. Results

This section presents the main results obtained from the application of the automated PAMC approach to the design of a two-wheel tractor adapted to the Burkinabe context. It successively describes :

- The identification of maintenance criteria derived from the field survey ;

- The construction and interpretation of the initial pamc wall ;
- The translation of stakeholder recommendations into technical solutions, followed by the simulation of the final wall using the solution vector ;
- The materialization of these design choices through the 3d model and the final prototype.

This progression provides a coherent illustration of the transition from maintenance diagnosis to the effective redesign of the two-wheel tractor.

3.1. Identification of maintenance criteria using boxplots

This approach makes it possible to identify criteria that exhibit significant disagreement, thereby reflecting the heterogeneity of expectations within the sociotechnical maintenance network.

Furthermore, the representativeness of the sample of 33 stakeholders was assessed according to the principle of qualitative data saturation. The analysis of the interviews showed that beyond the 25th respondent, no new category of maintenance criterion emerged, indicating a stabilization of the information corpus. This observation confirms the adequacy of the sample size for the present study.

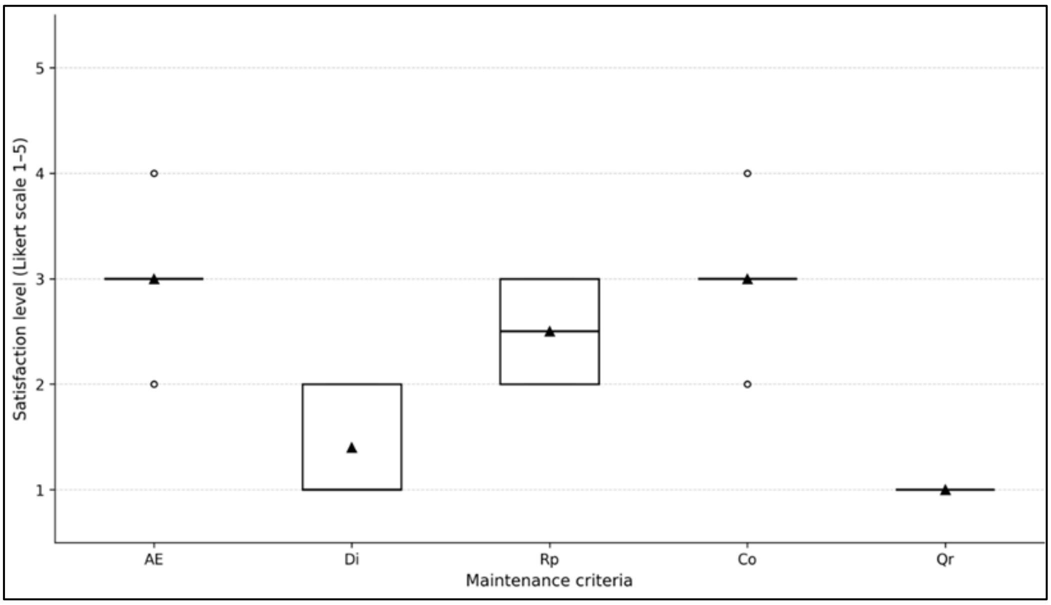


Figure 2 Additional statistical analysis - user criteria

This analysis provides insight not only into the central tendency of stakeholder ratings (median), but also into the dispersion of responses and the degree of consensus across stakeholder groups. The main observations are as follows :

- **AE (Auto-maintenance) :** A moderate spread of ratings is observed, reflecting partial agreement among stakeholders. This suggests that while some users consider the equipment reasonably maintainable at the operator level, others still experience significant technical constraints.
- **Di (Spare parts availability) :** The ratings are clustered around the lowest values, indicating a uniformly low satisfaction level and highlighting a structural weakness in the spare-parts supply chain.
- **Rp (On-site repairability) :** The observed intermediate dispersion suggests that repairability depends strongly on local operating conditions and the availability of maintenance skills within the surrounding technical environment.
- **Co (Overall cost) :** The distribution remains relatively concentrated around the median, indicating a fairly stable perception of the overall cost, although some variability in stakeholder judgment remains.
- **Qr (Quality of spare parts) :** The very limited dispersion indicates a high level of consensus among stakeholders regarding the insufficient quality of the spare parts currently available on the local market.

3.2. Definition of the maintenance criteria identified during the field survey

The field survey conducted among the different stakeholders involved in the two-wheel tractor life cycle enabled the identification of maintenance assessment criteria specific to each stakeholder category. Table 3 summarizes all the maintenance criteria identified through the field investigation.

Table 3 Maintenance criteria identified by stakeholder category

Code	User criterion	Definition
AE	User self-maintenance capability (Levels 2–3)	Refers to the qualification and practical ability of users to perform first- and second-level maintenance operations independently.
Di	Availability of spare parts	Availability of spare parts in the local market.
Fp	Ease of on-site repair	Availability of proximity-based maintenance and repair services provided locally, including on-site interventions.
Co	Overall cost (purchase and repairs)	Financial affordability of the equipment and its spare parts for the end user.
Qr	Quality of spare parts	Use of durable and good-quality spare parts.
Code	Manufacturer criterion	Definition
Ma	Availability of raw materials / parts	Availability of materials and components required to reproduce or manufacture the subsystem locally.
St	Standardization (commercially available parts)	Availability of standardized subsystem components in the local market.
Fo	Observed failure frequency (breakage, wear)	Reliability of the subsystem under actual operating conditions, reflected by the frequency of observed failures.
Co	Cost (manufacturing and maintenance)	Financial affordability of the subsystem in terms of both manufacturing and maintenance.
Au	User self-maintenance capability (Levels 2–3)	Qualification of users or local manufacturers to maintain the subsystem with limited technical complexity.
Code	Maintenance technician / repairer criterion	Definition
Fr	Ease of on-site repair	Degree of local technical mastery required to diagnose and repair the equipment.
Di	Supply / availability of spare parts	Availability of spare parts in the local market.
Qr	Quality of spare parts	Use of good-quality and reliable spare parts.
Fu	User training	Training, guidance, and follow-up support provided to users for proper operation and maintenance.
Code	Spare-parts trader / retailer criterion	Definition
Ap	Ease of procurement for the trader	Ease of sourcing and supplying spare parts.
Di	Availability of spare parts for customers	Market diffusion and local availability of subsystems and spare parts for customers.
Ec	Stock turnover / ease of selling inventory	Increased sales flow and turnover of spare parts used in the equipment design.
Co	Cost of spare parts for the final customer	Financial affordability of spare parts for the end user.

3.3. Automation and simulation of the two-wheel tractor solution vector

The software developed in this study enables the real-time processing of survey data. For each maintenance criterion, the algorithm calculates the median value of the scores assigned within each stakeholder group and automatically positions the corresponding bricks on the initial maintenance wall. To validate the mathematical model, a solution vector corresponding to the selected technological design options was introduced into the simulation process.

For example, for the AE criterion (Auto-Maintenance) :

Initial value : $v^{init}_{AE} = 2$

Selected solution S_1: utilisation de boulonnerie standard (impact $\omega_{AE,} S_1 = +1$)

Calcul : $v^{final}_{AE} = \min(5, \max(1, 2 + 1)) = 3$

By successive iterations, the full set of selected technological solutions (S1 to Sn) enables a progressive improvement in the global satisfaction level of the maintenance criteria.

Overall, the software automatically generates the initial wall, the maintenance oriented design guidelines, the selected solution vector, and the resulting final wall. It therefore produces two complementary outputs :

the initial wall, built from the raw survey data collected in the field ; and

the final wall, generated through the simulation framework based on the solution vector concept.

In this study, a solution vector is defined as a coherent combination of technical solutions (S_1, S_2,...,Sn) intended to be jointly integrated into the prototype design. Each solution is characterized by its specific impact on the full set of maintenance criteria, thereby enabling predictive assessment of the design scenario before prototype manufacturing.

3.3.1. Construction of the initial wall

When the stakeholder survey data specifically the evaluation scores assigned to the maintenance criteria are entered into the application, the software automatically generates the initial maintenance wall, as shown in Table 4. The diagnostic results reveal an initial maintenance wall with numerous missing bricks (i.e., unfilled areas without crosses), indicating substantial weaknesses in the maintenance suitability of the imported equipment under local operating conditions. Such a configuration highlights the need for immediate design intervention before moving to the prototype development phase.

Through successive iterations, the set of selected technological solutions (S_1 to S_n) enables a progressive improvement in the overall satisfaction level associated with the maintenance criteria.

Overall, the software automatically generates the initial maintenance wall, the technical orientations, the selected solution vector for design, and, ultimately, the final maintenance wall.

More specifically, the software produces two distinct maintenance walls :

- An initial wall, constructed from the raw field data collected from stakeholders, and
- A final wall, derived from the simulation framework based on the solution vector concept.

A solution vector is defined as a coherent set of technical solutions (S_1, S_2, ..., S_n) intended to be jointly incorporated into the prototype design. Each solution within the vector is characterized by its specific impact on the full set of maintenance criteria.

3.3.2. Construction of the Initial Maintenance Wall

Once the survey data collected from stakeholders limited here to the evaluation scores assigned to the maintenance criteria are entered into the application, the software automatically generates the initial maintenance wall, as presented in Figure 3 below.

However, the diagnostic analysis reveals that the initial maintenance wall exhibits numerous missing bricks (i.e., empty zones without crosses), highlighting substantial maintenance-related shortcomings. This situation calls for urgent corrective action before moving forward to the design phase.

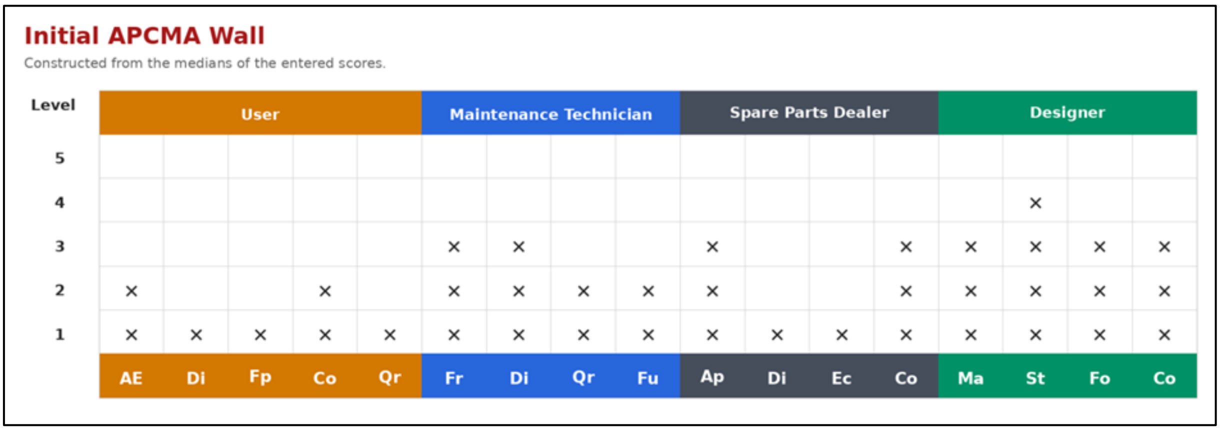


Figure 3 Initial wall before design

The initial APCMA wall highlights a structural mismatch between imported two-wheel tractors and the Burkinabe sociotechnical context. Several critical criteria exhibit low satisfaction levels (scores of 1 and 2), indicating a systemic vulnerability of the maintenance system. In particular, the criteria related to spare-parts availability (Di) and spare-parts quality (Qr) display the lowest satisfaction levels. This situation reveals a strong dependence on external supply chains, which are often discontinuous, as well as a lack of local standardization of components.

These findings are consistent with the observations of Mrema et al. (2008) and Sims and Kienzle (2017), who argued that the failure of many agricultural machines in sub-Saharan Africa is less attributable to their mechanical performance than to their lack of maintainability under local operating conditions (Houmy et al., 2013 ; Sims & Kienzle, 2017). Furthermore, the criteria AE (auto-maintenance) and Rp/Fr (on-site repairability) are positioned at intermediate levels, reflecting a technological complexity that is insufficiently mastered by users and local maintenance technicians. This condition increases dependence on specialized skills that are scarce in the local context, thereby accelerating equipment immobilization after the first failures.

Thus, the initial wall reflects a clear disconnect between technological design choices and the practical realities of life-cycle stakeholders, a phenomenon already emphasized by Bationo (2007) and Dhillon (2008). Overall, the initial APCMA wall provides an objective diagnosis of a non-resilient maintenance system, characterized by low spare-parts reliability, limited repairability under local conditions, and a global cost perceived as insufficiently justified in relation to the services delivered.

3.3.3. Simulation of the final wall or design target

Stakeholders formulated a set of technical orientations to address the deficiencies identified in the initial wall and to guide the design process :

- Users : enable level 2 to 3 auto-maintenance, with simple interventions that do not require specialized skills.
- Maintenance technicians : ensure easy access to internal components using standard tools available locally.
- Spare-parts traders : recommend the use of components derived from equipment that is already widespread locally in order to facilitate supply.
- Designers/manufacturers : ensure the availability of raw materials and components for fabrication, with a preference for standard materials.

These technical orientations were translated by the design team into technological solutions to be integrated into the design of the two-wheel tractor. These include :

Eliminating non-removable assemblies (e.g., riveting) by using standard bolted joints (M8, M10, M12, M16, etc.) to secure mechanical connections (ISO 898-1, 2013).

Replacing the cast-iron power transmission system, which is difficult to repair due to the limited local mastery of the imported model's technology (dog-clutch system and independently cast gears), with a motorized tricycle differential axle, which is robust, locally recoverable, and readily available through local traders. This differential axle also improves maneuverability during turning operations.

Prioritizing locally available standard materials for fabrication, including S235 steel for the frame, C45 steel for shafts, and 35 × 35 mm square hollow sections, in accordance with EN 10025 (2004).

Designing a simple spur-gear gearbox that is easy to repair and coupling it with the differential axle.

Using locally forged plowshares manufactured from reclaimed leaf springs for tillage tools, providing high abrasion resistance (Khurmi & Gupta, 2005).

3.4. Vector solution chosen Vr following the technical solutions

In the case of the tiller, a reference solution vector "Vr= (S 1, S2, S3, S4, S5)" has been established, including five major technical solutions :

- **S_1 – Standard fasteners :** exclusive use of locally available ISO metric bolts (M6, M8, M10, M12), property class 8.8.
- **S_2 – Tricycle differential axle :** integration of a transmission axle recovered from a motorized tricycle, equipped with standard universal bearings (6204, 6205).
- **S_3 – Welded tubular frame :** structure made of 35 × 35 × 2.5 mm square S235 steel sections, assembled by arc welding.
- **S_4 – Standard gear reducer :** gearbox composed of commercially available gears, with a removable housing to facilitate maintenance.
- **S_5 – Locally forged tillage tools :** plowshares manufactured from reclaimed leaf-spring steel.

Based on the solution vector Vr, the software application then evaluates the impact of each solution on all maintenance criteria, formalized through an impact matrix. These impacts are used to weight the initial wall, thereby enabling its evolution toward a proposed final wall before the actual design phase.

3.5. Visualization of the final/target wall before design

The integration of the solution vector Vr into the initial wall leads to the configuration of the final wall, as presented in the table below.

Final APCMA Wall

Formula: V_final = min(5, max(1, V_init + Σ impacts))

Level	User					Maintenance Technician				Spare Parts Dealer				Designer			
5	✓	✓	✓			✓	✓		✓	✓				✓	✓		
4	✓	✓	✓			✓	✓		✓	✓	✓		✓	✓	✓		✓
3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AE	Di	Fp	Co	Qr	Fr	Di	Qr	Fu	Ap	Di	Ec	Co	Ma	St	Fo	Co

Figure 4 Simulated final APCMA wall generated from the technical solution vector

The simulated final APCMA wall, generated from the selected technical solution vector, reveals a substantial and consistent increase in the satisfaction levels of all maintenance criteria. This result indicates a deep reconfiguration of the design system toward a maintenance-oriented design logic. In particular, the criteria Di (*spare parts availability*) and Qr (*spare parts quality*) show the most significant improvements.

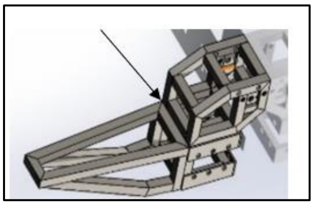
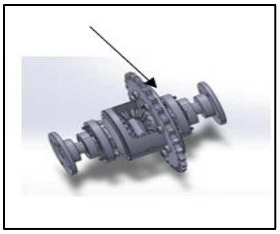
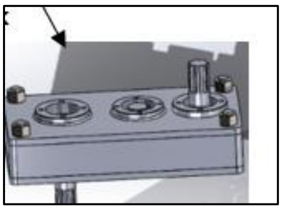
The adoption of components already disseminated within the local technical ecosystem such as tricycle differential axles, standardized rolling bearings, and ISO-compliant fastening systems contributes to the relocalization of the maintenance supply chain, thereby reducing import dependency and improving system resilience. Such progress is consistent with the principles of Design for Maintenance and Design for Local Manufacturing (Jamieson, 2004 ; Tsoukiàs, 1994).

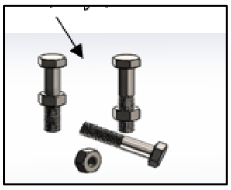
Similarly, the criteria AE and Fr/Rp improve markedly as a result of the simplification of the mechanical architecture, the enhanced dismantlability of subassemblies, and the use of standard maintenance tools. The final wall thus reflects a stronger technological appropriation by both users and maintenance operators, which constitutes a key prerequisite for the sustainability of agricultural equipment in low-resource settings (Food and Agriculture Organization of the United Nations [FAO], 2022).

Overall, the transition from the initial APCMA wall to the final simulated wall provides clear evidence of the ability of the formalized and automated APCMA framework to transform a deficient maintenance diagnosis into an optimized design configuration prior to prototype fabrication.

Table 4 below presents the direct translation of stakeholder-defined design orientations into practical technical solutions, together with the maintenance criteria explicitly incorporated for each designed component.

Table 4 Technical solutions and maintenance criteria integrated into the frame design

Designed component	**Selected technical solutions**	**Integrated maintenance criteria and justification**
Main frame of the two-wheel Tractor 	• 35 × 35 × 2.5 mm square steel tube, locally available profile • Simple and rigid structure (static load **R = 1950 N**) • Standardized sections and standard fasteners • Class 8.8 bolts (M8, M10, M12) • Welded assembly feasible with local workshop capabilities • Design facilitating access to serviceable components	**Ma** : local availability of tubes and profiles **St** : standardized sections and fasteners **Fo** : reduced risk of structural failure **Co** : controlled overall cost **Fr** : on-site repairability **Di** : local availability of spare parts and materials **Qr** : acceptable component quality **AE** : ease of maintenance by users **Fp** : simple field repair operations **Ap** : easy procurement **Ec** : high commercial turnover of components
Transmission differential axle 	• Rigid axle ensuring final power transmission • Standard universal bearings (6204, 6205) • Removable housing to facilitate maintenance • Repairable with basic tools • Robust structure adapted to agricultural loading conditions	Ma : local availability of components St : standardized bearings and interfaces Fo : reduced likelihood of failures Co : reduced cost Fp : repair possible in field conditions Di : locally available spare parts
Reduction gearbox / transmission Gearbox 	• Standard gears available on the local market • Two-part welded housing with removable sections • Standard bearings and sealing elements • Simple oil-bath lubrication system • Robust and easily maintainable gearbox design	Ma : locally available materials and components St : standardized gears and bearings Fo : simple and robust design Co : controlled manufacturing cost Fr : disassembly and repair feasible by local artisans Di : spare-part availability Fp : on-site intervention possible

Commercially available bolts, nuts, studs, keys, etc. 	• Standard ISO fasteners (M6, M8, M10, M12 ; class 8.8) • Standardized keys and pins • Local market availability • Easy field replacement • Surface treatment to reduce seizure and galling	Ma : local availability of fastening elements St : dimensional standardization Fr : ease of replacement AE : accessible disassembly/reassembly Ap : simple procurement Ec : high market turnover Co : low unit cost

The mechanically welded tubular chassis developed in this study ensures high repairability, as it can be restored using standard electric arc welding techniques that are widely accessible to local fabricators. This stands in clear contrast to the cast-iron chassis commonly used in imported models, which generally require more specialized repair processes and are therefore less compatible with local maintenance capabilities. This design choice directly addresses the Fr criterion (ease of on-site repair), identified as one of the most critical maintenance constraints during the field investigation.

Similarly, the incorporation of a tricycle differential axle as a combined steering and speed-reduction subsystem represents a key strategic decision. By replacing highly specific imported drivetrain components with locally available parts already supported by existing supply and repair networks in Burkina Faso, this solution significantly improves maintainability and spare-parts accessibility. More broadly, it exemplifies the core principle of the Preliminary Analysis of Maintenance Criteria (PAMC/APCMA) methodology : technology should be designed in alignment with the local sociotechnical maintenance ecosystem, rather than transferred as an externally optimized but locally inappropriate system.

3.5.1. Final 3D assembly of the selected design solutions and technical performance of the prototype

Figure 5 presents the final 3D assembly of the selected design solutions integrated into the two-wheel tractor prototype.

Figure 5 Final assembly in retained solutions of a tiller

The technical performance tests conducted on the two-wheel tractor prototype resulted in the following technical specifications.

Table 5 Technical specifications of the CEAS ZS1115 two-wheel tractor prototype

Parameter	Specification
Model	CEAS ZS1105 NF two-wheel tractor
Engine	ZS1115 diesel engine (or equivalent)
Rated power	18 hp (≈ 13.4 kW)
Transmission	Four forward progressive gears

Differential	Present, with independent gearing
Total mass	≈ 260 kg
Overall dimensions (L × W × H)	190 × 85 × 105 cm
Working width	80 cm
Average fuel consumption	24 ± 5 L/ha
Effective travel speed	2.0 km/h
Wheel slip ratio	12–15%
Tillage depth	18–22 cm
Effective field work rate	≈ 9.5 ± 1.5 h/ha
Hitch system	Universal, compatible with commercially available implements
Indicative price	≈ 1,500,000 FCFA
Maintenance characteristics	Simple maintenance ; spare parts available locally

From a functional standpoint, the design sizing validated an operational capacity of approximately 1 hectare per day based on an 8-hour working day, thereby meeting the needs of smallholder farmers. The systematic use of standardized bolts and fasteners (M8, M10, and M12) directly addresses the AE criterion (Auto-Maintenance) by enabling users to perform first- and second-level maintenance operations independently, without systematically relying on specialized maintenance technicians. Observations of the machine's overall behavior during field trials indicated moderate wheel slip of the cage wheels, while a substantial manual downward force on the two-wheel tractor handles was required during operation.

4. Discussion

This study makes an original scientific contribution by proposing a mathematical formalization and software-based automation of the PAMC/APCMA method, which was initially qualitative in nature. Each maintenance criterion was represented using boxplots, making it possible to assess whether stakeholder consensus was strong or whether significant divergences existed among actor groups. In addition, the use of the statistical median as the aggregation operator constitutes a robust methodological choice, particularly well suited to data derived from Likert-type scales (e.g., Grim, 1936 ; Jamieson, 2004 ; Pimentel, 2010 ; Rousseeuw & Hubert, 2011). This approach makes it possible to faithfully represent the dominant stakeholder perception while limiting the influence of extreme values.

Furthermore, the introduction of an impact matrix combined with bounded evolution equations transformed the APCMA framework into a genuine predictive simulation tool. Unlike conventional multicriteria approaches often applied *a posteriori* such as the Analytic Hierarchy Process (AHP) and TOPSIS the proposed model enables the *ex ante* evaluation of the combined effects of technological design choices on the overall maintainability of the system (Larivet & Brouard, 2007 ; Tsoukiàs, 1994 ; Saaty, 2008 ; Behzadian et al., 2012). This simulation capability represents a major methodological advance for the design of equipment adapted to the socio-technical realities of Burkina Faso.

The results confirm that the explicit integration of maintenance requirements from the design stage helps break away from the prevailing logic of importing poorly adapted technologies. The developed two-wheel tractor prototype illustrates a frugal yet high-performing design, based on standardization, repairability, and economic accessibility, thereby aligning with recent work on appropriate mechanization in sub-Saharan Africa (FAO, 2022 ; Sims & Kienzle, 2017 ; Baudron et al., 2015). The overall improvement observed in the final APCMA wall validates the hypothesis that the durability of agricultural equipment depends more on its integration into a functional local sociotechnical network than on its level of technological sophistication. This finding extends and operationalizes the work of Bationo (2007) by introducing a quantitative and automated dimension absent from earlier approaches (Bationo, 2007 ; Bationo & Boujut, 2022).

The transition to a mathematical model also removed the ambiguities associated with the manual analysis of the APCMA method. The use of the median instead of the mean made it possible to maintain the focus on the actual needs expressed by the majority of stakeholders, while eliminating the influence of outliers that could distort the diagnosis. This robust approach ensures that design decisions are based on a consensus that is truly representative of field realities. Unlike the manual approach, which requires hours of calculations to explore different scenarios, the software enables rapid iteration across technical solutions, thereby facilitating multicriteria optimization. Automation thus significantly reduced computation time while providing greater precision in the selection of technical solutions.

5. Conclusion

The implementation of the APCMA tool, through mathematical modeling and software automation, transformed field constraints into technological opportunities, ultimately leading to a robust, repairable, and economically competitive prototype. The proposed approach is structured around three complementary dimensions:

- Field-based analysis to capture the actual needs of stakeholders:
- Mathematical modeling to quantify and simulate design choices ; and
- Software automation, developed in python, to accelerate the decision-making process.

The study also demonstrated the scientific and operational relevance of the systematic integration of maintenance criteria from the design phase of agricultural equipment. Based on a field survey involving the main stakeholders responsible for the maintenance of two-wheel tractors in Burkina Faso, an initial maintenance wall was constructed, highlighting critical shortcomings related to the availability and quality of spare parts, repairability, and the economic accessibility of imported equipment.

The mathematical formalization of the APCMA method, based on the use of robust statistics (median), impact matrices, and evolution equations inspired by multicriteria utility theory, made it possible to transform an initially qualitative tool into a quantitative decision-support framework with the capacity to evaluate and simulate technical solutions. Beyond the specific case study of the two-wheel tractor, this research makes an original methodological contribution by proposing a generic decision-support framework for the design of equipment adapted to resource-constrained contexts. Moreover, the proposed framework is transferable to other types of agricultural or industrial machinery, provided that the relevant criteria and stakeholder groups are appropriately adapted.

Future research should focus on the long-term validation of the prototype under real operating conditions, the enhancement of the model through advanced weighting of multicriteria impacts, and the extension of the software into a library of locally relevant technological solutions.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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