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Eco-Design and Additive Manufacturing of an Innovative Double-Casing Pedometer for Oestrus Detection in Dairy Cow †

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† This paper is an extended version of our published papers "Proposal for a Double-Casing Prototype of a Pedometer for Dairy Cows, Made to Be Interchangeable, Through Numerical Investigation and 3D Modeling of Geometry"—International Conference on Flexible Automation and Intelligent Manufacturing FAIM 2022 (FAIM 2022) and Flexible Automation and Intelligent Manufacturing: "The Human-Data-Technology Nexus" Proceedings of FAIM 2022, 19–23 June 2022, Detroit, MI, USA, Volume 2.

Abstract: The analysis of motor activity has been revealed to be essential for monitoring dairy cows' behavior, with the main aim of identifying the onset of oestrus in time. Pedometers used for oestrus detection have a current average working life on the market of about 5 years. At the end of that period, devices are disposed of, posing a relevant question regarding environmental sustainability. The present work proposed a method to achieve an eco-design of pedometers compliant with the guidelines of the Green Deal. Specifically, a new thermo-plastic organic compound made of polyamide 66 reinforced with organic hemp fibers (trade name SDS Nylon) was adopted. The feasibility, benefits, and performance of this material were assessed with a major emphasis on strength, lightweight, and surface finish. The material in addition to ensuring adequate chemical and mechanical resistance is biocompatible and recyclable. It assures better animal welfare and reduces both environmental impacts and management costs for farmers. Other innovations introduced in this study consisted of the adoption of a double casing. An external case was conceived with a protective function of the measurement system and fixed to a cow's foreleg by an easy anchor system. An internal case was specifically designed to house the electronic components and to be moved from one cow to another after the pregnancy diagnosis. The solutions proposed in this research will contribute to guaranteeing pedometers a longer lifetime and better recyclability than existing commercial ones, consequently limiting the environmental load derived from their disposal.

Keywords: stand-alone smart device; custom design; digital product optimization; tolerances assignment; biocompatible materials for FDM

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1. Introduction

New technologies to support farm management date back to the second half of the last century when the first automated milking systems were installed in intensive livestock systems for dairy cows. Such systems were introduced because of the importance of an early and accurate determination of oestrus events that became crucial to improving farm production. To the authors' knowledge, the first automatic systems for the electronic recording of milk production were developed in the 1970s, while the first attempts at automatic oestrus detection had to wait until the 1980s [1].

Particular attention was paid to the variation of some physiological parameters. For example, the average skin temperature of cows was found to increase during oestrus [2], mainly in some anatomical parts such as the muzzle and vagina [3]. Milk production was also found to be linked to the oestrus cycle, undergoing a decrease in proximity to the oestrus event [4,5]. Additionally, the milk produced showed variations in both temperature and conductivity [6,7]. Moreover, during the oestrus event, the motor activity of cows increases by nearly 400% in 93% of the observed cases [8,9]. This cow behavioral activity suggested the use of electronic devices attached to the cow body, such as pedometers and collars.

Usually, pedometers are used as step counters. When the step count exceeds a predetermined threshold defined by the direct observation of the farmer, the cow is considered to be in a state of oestrus. The main variables involved in this process are, therefore, the frequency of the total step count and the multiplier used to set the aforementioned oestrus alert threshold. Over the years, various scientific methods have been proposed to detect oestrus by pedometer: exceeding the average value by 1 or 2 standard deviations [5,10]; exceeding a scale value [11] and defining a confidence interval [12,13]. The most popular methods were based on relative increase thresholds compared to previous measurements [14].

These methods were based on a moving average and compared the current value with that obtained by averaging the data coming from a moving window containing a prefixed number of previous observations of the same cow [15,16]. Alternatively, other methods were based on the analysis of the exponential smoothing, according to which different weights could be assigned to the previous observations [17]. The main investigations in the scientific literature concerning the use of pedometers [18–20] have found an associated sensitivity (percentage of ovulating cows detected) well below 70%. This is because about 20% of the cows show no noticeable changes in the overall number of steps.

Thanks to research projects that are still in progress at the Department of Agriculture, Food and Environment of the University of Catania (Italy), a prototype of a pedometer for monitoring dairy cow oestrus was developed. The pedometer is characterized by an eco-design casing developed taking into account cow foreleg anatomy and an electronic device able to perform non-invasive measurements of cow activity through specific firmware for data acquisition and transferring [21]. Firstly, the research activities for the development of the pedometer prototype [22,23] were focused on the determination of cow behavioral algorithms based on accelerometer thresholds defined by processing data coming from uniaxial accelerometers. These algorithms are easily implemented within firmware that can be executed by microcontrollers installed on the mainboards of devices worn by animals. This feature is crucial in real-time monitoring of animal behavior and physiological states, such as the estrous event [23], because it allows the use of Low Power Wide Area telecommunications Network (LPWAN), i.e., LoRa, LoRaWAN, and Sigfox. These networks allow for the connection of numerous devices and low energy consumption which guarantees a longer life of the power supply units, reducing over time the costs of replacing and disposing of the batteries. The pedometer prototype is a stand-alone smart device (SASP), equipped with a triaxial accelerometer, a rechargeable power supply system, a microcontroller and a communication module for working by using LPWANs.

Once the hardware and firmware were defined, the research focused on the implementation of the SASP inside of an innovative biocompatible and recyclable casing. Preliminary results relating to the design of the protection case of the prototype electronic devices were published by the authors in a short note at the Flexible Automation and Intelligent Manufacturing Conference (FAIM 2022) [24]. In this extended research article, some aspects regarding three-dimensional modeling from an industrial manufacturing perspective were explored in depth. Therefore, the project models were described in detail, starting from the preliminary phase of acquiring the geometries up to the choice of tolerances necessary for industrial production.

The main elements of novelty are the adoption of a double casing and the design of a more suitable and functional anchor system for the cow leg. The SASP is equipped with an external case, with a protective function of the measurement system and fixed to one foreleg, and an inner case, specifically designed to be moved from one cow to another after the pregnancy diagnosis. This aforementioned feature makes it possible to reuse the pedometer, after being recharged, for detecting another oestrus event. This solution reduces drastically the number of pedometers to be used in a dairy farm with a consequent reduction in management costs. Concerning the anchor system, a fastening strap able to provide a gradual increase in the locking force was developed for an easy fix to the cow leg. The pedometer shape and its geometrical sizes were optimized by the Topological Optimization (TO) method integrated with Finite Element Analysis (FEA) performed with e ANSYS Mechanical® version 18.0 commercial software.

Nowadays, commercial pedometers have a working life of nearly 5 years. After this period, all the devices are disposed of, worsening the sustainability of intensive livestock farming because of the non-recyclable and non-biocompatible materials. The eco-design proposed could contribute to limiting the environmental burden derived from the disposal of pedometers by reducing the number of pedometers to be used as well as adopting biocompatible and recyclable material. This manuscript was structured as follows: in Section 2 the materials and methods adopted were described; in Section 3, the preliminary testing and the results of implementation on cows were reported; in Section 4 the main results obtained were discussed, while in Section 5 the conclusions of the research were drawn.

2. Materials and Methods

The analysis of the data available in the scientific literature and those that were collected in a previous research project "Smart dairy farming: innovative solutions to improve herd productivity" (CUP: E64I18002270001, PRIN 2017) which was carried out at the Department of Agriculture, Food and E nvironment of the University of Catania (Italy) allowed the authors to establish an effective strategy for the eco-design of the SASP.

A step forward achieved in the study reported in this paper concerned the improvement of the SASP casing geometry by using innovative material for its manufacturing with Fusion Deposition Modeling (FDM), taking into account the anatomy of the cow leg.

2.1. Cow Foreleg Anatomy Acquisition

The accurate acquisition of the cow foreleg surface was the first step to developing a bio-compatible pedometer. This was obtained by using Einscan pro HD (SHINING 3D, Hangzhou, China), a structured light portable 3D scanner, which is easy to use in natural outdoor environments (Figure 1).

Figure 1. Cow foreleg acquisition with Einscan pro HD scanner.

However, the 3D acquisition of surfaces with mobile sensors around the foreleg in protracted periods of time can cause acquisition errors and artifacts since maintaining the cow fixed may be very difficult. Thus, the issue was resolved by also proposing an alternative way that would allow real-time cow foreleg surface acquisition by synchronizing three scanner sensors. A series (daisy) configuration that allows synchronization of a master device with two subordinate devices was adopted (Figure 2). Proper software compiled by the authors made it possible to synchronize the activation times of the sensors after a preliminary calibration. Figure 3 shows a 3D model of cow forelegs acquired by using three Microsoft Kinect DK sensors (Redmond, WA, USA) in-series configuration.

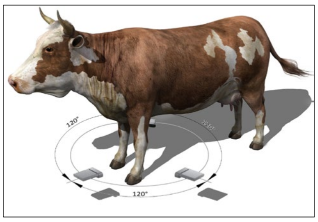


Figure 2. Acquisition layout using three Microsoft Kinect DK scanners.

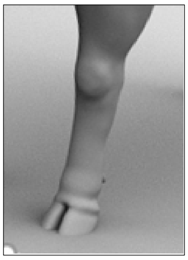


Figure 3. 3D CAD model of cow foreleg surface.

2.2. Pedometer Shape Design

To ensure the comfort of the cow, a cylindrical parametrical geometry was chosen for the casing eco-design of the pedometer (Figure 4). By analyzing an appropriate number of foreleg anatomies acquired from different species of cows, it was found, through a linear regression of the acquired surfaces, that the double-curved cylindrical surface guarantees that the contact of the pedometer to the leg has with highest adhesion and anatomical comfort. In addition, a low surface roughness average value of Ra = 0.8 μm was imposed during FDM pedometer manufacturing. Finally, pedometer surfaces are free of sharp edges that could constitute highly mechanically stressed areas and security risks (Figure 5).

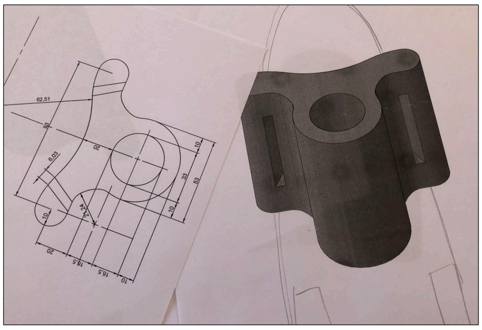


Figure 4. 3D CAD parametric model of the pedometer.

Figure 5. Detail of the double curvature surface in the 3D printed version.

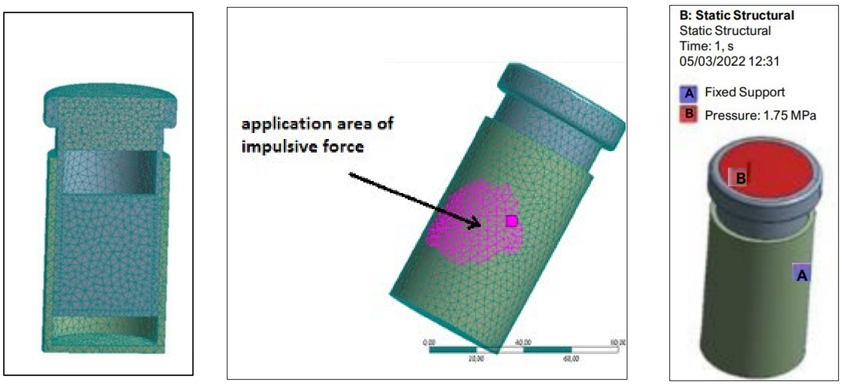
In the first version of the casing developed within PRIN 2017, the mainboard embedding the electronic components was placed along the longitudinal axis of a cylindric hole closed at the top as in Figures 4 and 5. In this version of the pedometer, however, the mainboard was subject to both rapid oxidation due to the bad sealing of the cap and vibrations caused by the gaps between the casing and the battery. Moreover, the thickness of the fins modeled to follow the anatomy of the leg was insufficient to ensure adequate mechanical resistance.

In a second version of the casing, the side in contact with the cow's leg was reinforced by varying the thickness and the anchor system. The main board was housed inside the cap and then filled with resin to avoid oxidation. Moreover, the cap was connected to the casing by a thread system. In this version, since the fins were reduced in order to test the robustness of the case when worn by the cows, the double curvature surface was avoided (Figure 6).

Figure 6. Pedometer with reinforced casing, top cap thread and mainboard housed in the cap.

2.3. Finite Element Analyses

A Finite Elements Analysis (FEA) was performed by using ANSYS 2018 commercial software. It was applied to the last version of the casing prototype (Figure 7).



(**a**) (**b**) (**c**)

Figure 7. (**a**) Assembly mesh; (**b**) impulsive force application; (**c**) distributed force application (Reproduced from [24] with permission from Springer Nature Switzerland AG).

The mesh of the CAD model was made by using solid tetrahedral elements according to the Voronoi-Delaunay algorithm with 16 Jacobian points per element. A selective set of mesh controls resulted in a finer mesh at the threads and thinner parts. Figure 7 shows the assembly mesh (Figure 7a) and load distributions (Figure 7b,c).

Any possibility of penetration between the surfaces in contact was excluded to better simulate the mechanical behavior of the pedometer subjected to the possible load configurations. The overall mesh counted a total of 16,458 nodes and 11,112 tetrahedral elements for the top cap, 23,606 nodes and 12,262 tetrahedral elements for the inner case, and 16,111 nodes and 8079 tetrahedral elements, respectively.

Boundary conditions were applied as fixed constraints along the generatrix of the external cylindrical part of the pedometer to simulate the anchor system to the cow leg. Two load configurations were analyzed:

- An impulsive force of 3000 N acting on the side opposite the constraints, to simulate an accidental impact, i.e., against a fence post, a cow kick, or a cow tipping by other cows [25]. The application area of the impulsive force was assumed to be circular with a radius of 25 mm (Figure 7b).
- A force distributed on the upper surface of the cap equal to 1.75 MPa, to simulate a possible laying of the animal above the leg. This value came from considering a maximum value of half of the weight of an adult Friesian cow and should not exceed 300 kg [26] (Figure 7c).

Figures 8 and 9 show elastic strains and the maximum values of von Mises stress under both load conditions. The values of maximum equivalent stresses, evaluated according to the von Mises criterion, were found to be equal to 42.11 MPa in the impulsive force configuration and 54.63 MPa in the distributed force configuration, respectively. Both values are sufficiently lower than the yield tensile strength of the material considered (σ_y = 62.5 MPa). In addition, the elastic strains found in both conditions (1.68 mm and 0.64 mm) fall within the elastic range of the material. Indeed, the worst value, found in the application area of the impulsive force where the overall thickness of the resistant material is 6 mm = 3 + 3 mm (Table 1), corresponds to an elongation of 27.9%, which is lower than the elongation at yield (ξ_y = 50–70%). This is a confirmation that, even in extreme conditions, the design proposed for the casing of the pedometer prototype proves adequate mechanical resistance.

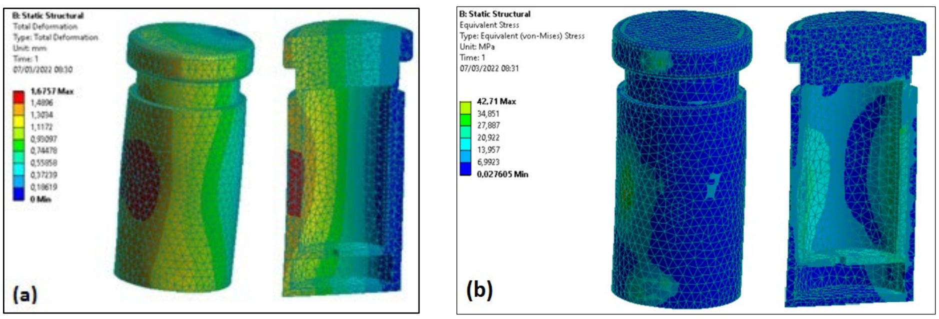


Figure 8. (**a**) Deformation and (**b**) Von Mises stress under impulsive force (Reproduced from [24] with permission from Springer Nature Switzerland AG).

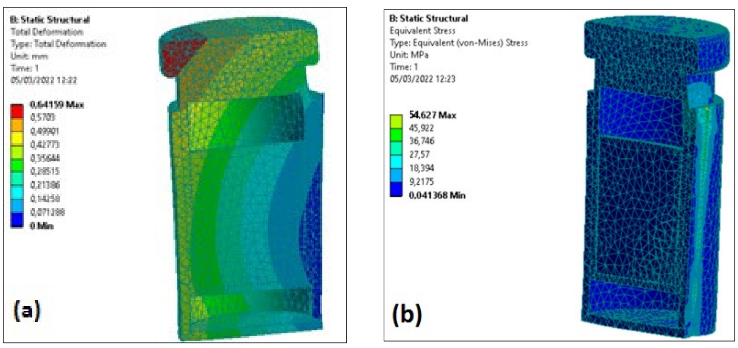


Figure 9. (**a**) Deformation and (**b**) Von Mises stress under distributed force (Reproduced from [24] with permission from Springer Nature Switzerland AG).

Table 1. Main geometrical dimensions of double-casing pedometer (Reproduced from [24] with permission from Springer Nature Switzerland AG).

	External Casing	Inner Casing (Central Body)	Top Cap	Assembly
External diameter [mm]	1	45	45	55 (Upper part) 51 (Central body)
Thickness [mm]	3	3	10	-
Length [mm]	95	80	-	110
Thread [mm]		M45 × 4.5 *	M39 × 4 **	
Separator				
Thickness [mm]		1.5		
Length [mm]		50		

* Screwing to the external casing; ** Screwing to the inner casing.

A set of seven modified prototypes, ready to be tested in the barn, has been proposed (Figure 10). The printing of these two versions of the prototype casing was carried out by a 3D PRUSA i3 MK3s FDM printer using a new thermo-plastic organic compound made of polyamide 66 reinforced with organic hemp fibers (hereinafter SDS Nylon), which was developed by one of the authors in previous studies.

Figure 10. Set of pedometer prototypes.

Despite these changes, problems of interruption of the signal continued to occur, mainly due to disconnections between the mainboard and the battery.

To deal with the problem, while maintaining the pseudo-cylindrical shape of the casing, as it conforms to animal welfare, a double-casing geometry was adopted, as shown in Figures 11 and 12. The activity related to this new design was carried out thanks to the funding of CowTech, a project financed by the European Union within the P.O. FESR SICILIA 2014/2020 (CUP: G69J18001020007). In detail, the external part with the protective function was to be fixed to the cow's foreleg; while the inner one, which was used to house the mainboard and the battery, was decided to be removable and interchangeable (Figure 11). The assembly of the prototype was designed to obtain a battery compartment, a mainboard compartment and a compartment for the battery charging terminal. The bottom of the inner case, in the battery compartment, has a hole for the passage of the battery terminal connector (Figure 13).

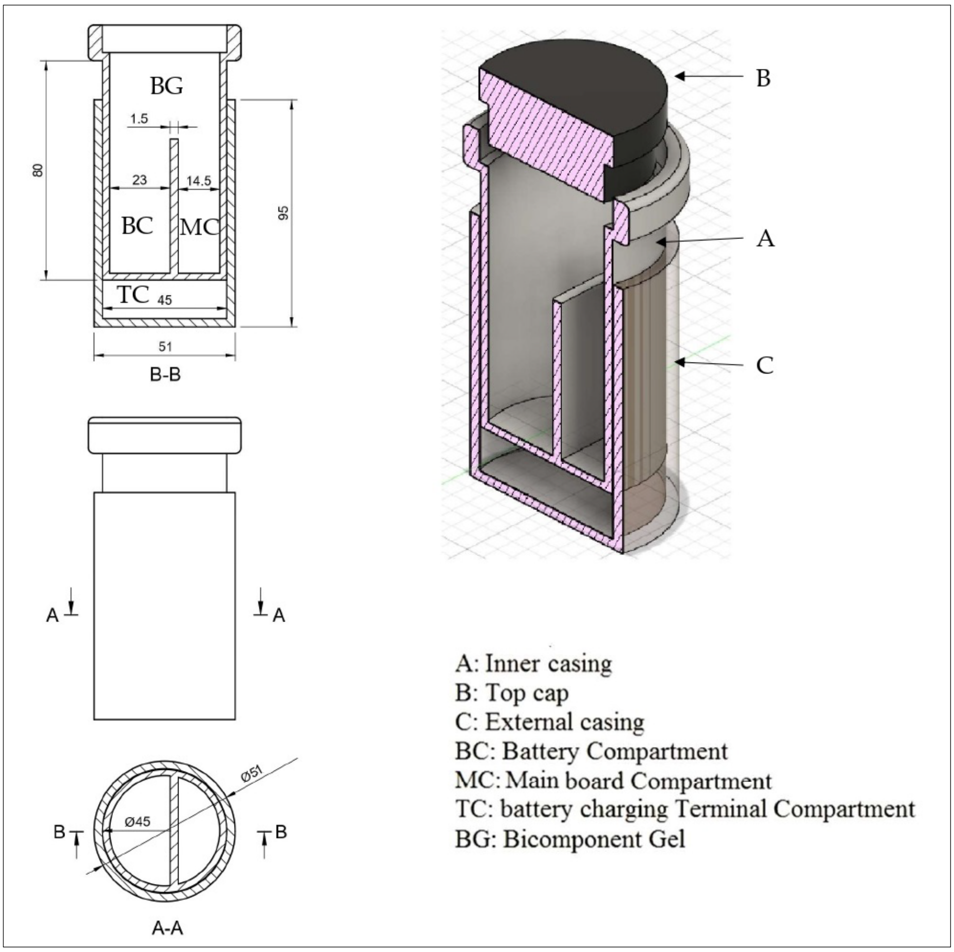


Figure 11. Double-casing assembly.

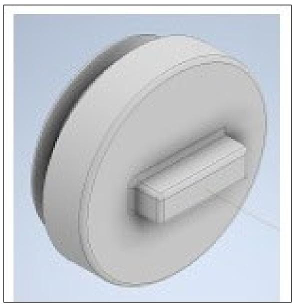


Figure 12. Cap of the external case.

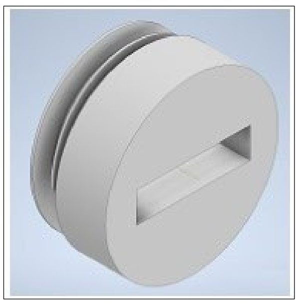


Figure 13. Cap of the inner case.

The printing of this final version of the pedometer was carried out by FDM and performed by a high-quality and high-performance 3D printer: Ultimaker S5 Pro Bundle. The high quality and performance of this printer are ensured by the following technical characteristics:

- Double extrusion ready for composites;
- Filtering capacity of ultrafine particles equal to 95%;
- Storage of the reels of material with controlled humidity;
- Compatibility with over 90 materials.

Once the battery and mainboard were connected and housed in the inner case, the entire compartment was filled with a special bi-component gel with very high dielectric and thermal characteristics (Magic Gel 1000 Ray Tech, Settimo Milanese, Italy). Such a gel, commonly applied to connection systems (joint shells or enclosures) for power cables is aimed at minimizing both the risk of accidental inner disconnections in the electronic circuit and unwanted corrosion phenomena. Table 1 shows the main geometrical dimensions of the prototype components, assumed based on the battery and mainboard sizing.

The double-casing design proposed in this paper makes it possible to remove the inner case from the monitored cow after the pregnancy diagnosis. After recharging the battery, the inner case can be plugged into another external case attached to the leg of another cow that would be monitored for oestrus onset. This solution drastically reduces the number of pedometers to be used in a dairy farm. As an example, in a typical barn of 100 cows with an average oestrus window of 22 days and considering that the average period of oestrus is about 18 h, the average number of cows simultaneously in oestrus is 3.5. Therefore, to identify the oestrus cycle in time, it will be necessary to attach the pedometer to those cows that are believed to be close to oestrus, which is equal to about ten. This means that, by adopting the concept of double-casing, it will be sufficient to purchase just 10 devices, i.e., 10 inner cases, to be exchanged between the cows according to their oestrus cycle, in contrast to the purchase of 100 units of commercial pedometers. At the same unit cost, it is logical to foresee an overall average savings of 90% on the company purchase of pedometers (net of the negligible cost of external case, without onboard electronics and equal to the total number of cows).

Nowadays, each cow housed in a dairy barn is equipped with a commercial pedometer with a non-rechargeable battery that, after about 5-years lifetime, is disposed of, worsening the sustainability of intensive livestock farming because of their non-recyclable and non-biocompatible materials. Indeed, as found by Henriksen and Munksgaard [27], widespread devices such as AFITAG can cause sensitive skin lesions in cows, demonstrating limited biocompatibility over time.

2.4. Pedometer Material Choice

The printing material to be used for the casing was chosen to ensure, in addition to biocompatibility and recyclability [28–30], adequate resistance to both the chemical agents used in the barn environment (CO_2, NH_3, CH_4) and the hard-physical impact due to the behavioral activities of the cows. Especially during the oestrus status, cows' mounting activities could result in hard impacts on the external case.

SDS Nylon supplied by Ultimaker Company was chosen because of the mechanical and physical-chemical properties reported in Table 2. Moreover, this material combines low-density materials, which makes the finished product light with easy printing workability. The eco-sustainable aspect of the design is further supported by specific thermal and manufacturing features of the material. In detail, in addition to being non-degradable, SDS nylon undergoes thermal decomposition for temperatures above 300 °C, reaching the flash point over 400 °C. Its components are compliant with REACH (an acronym for "Regulation concerning the registration, Evaluation, Authorization and restriction of Chemicals"), which is the European regulation for chemicals. Entered into force in 2007 with numbering 1907/2006, this regulation standardizes the law on chemical substances in

Europe and at the same time serves as a searchable database on the potential dangers and risks deriving from various chemical products.

Table 2. Mechanical and physical-chemical properties of SDS Nylon material (Reproduced from [24] with permission from Springer Nature Switzerland AG).

Mechanical Properties	
Poisson ratio	0.4
Elastic Modulus [MPa]	2230
Yield Tensile Strenght [MPa]	62.5
Elongation at Yield [%]	50–75
Physical-Chemical Properties	
Density [g/cm^3]	1.14
Solubility in water	Insoluble
Solubility in other solvents	96% in sulfuric acid
Melting point [°C]	185–195
Thermal decomposition [°C]	>300
Flash point [°C]	>400
REACH/EU	Components compliant with REACH

2.5. The Hardware of the Stand-Alone Smart Pedometer (SASP)

The hardware has been designed to obtain a stand-alone smart pedometer equipped with firmware; which is easily upgradeable and developed to run algorithms based on predetermined accelerometric thresholds. This feature will allow both plug-and-play installation, avoiding the phase of adaptation to animals which is generally required in other commercial systems and on-board computing of threshold values. Therefore, no other IoT devices are required to be installed in the barn other than the stand-alone pedometers.

The basic components required to carry out the functions are a triaxial accelerometer, a mainboard for microcontroller and sensor integration, a unity for power supply, and a communication module. Detailed information on hardware components cannot be provided because of the confidentiality clauses of the research projects that are still in progress.

Based on the different arrangements of the hardware components as well as on animal comfort requirements, changes in progress to the pedometer geometry, which led to different versions before the achievement of the final prototype, were necessary.

3. Functional Evaluation and Coupling Tolerances Assignment

Some changes and additions to the previous version were necessary to make the prototype functional and ready for use in the barns. These are non-structural modifications and, therefore, do not alter the overall mechanical resistance of the pedometer. However, they improve the functionality of the device.

In the final version of the prototype, a cap was provided for the external case to preserve the internal thread during the period of non-use; in which the internal case that houses the onboard sensors is missing because it is mounted on another bovine. As shown in Figure 12, the external cap is equipped with an ergonomic prominence to facilitate manual screwing/unscrewing by the farmer.

On the inner case cap, a socket opening, suitable for inserting the tip of a flathead screwdriver, was made (Figure 13).

The upper part of the inner case was given a hexagonal shape to facilitate manual screwing and unscrewing by the farmer (Figures 14 and 15). Moreover, a horizontal cantilever was added in the separator on the side of the mainboard compartment, to further limit any movement of the mainboard during operation.

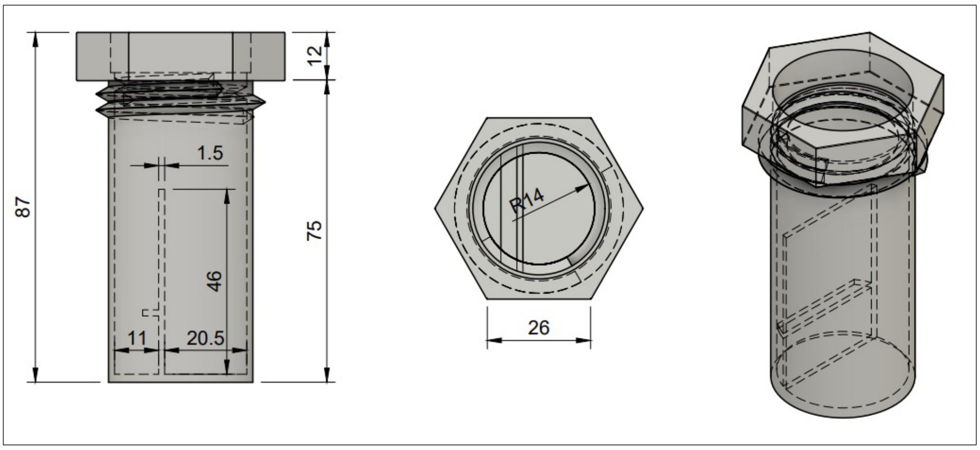


Figure 14. Hexagonal shape for the upper part of the inner case.

Figure 15. Detail of the rounded edges of the inner case.

Two symmetrical axial trapezoidal slots were obtained in the external case for the insertion of a fastening strap (size 38 × 3 mm) (Figure 16). This belt was fixed inside one of the two slots by means of a "drop" shaped wedge at the locking end, allowing a gradual increase in the locking force (Figure 16a). Also, the wedge was made in SDS Nylon. The external case was modeled on the side in direct contact with the cow body by following the anatomy of the foreleg, as shown in Figure 16. The final version of the pedometer is shown in Figure 16. All components of the pedometer are shown in Figure 16b. Figure 16c shows the assembly of the pedometer during the monitoring of the oestrus event and Figure 16d reports the assembly without the internal case adopted by the farmer after the pregnancy diagnosis.

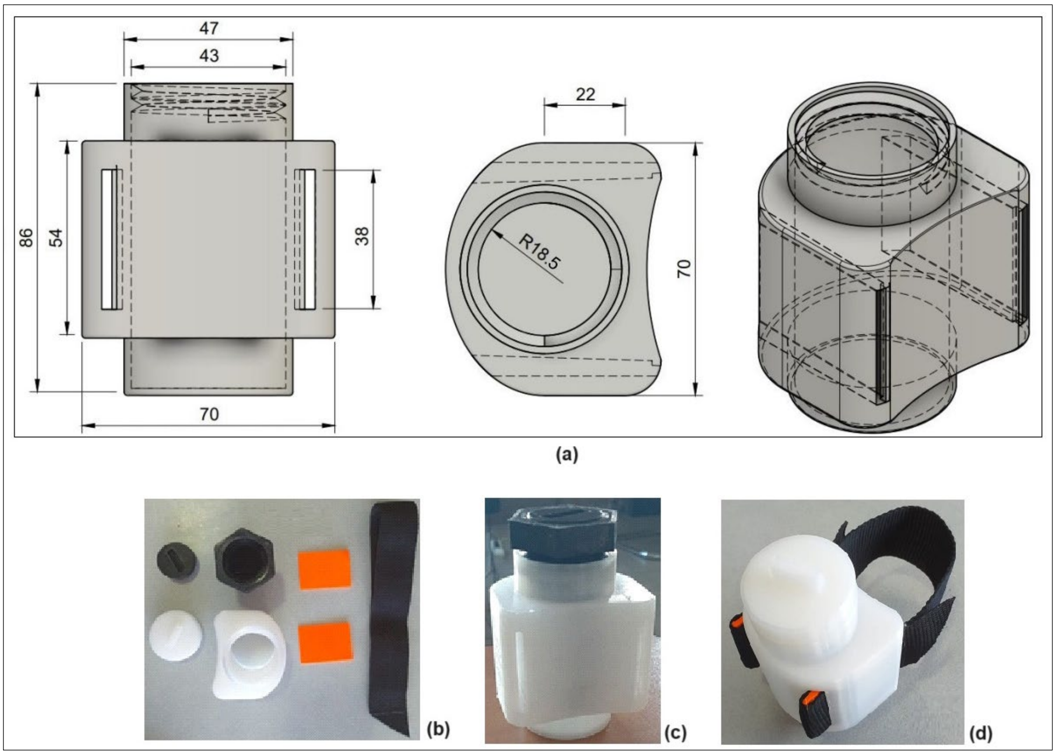


Figure 16. Pedometer final model: (**a**) 3D CAD model of the pedometer; (**b**) single components and belt; (**c**) pedometer assembly ready to be attached to the cow leg during the monitoring of oestrus event; (**d**) pedometer assembly after the pregnancy diagnosis.

4. Main Outcomes from Manufacturing Adoptions

Fused deposition modeling (FDM) is an innovative and widely used technology, which is able to ensure the manufacturing of functional and accurate plastic prototypes over time. As known from scientific literature, the main process parameters (layer thickness, part build orientation, temperature and deposition speed and so on) could significantly affect the dimensional accuracy, roughness and mechanical strength of the realized part [31,32]. Regarding the latter quantity, the numerical investigation performed in this paper has proven the adequate mechanical resistance of the prototype, in terms of both static and impact strength. In this specific application, the roughness of the piece has limited values of Ra = 0.8 µm. The dimensional accuracy achieved by using an Ultimaker 3D printer (Ultimaker, New York, NY, USA) is the most important parameter to be evaluated. Since this depends on the maximum dimension error, the measurement of the main dimensions was carried out on the 3D-printed prototype. For this purpose, a Vogel Germany digital vernier caliper (Kevelaer, Germany) was used, with a full scale of 200 mm and an accuracy of 0.01 mm.

From the comparison between the measured dimensions of the prototype and corresponding nominal values set for the print (Table 1), the maximum error was found in the measurement of the external diameter of the inner case. In detail, the measured value was 44.89 mm vs. the nominal value of 45.00 mm, committing an absolute error of 0.11 mm which is an acceptable value for the current application.

The designed geometries were printed from a stereolithography (STL) file using the mold parameters shown in Table 3. The FDM technique adopted allowed accurate printing without support, avoiding the delicate phase of support removal, and also saving material and time.

Table 3. Main printing parameters adopted.

Parameter	Working Value	Variation Range	Parameter	Working Value	Variation Range
Layer thickness [mm]	0.2	0.1–0.5	Print velocity [mm/s]	20	5–210
Initial thickness [mm]	0.3	0.1–0.6	Filling velocity [mm/s]	50	5–210
Perimeter threads	2	1–∞	Outer wall print velocity [mm/s]	20	5–210
Horizontal expansion %	0	0–100	Lower surface print vel. [mm/s]	30	5–210
N° upper layers	3	1–∞	Movement velocity [mm/s]	100	5–210
N° lower layers	3	1–∞	Lower layers print vel. [mm/s]	25	5–210
Fill density	20	10–30	Print acceleration [mm/s^2]	1000	0–1000
Fill configuration	Zig Zag	–	Feedback distance [mm]	6	0–300
Print temperature [°C]	230	180–240	Feedback velocity [mm/s]	40	30–60
Print bed temperature [°C]	70	20–100	Fan speed %	100	0–100
Flow %	100	0–100	Print bed adhesion type	Brim	–
Initial layer flow %	105	0–100	Brim line number	3	1–∞

The structures were manufactured by enabling the control of the acceleration and variability of the feedback of the head (nozzle). Z Hop was also enabled during print retraction. These settings made it possible to print the prototypes without using support by assigning only two parameters among those available, i.e., the "Layer thickness" and the "Feedback velocity", which are the most critical ones for the accuracy of the printed models as the environmental conditions of temperature and humidity varied.

By using the printing parameters shown in Table 3, it was possible to optimize the values of the "Layer thickness" and the "Feedback velocity" as temperature and humidity changed (Figure 17). The values shown in Figure 17 allow us to print the structures with considerable accuracy.

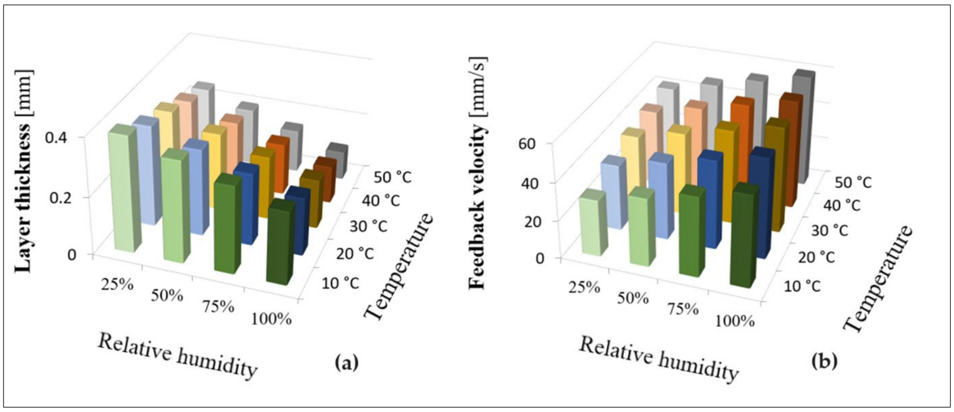


Figure 17. Printing parameters: (**a**) Layer thickness; (**b**) Feedback velocity.

5. Discussion and Conclusions

A novel methodology to implement the eco-design of a recyclable pedometer for dairy cows was presented. Such methodology allowed housing the electronic components required for monitoring cow motor activity during an oestrus event. SASP prototype shape and geometrical dimensions were optimized by 3D Fusion Deposition Modeling (FDP) techniques and numerically validated by a Finite Element Analysis (FEA). The main elements of novelty consist of adopting a double casing and a more suitable and efficient anchor system to the cow leg. In detail, the pedometer has an external shell fixed to one foreleg, with a protective function, and a removable and interchangeable inner case for housing onboard electronics. This feature allows the reuse of the same device on a different animal considered next to the oestrus event, drastically reducing the overall number of pedometers required on a dairy farm. The anchor system to the cow leg, representing one of the most critical parts of the prototype, was modified with a special system equipped with a fastening strap in order to achieve a gradual increase in the locking force. In addition, the part of the device in direct contact with the cow was restricted to the leg profile, respecting the anatomical comfort.

An interesting further step could be represented by the development of a LCA (Life-Cycle Assessment) on the whole prototype proposed, in order to assess the impacts on human health, ecosystem health and natural resources.

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References

1. Mottram, T. Animal board invited review: Precision livestock farming for dairy cows with a focus on oestrus detection. *Anim.* **2015**, *10*, 1575–1584. [CrossRef]
2. Hurnik, J.F.; Webster, A.B.; DeBoer, S. An investigation of skin temperature differentials in relation to estrus in dairy cattle us-ing a thermal infrared scanning technique. *J. Anim. Sci* **1985**, *61*, 1095–1102. [CrossRef] [PubMed]
3. Perez Marquez, H.J.; Ambrose, D.J.; Schaefer, A.L.; Cook, N.J.; Bench, C.J. Infrared thermography and behavioral biometrics associated with estrus indicators and ovulation in estrus-synchronized dairy cows housed in tiestalls. *Int. J. Dairy Sci* **2019**, *102*, 4427–4440. [CrossRef]
4. Blanchard, T.; Kenney, D.; Garcia, M.; Kristula, M.; Wolfer, J.; Haenlein, G. Relationship of declines in grain consumption and milk-yield to estrus in dairy-cattle. *Theriogenology* **1987**, *28*, 407–415. [CrossRef] [PubMed]
5. Schofield, S.A.; Phillips, C.J.C.; Owens, A.R. Variation in the milk-production, activity rate and electrical-impedance of cervical-mucus over the estrus period of dairy cows. *Anim. Reprod. Sci* **1991**, *24*, 231–248. [CrossRef]
6. Muxlov, J. Importance of estrus detection on dairy farms. *Afimilk*, 7 April 2005.
7. Firk, R.; Stamer, E.; Junge, W.; Krieter, J. Automation of oestrus detection in dairy cows: A review. *Livest. Prod. Sci.* **2002**, *75*, 219–232. [CrossRef]
8. Wendl, G.; Klindtworth, K.; Wagner, M. Einsatz von Aktivitatssensoren und injizierbaren Transpondern mit integ-riertem Tem-peratursensor in der Milchviehhaltung. In Proceedings of the 46th Annual Meeting of the European Association of Animal Production, Prague, Czech Republic, 5–8 September 1995.
9. Kiddy, C.A. Variation in physical activity as an indicator of oestrus in dairy cows. *Int. J. Dairy Sci.* **1977**, *60*, 235–243. [CrossRef]
10. Williams, W.F.; Yver, D.R.; Gross, T.S. Comparison of oestrus detection techniques in dairy heifers. *Int. J. Dairy Sci.* **1981**, *64*, 1738–1741. [CrossRef]
11. Yang, Y. *Rechnergestutzte Ostrusuberwachung bei Milch-kuhen unter Anwendung der Fuzzy-Logic-Methode*; Institut für Landtechnik der Technischen Universität: München, Germany, 1998.
12. De Mol, R.M.; Kroeze, G.H.; Achten, J.M.F.H.; Maatje, K.; Rossing, W. Results of a multivariate approach to automated oestrus and mastitis detection. *Livest. Prod. Sci.* **1997**, *48*, 219–227. [CrossRef]

13. De Mol, R.M.; Keen, A.; Kroeze, G.H.; Achten, J.M.F.H. Description of a detection model for oestrus and diseases in dairy cattle based on time series analysis combined with a Kalman filter. *Comput. Electron. Agric.* **1999**, *22*, 171–185. [CrossRef]
14. Eradus, W.J.; Rossing, W.; Hogewerf, P.H.; Benders, E. Signal processing of activity data for oestrus detection in dairy cattle. In Proceedings of the International Symposium on Prospects for Automatic Milking, Wageningen, The Netherlands, 23–25 November 1992.
15. Deluyker, H.A.; Shumway, R.H.; Wecker, W.E.; Azari, A.S.; Weaver, L.D. Modeling milk yield in Holstein cows using time series analysis. *Int. J. Dairy Sci* **1990**, *73*, 539–548. [CrossRef]
16. Mottram, T. Automatic monitoring of the health and metabolic status of dairy cows. *Livest. Prod. Sci.* **1997**, *48*, 209–217. [CrossRef]
17. Makridakis, S.; Wheelwright, S.C.; McGee, V.E. Forecasting: Methods and Applications. *J. Oper. Res. Soc.* **1984**, *35*, 79.
18. Peter, A.T.; Bosu, W.T.K. Postpartum ovarian activity in dairy cows: Correlation between behavioural oestrus, pedometer measurements and ovulations. *Theriogenology* **1986**, *26*, 111–115. [CrossRef] [PubMed]
19. Koelsch, R.K.; Aneshansley, D.J.; Butler, W.R. Analysis of activity measurement for accurate estrus detection in dairy-cattle. *J. Agric. Eng. Res.* **1994**, *58*, 107–114. [CrossRef]
20. Van Vliet, J.H.; Van Eerdenburg, F.J.C.M. Sexual activities and oestrus detection in lactating Holstein cows. *Appl. Anim. Behav. Sci.* **1996**, *50*, 57–69. [CrossRef]
21. Brehme, U.; Stollberg, U.; Holz, R.; Schleusener, T. ALT pedometer—New sensor-aided measurement system for improvement in oestrus detection. *Comput. Electron. Agric.* **2008**, *62*, 73–80. [CrossRef]
22. Arcidiacono, C.; Mancino, M.; Porto, S.M.C. Moving mean-based algorithm for dairy cow's oestrus detection from uniaxial-accelerometer data acquired in a free-stall barn. *Comput. Electron. Agric.* **2020**, *175*, 105498. [CrossRef]
23. Porto, S.M.C.; Bonfanti, M.; Midolo, G.; Castagnolo, G.; Valenti, F.; Arcidiacono, C.; Cascone, G. Preliminary outcomes of a low-power cow oestrus detection system in dairy farms. In Proceedings of the 10th European Conference on Precision Livestock Farming ECPLF 2022, Vienna, Austria, 29 August–2 September 2022.
24. Bonfanti, M.; Cascone, G.; Porto, S.M.C. Proposal for a double-casing prototype of a pedometer for dairy cows, made to be in-terchangeable, through numerical investigation and 3D modeling of geometry. In Proceedings of the 31st International Conference on Flexible Automation and Intelligent Manufacturing FAIM 2022, Detroit, MI, USA, 19–23 June 2022.
25. Haines, L. Boffins Debunk Cow-Tipping Myth. *The Register*, 9 November 2005.
26. Heinrichs, A.J.; Hargrove, G.L. Standards of Weight and Height for Holstein Heifers. *Int. J. Dairy Sci* **1987**, *70*, 653–660. [CrossRef]
27. Henriksen, C.J.; Munksgaard, L. Validation of AfiTagII, a device for automatic measuring of lying behaviour in Holstein and Jersey cows on two different bedding materials. *Animal* **2017**, *13*, 617–621. [CrossRef]
28. Calì, M.; Pascoletti, G.; Gaeta, M.; Milazzo, G.; Ambu, R. A new generation of bio-composite thermoplastic filaments for a more sustainable de-sign of parts manufactured by FDM. *Appl. Sci.* **2020**, *10*, 5852. [CrossRef]
29. Calì, M.; Pascoletti, G.; Gaeta, M.; Milazzo, G.; Ambu, R. New filaments with natural fillers for FDM 3D printing and their applications in bio-medical field. *Procedia Manuf.* **2020**, *51*, 698–703. [CrossRef]
30. Aida, H.J.; Nadlene, R.; Mastura, M.T.; Yusriah, L.; Sivakumar, D.; Ilyas, R.A. Natural fibre filament for Fused Deposition Modelling (FDM): A review. *Int. J. Sustain. Eng.* **2021**, *14*, 1988–2008. [CrossRef]
31. Garg, A.; Tai, K.; Savalani, M.M. State-of-the-art in empirical modelling of rapid prototyping processes. *Rapid Prototyp. J.* **2014**, *20*, 164–178. [CrossRef]
32. Baturynska, I.; Semeniuta, O.; Martinsen, K. Optimization of Process Parameters for Powder Bed Fusion Additive Manufacturing by Combination of Machine Learning and Finite Element Method: A Conceptual Frame-work. *Procedia CIRP* **2018**, *67*, 227–232. [CrossRef]