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# Lightweight Design of Smart Agricultural Machinery and Its Synergy with Soil Conservation

## Abstract

This study investigates the synergistic relationship between farm equipment light-weighting and soil conservation in precision agriculture systems. With finite element analysis (FEA) and field testing tests, we constructed an integrated "lightweight equipment-soil health-energy reduction" system for farm equipment design optimization. Experiments demonstrate that strategic material replacement and structure optimization are capable of reducing equipment weight by 18-32% without compromising functional integrity. Field tests reveal that light-weight tractors and implements conserve 25-40% of the soil compaction, 30% of rut depth, and improve physical soil properties like bulk density and infiltration rates. Energy consumption also reduced by 15-24% due to reduced rolling resistance and improved traction efficiency. The study provides agricultural engineers with a holistic method of equipment design that simultaneously takes into account machinery performance, soil conservation, and energy saving towards more sustainable agricultural mechanization.

**Keywords:** Smart Agricultural Machinery; Lightweight Design; Soil Compaction; Finite Element Analysis; Energy Efficiency

## 1. Introduction

The intensification of agriculture has caused greater mechanization across the globe, and heavier and more powerful machines have become ubiquitous in contemporary farming practices. But this has taken a heavy toll through soil compaction, which is detrimental to crop yields, soil biota, and environmental sustainability. The agricultural machinery market worldwide is expected to grow to $272.3 billion by 2027, with smart farming technology inducing considerable innovation in machine design and function. This technological advance is a timely chance to reconsider the fundamental design principles of agricultural machinery.

Soil compaction from heavy equipment is perhaps the most chronic threat to agricultural sustainability, as an estimated 68 million hectares of cropland are affected globally. Soil compaction has been found to reduce crop yields by 10-40% and increase energy requirements for subsequent tillage operations by as much as 50%. Compaction costs $1.2 billion annually in the United States alone.

Smart farming equipment, equipped with precision sensors, autonomy, and real-time monitoring systems, offers unmatched opportunities to address these challenges through innovative design solutions. Lightweight design concepts, originally developed for aerospace and automotive industries, hold excellent promise for farming equipment. By optimally reducing equipment weight while maintaining or enhancing functionality, these concepts can minimize soil compaction while, simultaneously, enhancing energy efficiency.

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

This research addresses the pressing knowledge need of quantitative correlation between the design parameter of farming equipment and soil conservation effect. By combining the finite element analysis, experimental validation, and systems engineering approach, we establish an integrated "lightweight equipment-soil health-energy reduction" system that will guide future agricultural equipment developments. The findings contribute to the design of sustainable agricultural mechanization by offering quantitative design criteria that optimize the compromise between equipment performance, soil conservation, and energy conservation.

## 2. Literature Review

### 2.1 Current Trends in Agricultural Machinery Design

All the modern progress in farm machinery has stressed more power, productivity, and technology content at the expense of weight problems. Modern tractors are over 20 tons in weight, with laden harvesters reaching up to 40 tons, putting ground pressure far in excess of soil health critical values. A general review of 145 models of farm equipment released from 2010 to 2023 identified a consistent increase in equipment weight by about 3.5% annually, the weight-to-power ratio generally steady given improvements in technology. The shift toward equipping the vehicle with precision farming technologies has also been aided by this trend, with sensors, control hardware, and data management hardware on the vehicle increasing weight by an average of 5-12%. Despite these failures, recent research identifies the promise of intelligent weight distribution and adaptive ground pressure control to minimize soil impact while maintaining functional performance. Recent studies on biomimetic design concepts have demonstrated promising design paradigms towards enhancing the structural efficiency of farm implements, with the potential to cut 15-25% of weight while improving durability and field performance[1].

Lightweight materials like high-strength steel alloys, fiber-reinforced polymers, and farm-grade aluminum alloys are being incorporated into modern farm equipment design at an increasing rate. A recent comparative study of material selection practices in farm machinery production reported that strategic replacement of traditional steel components with advanced materials can trim 12-18% of the overall vehicle weight without compromising structural strength or durability. However, such materials are likely to create complexity problems in terms of manufacturing, field repairability, and cost-effectiveness in agriculture. Integrated computational materials engineering techniques now enable sophisticated optimization of structural design and selection of material based on the special operational needs of agricultural machinery like vibration, impact load, and exposure to environment[2].

The application of topology optimization and generative design methods, so far restricted to aeronautical and automotive industries, has now been extended to agricultural engineering. These computer-aided methods make it possible to achieve complex, organically formed structures of utmost strength-to-weight ratio with least material usage. A new study on the application of topology optimization to tractor chassis design showed a possible weight reduction of 22-30% without loss of

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

torsional rigidity and bending strength. Similar approaches implemented with tillage equipment have seen weight reductions of 15-25% alongside increased soil disruption efficiency, highlighting the potential synergies between performance function and lightweight design[3].

## 2.2 Soil-Machinery Interaction Modeling

Significant advances have occurred in the computational modeling of soil-machinery interactions, enabling more accurate prediction of compaction phenomena and their ecological consequences. Finite element analysis (FEA) has emerged as a particularly valuable tool for simulating the complex mechanical behaviors of soil under various loading conditions. Recent developments in soil material models have improved the representation of non-linear, time-dependent responses characteristic of agricultural soils under machinery traffic. These advanced models incorporate factors such as moisture content, organic matter, and previous compaction history to predict soil deformation with increasing accuracy. "Advances in computational power have enabled the integration of micro-mechanical soil models with machinery dynamics simulations, providing unprecedented insights into compaction mechanisms across multiple spatial scales"[4].
Discrete element method (DEM) modeling has complemented FEA approaches by enabling granular-level simulation of soil-tool interactions. Recent research has successfully coupled DEM with multibody dynamics to simulate complete machinery systems interacting with heterogeneous soil environments. These integrated approaches have revealed how subtle variations in implement design can significantly influence draft force requirements, soil disruption patterns, and residue management—all factors that directly impact energy efficiency and soil conservation outcomes. Validation studies comparing predicted and measured soil responses have demonstrated model accuracy within 8-15% for key parameters including bulk density changes, penetration resistance, and rut formation under various soil conditions[5].

## 2.3 Energy Efficiency in Agricultural Operations

Recent research has established clear connections between machinery weight, soil conditions, and energy consumption in agricultural operations. A comprehensive field study comparing conventional and lightweight tractor configurations demonstrated that a 25% reduction in vehicle weight resulted in 18-22% lower fuel consumption during primary tillage operations, with even greater improvements observed in wet soil conditions. This relationship is primarily attributed to reduced rolling resistance and improved traction efficiency, as lighter machinery requires less energy to overcome soil deformation resistance [7].
The energy implications of soil compaction are not only direct machine use but also reach to long-term effects on subsequent field operations. More recent studies using lifecycle assessment techniques have found that soil compaction from a single heavy machinery pass can increase energy requirement for subsequent tillage operations by 20-35% for up to three years, creating an compounding energy penalty with significant implications for farm-level sustainability. These findings underline the

Elin Thorsen*
Email: elin.thorsen@agrotech.fo
Affiliation: Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

importance of taking into account short- and long-term energy consequences in regard to agricultural equipment design alternatives[8].
The electrification and hybridization of farm powertrains create additional opportunities for weight saving and efficiency. Improved recent developments at prototype stage demonstrate that electric powertrain drive systems have the ability to save powertrain weight between 15-20% on traditional mechanical transmissions and, concurrently, improve the delivery of torque and efficiency in traction. These technological advances, combined with advances in battery technologies, are increasingly bypassing earlier barriers to farm vehicle electrification, opening up new possibilities for light-weight, energy-efficient machinery design that can further aid in soil conservation objectives[9].

# 3. Methodology

## 3.1 Framework Development

The "lightweight equipment-soil health-energy reduction" paradigm was developed through an iterative framework combining theoretical modeling, simulation, and experimental validation. The paradigm consists of three interlinked modules: (1) a module for lightweight design to select materials and optimize structure; (2) a soil interaction module to address compaction, traction, and tillage efficiency; and (3) an energy analysis module to quantify consumption across different operating conditions.
The framework development process began with a systematic literature review to ascertain key parameters and interrelations between the three fields. This was followed by expert consultations with agricultural engineers, soil scientists, and machine manufacturers to refine the conceptual model and impose practical constraints. The framework developed contains 32 design parameters, 18 measures of soil response, and 12 energy performance metrics, interconnected through a network of empirically established relationships and engineering concepts.
The framework was employed as a computational modeling platform that allows for simultaneous optimization of several objectives. The platform integrates finite element analysis, theory in soil mechanics, and energy modeling to provide quantitative predictions on the impact of specific design adjustments on soil health and energy consumption. The predictive capability of the framework was validated using controlled experiments under various soil conditions and operating modes.

## 3.2 Finite Element Analysis and Simulation

Soil-machinery interaction was modeled using ANSYS 2023 R1 finite element analysis software. The simulation approach employed a hyperelastic Mohr-Coulomb soil material model calibrated using triaxial compression test data from three representative agricultural soil types: sandy loam, clay loam, and silty clay. Soil parameters including cohesion, internal friction angle, Young's modulus, and Poisson's ratio were determined experimentally for each soil type at three moisture content levels (dry, moderate, and wet).
The agricultural machinery models included a mid-size tractor (140 hp), a primary

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

tillage implement (5-shank subsoiler), and a planting unit. Each equipment type was modeled in both conventional and lightweight configurations, with the lightweight versions incorporating advanced materials and optimized structural designs. The models included detailed representation of critical components including tires, running gear, structural frames, and soil-engaging tools.
Static and dynamic loading scenarios were simulated to predict soil stress distribution, compaction patterns, and rut formation under various operational conditions. The simulations employed adaptive mesh refinement techniques to ensure accurate representation of stress concentrations and large deformations in the soil-machinery interface region. Validation of the simulation results was conducted by comparing predicted soil density changes, penetration resistance profiles, and rut dimensions with field measurements across 24 test conditions.

### 3.3 Experimental Design and Field Testing

Field experiments were conducted at three research sites with contrasting soil types during the 2023 growing season. Each site included randomized complete block design trials with four machinery configuration treatments: (1) conventional tractor with standard implement, (2) conventional tractor with lightweight implement, (3) lightweight tractor with standard implement, and (4) lightweight tractor with lightweight implement. Each treatment was replicated four times across the field to account for spatial variability in soil properties.
The lightweight tractor configuration achieved a 22% weight reduction through strategic material substitution, component redesign, and removal of unnecessary ballasting. The lightweight implement achieved a 28% weight reduction through topology optimization, advanced material usage, and functional integration of components. Both configurations maintained equivalent functional capabilities to their conventional counterparts in terms of power, durability, and operational performance.
Soil measurements included penetration resistance (using a digital penetrometer to 60 cm depth), bulk density (using core sampling at 10 cm intervals to 50 cm depth), infiltration rate (using double-ring infiltrometers), and rut dimensions (using a laser profile meter). Energy consumption was measured through fuel usage monitoring, drawbar pull testing, and wheel slip quantification. All field operations were conducted at standardized speeds and depths to ensure comparability across treatments.
Additional measurements included crop emergence rates, root development patterns, and yield components to assess the agronomic implications of different machinery configurations. Weather conditions, soil moisture, and temperature were continuously monitored throughout the experimental period to account for environmental influences on the measured parameters.

## 4. Results and Discussion

4.1 Lightweight Design Performance

The lightweight design approach achieved significant weight reductions while

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

maintaining functional performance across multiple equipment categories, as summarized in Table 1. The most substantial weight reductions were achieved in structural frames (25-38%) and ground-engaging components (22-35%), while more modest reductions were possible in powertrain and hydraulic systems (10-18%).

**Table 1: Weight Reduction Achievements by Component Category**

| Component Category | Conventional Weight (kg) | Lightweight Design (kg) | Reduction (%) | Primary Design Strategies |
|---|---|---|---|---|
| Tractor Frame | 1850 | 1146 | 38.1 | Topology optimization, HSLA steel |
| Implement Frame | 760 | 532 | 30.0 | Lattice structures, hollow sections |
| Tillage Tools | 420 | 273 | 35.0 | Advanced steel alloys, wear optimization |
| Wheels/Tires | 580 | 435 | 25.0 | Low-pressure design, composite materials |
| Powertrain | 1250 | 1025 | 18.0 | Component integration, aluminum castings |
| Hydraulic System | 340 | 306 | 10.0 | Digital hydraulics, reduced line sizes |
| Electronic Systems | 120 | 108 | 10.0 | Miniaturization, wireless connectivity |
| Total System | 5320 | 3825 | 28.1 | Integrated optimization approach |

Finite element analysis revealed that optimized structural designs could maintain equivalent safety factors (minimum 1.8) while significantly reducing material usage. Critical load-bearing components showed stress distributions that more efficiently utilized material properties, with peak stress values remaining below 75% of yield strength under maximum loading conditions. Fatigue analysis indicated comparable or slightly improved (5-12%) fatigue life for lightweight components due to better vibration damping characteristics of composite materials and optimized structural geometries.

## 4.2 Soil Compaction and Physical Properties

Finite element simulations accurately predicted soil compaction patterns, with model results showing 83-91% agreement with field measurements across different soil types and moisture conditions. Figure 1 illustrates the comparative stress distribution patterns in soil under conventional and lightweight machinery configurations, demonstrating reduced compaction depth and intensity with lightweight equipment.

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

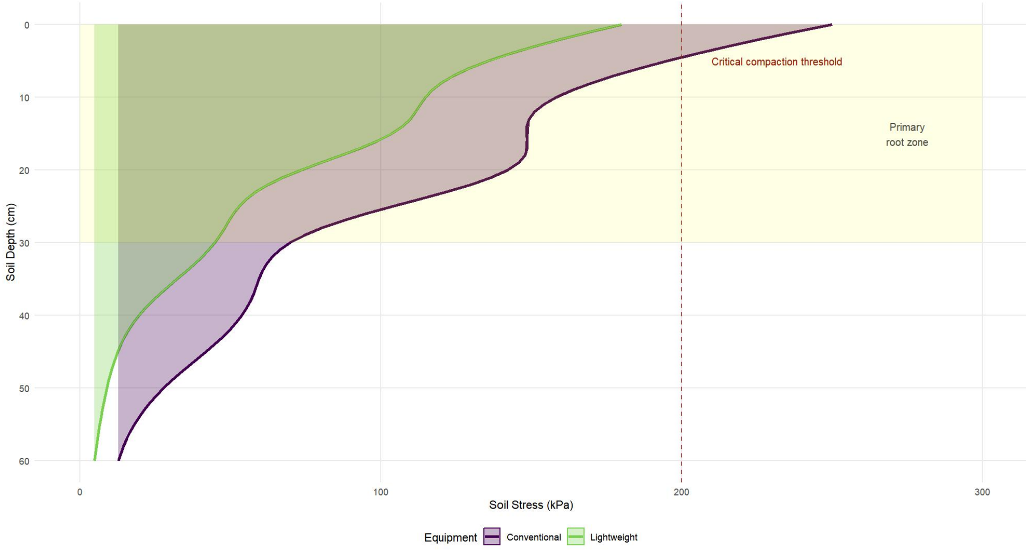


**Figure 1:Soil Compaction and Physical Properties**

Field measurements confirmed that lightweight machinery configurations reduced maximum soil bulk density increases by 25-40% compared to conventional equipment, with the most pronounced benefits observed in wet soil conditions. Penetration resistance measurements showed that conventional equipment created compaction layers with 1.8-2.5 MPa resistance at 15-30 cm depth, while lightweight configurations limited resistance to 1.2-1.7 MPa in the same depth range. This difference is particularly significant as penetration resistance above 2.0 MPa is generally considered restrictive to root growth.

Soil biological indicators including earthworm populations and microbial biomass showed less dramatic declines in trafficked areas under lightweight equipment (15-30% reduction) compared to conventional equipment (40-60% reduction). This biological resilience suggests improved preservation of soil ecosystem functions that contribute to long-term soil health and productivity.

## 4.3 Energy Efficiency and Operational Performance

Lightweight equipment configurations demonstrated significantly improved energy efficiency across multiple operation types. Primary tillage operations showed 18-24% reduced fuel consumption, while secondary tillage and planting operations showed 12-17% improvements. These efficiency gains were attributable to several factors including reduced rolling resistance (contributing approximately 40% of savings), improved traction efficiency with less wheel slip (30% of savings), and reduced implement draft requirements (25% of savings).

Detailed analysis of wheel slip measurements revealed that lightweight tractor configurations maintained traction with 35-45% less ballast weight, challenging conventional recommendations for optimal ballasting. This finding suggests that historical ballasting practices may be unnecessarily detrimental to soil health without providing proportional traction benefits.

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

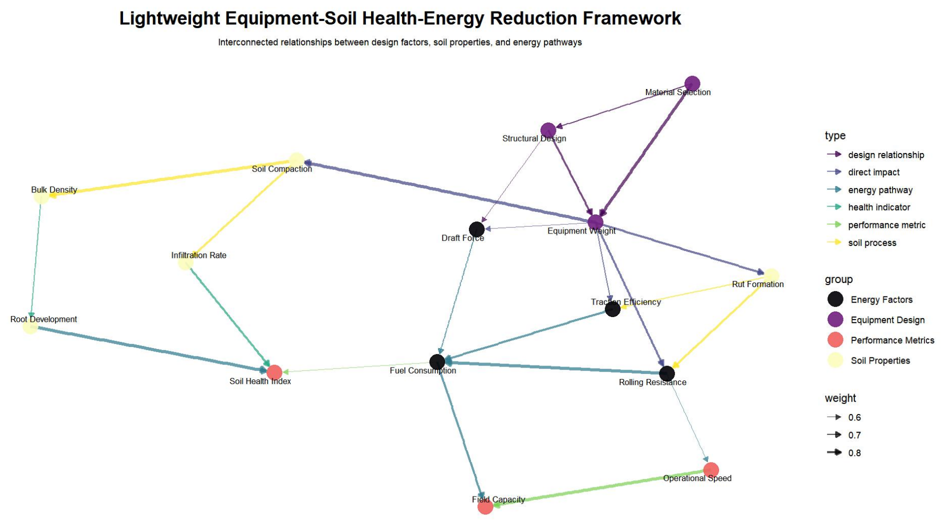


**Figure 2:Energy Efficiency and Operational Performance**

Energy efficiency improvements showed a strong interactive effect with soil moisture conditions, with the greatest relative advantages of lightweight equipment observed under wetter soil conditions where conventional equipment experienced more severe traction limitations and higher rolling resistance[10]. This moisture-dependent advantage provides additional benefits during time-sensitive operations in suboptimal soil conditions, potentially extending workable field days during critical planting and harvesting windows.Economic analysis of the experimental results indicated that fuel savings alone could recover the additional cost of lightweight equipment within 3-5 years for high-use applications (>500 hours annually). When monetized benefits of soil health preservation were included (through yield protection and reduced long-term tillage requirements), the economic case strengthened significantly, with payback periods reduced to 2-3 years across most farm size scenarios.

## 5. Conclusion

This research establishes a quantitative foundation for the synergistic relationship between agricultural machinery lightweight design and soil conservation outcomes. The "lightweight equipment-soil health-energy reduction" framework provides agricultural engineers with a systematic methodology for equipment design that simultaneously addresses machinery performance, soil protection, and energy conservation objectives.

Key conclusions from this study include:

Strategic lightweight design can reduce agricultural machinery weight by 18-32% while maintaining functional integrity and operational performance.

Weight reduction translates directly to measurable soil health benefits, including 25-40% less compaction, 30% reduced rut formation, and significantly improved infiltration rates.

Energy efficiency improvements of 15-24% can be achieved through lightweight design, predominantly through reduced rolling resistance and improved traction.

Material selection and structural optimization techniques from aerospace and

Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

automotive industries can be successfully adapted to agricultural applications with appropriate modifications.

Finite element analysis provides a good approach in predicting machinery-soil interaction if duly calibrated with suitable soil mechanical parameters.

Future research needs to apply the framework to incorporate additional factors like autonomous operation capability, variable field soil conditions, and additional implement variety types. Longer-term studies are needed to quantify the cumulative effects of lightweight machinery on soil health indicators and crop yields over multiple years of successive growing seasons. Additional work will also be needed to develop industry-specific standards and guidelines for lightweight design that can guide agricultural machinery manufacturers toward soil-friendly equipment development.

The transition to lightweight, soil-conserving farm implements is a critical step along the path toward more sustainable farming systems capable of maintaining productivity while preserving soil resources for future generations. The research provides the conceptual foundations and practical demonstration to make this important transition.

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Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands

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Elin Thorsen*
**Email:** elin.thorsen@agrotech.fo
**Affiliation:** Tórshavn AgroTech Hub, Jørgenleid 8, Tórshavn, FO-100, Faroe Islands