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An Empirical Evaluation Framework for Autonomous Vacuum Cleaners in Industrial and Commercial Settings: A Multi-Metric Approach

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Abstract

Despite advancements in cleaning automation, there is a noticeable gap in standardized evaluation methods for autonomous vacuum cleaners in industrial and commercial settings. Existing assessments often lack a unified approach, focusing narrowly on either technical capabilities or financial aspects, without integrating both perspectives. This research presents a framework for the evaluation of autonomous vacuum cleaners in industrial and commercial settings, focusing on eight key metrics. These metrics are designed to provide a unified empirical perspective of the vacuum cleaners' performance, operational efficiency, cost, productivity, durability, safety, return on investment, and adaptability. The proposed framework starts with an analysis of cleaning efficiency, examining both the area covered by the cleaners and the quality of cleaning. Advanced image processing techniques are suggested for mapping the area coverage, tailored to different vacuum designs. For assessing cleaning quality, the proposal highlights the potential integration of real-time dirt detection technologies, such as gravimetric sampling and light sensors, to dynamically adapt to varying dirt concentrations and types. Operational efficiency part encompasses the assessment of battery life, charge time, and operational downtime. It advocates for a dual approach of empirical testing and analytical modeling to measure battery life and charge time accurately. The evaluation of operational downtime incorporates tracking of maintenance, charging periods, and other non-operational activities, complemented by predictive modeling for efficient future planning. The financial aspect of the proposed framework encompassed under cost metrics, considers the initial investment, operational and maintenance costs, and potential labor cost savings. This study argues that these cost analysis aids in understanding the long-term financial implications of adopting autonomous vacuum cleaners. Productivity metrics focus on the cleaning speed and the level of autonomy of the vacuum cleaners. Cleaning speed is evaluated using formulas that take into account various environmental factors, while the autonomy level is determined using Sheridan's Levels of Autonomy, which reflects the vacuum's operational independence and its impact on human productivity. Durability, reliability, safety, and compliance are key for vacuum cleaners, evaluated through metrics like Mean Time Between Failures, Mean Time To Repair, Service Life, safety incidents, and adherence to standards and regulations. Lastly, the suggested framework evaluates the vacuum's flexibility and adaptability in different environments, such as various floor types and conditions, highlighting the importance of versatility in autonomous cleaning solutions.

Keywords: *Adaptability, Autonomous Vacuum Cleaners, Efficiency, Evaluation Framework, Industrial and Commercial, Performance Metrics, Safety Standards*

Introduction

Vacuuming task is both necessary and time-consuming. To meet the needs of contemporary life for more streamlined and automated solutions, autonomous vacuum cleaners have gained popularity. These devices are outfitted with sophisticated navigation systems, various sensors, and smart algorithms, enabling them to vacuum floors with minimal human intervention. The move from traditional manual vacuuming to the use of autonomous vacuum cleaners signifies a major change in home management. These vacuum cleaners not only provide the benefit of hands-free operation but also represent a step towards more interconnected and technologically advanced domestic environments. The rise of autonomous vacuum cleaners highlights the expanding role of robotic technology in daily life. Initially simple automated devices, these vacuum cleaners have developed into complex systems that can navigate through complex room layouts, adapt to different floor types, and self-charge. Their appeal lies in the convenience and time-saving benefits they offer, as well as their ability to maintain a consistent level of cleanliness.

The application of autonomous cleaning devices extends well beyond the confines of domestic environments. There exists substantial potential for their deployment in public and commercial spaces such as schools, auditoriums, and shopping malls. In these settings, the efficiency, consistency, and labor-saving attributes of these robots become even more pronounced. The adaptation of robotic cleaning technology to these environments reflects an understanding of the diverse requirements and challenges inherent in maintaining larger, more frequented spaces. The potential for these robots to operate outside of standard business hours and with minimal supervision makes them particularly suited to such applications. Furthermore, their use in public spaces can contribute to higher standards of cleanliness and hygiene, a consideration that is increasingly important in contemporary society [1].

Various components are integral to the functioning of autonomous systems. These include actuators, which are responsible for movement; sensors, which provide the robot with information about its environment; mechanical control devices used in the physical operation of the robot; and microcontrollers, which serve as the brain of the robot, processing inputs and dictating responses. The control of these robots is governed by sophisticated algorithms. These can include fuzzy controllers, which handle uncertain or imprecise information; machine learning-based practices, which enable the robot to learn from and adapt to its environment; and artificial neural network-based algorithms, which mimic the decision-making processes of the human brain.

On the technical front, autonomous vacuum cleaners are comprised of several key components that collectively enable their functionality. The chassis or platform forms the base of the unit, housing the electric motor and fan unit, which generates the suction necessary for cleaning. The inclusion of a nozzle and hose facilitates targeted cleaning, while the dust collection unit or dust bag and filter system ensure the effective capture and containment of dirt and debris. Beyond these physical components, the efficacy depends on its cleaning system, sensor array, and navigation strategy. The cleaning system determines the method and efficiency of dirt removal, the sensor array enables the robot to perceive and react to its environment, and the navigation strategy ensures the cleaner covers the cleaning area effectively.

A cornerstone of their design is the sensory apparatus used in navigation and environment mapping. Advanced models employ a combination of infrared and ultrasonic sensors, LIDAR (Light Detection and Ranging) systems, and sometimes even cameras. These sensors enable the vacuum to detect and avoid obstacles, map the cleaning area, and adapt to changes in the environment. For instance, infrared sensors are typically used to detect obstacles and cliffs, preventing the vacuum from colliding with furniture or falling down stairs. LIDAR systems, on the other hand, are often employed in more sophisticated models for precise spatial mapping, allowing the vacuum to navigate through complex environments with greater efficiency.

Table 1. key components of autonomous vacuum cleaners

Component Category	Description
Sensory Apparatus	Incorporates infrared and ultrasonic sensors, LIDAR systems, and sometimes cameras. Enables obstacle detection, area mapping, and environment adaptability. Infrared sensors prevent collisions and falls, while LIDAR is used in advanced models for precise spatial mapping.
Computational Systems	Centralized around a microcontroller or microprocessor. Executes navigation and cleaning algorithms based on sensor data and user input. Advanced models use AI and machine learning to optimize cleaning patterns. Manages battery usage and power systems, ensuring efficient operation and autonomous return to charging docks.
Mechanical and Power Systems	Consists of electric motors, battery, and mechanical parts like brushes and filters. Brushless DC motors are preferred for their efficiency and low noise. Lithium-ion batteries provide a balance of weight, capacity, and charge cycles. Design considerations include maintenance ease, with accessible replaceable parts for long-term effectiveness.

The computational and control systems of an autonomous vacuum cleaner are what truly set it apart from traditional cleaning devices. At the heart of these systems is a microcontroller or microprocessor, which acts as the brain of the vacuum cleaner. This processor executes the software algorithms that control the machine's navigation and cleaning patterns. These algorithms are based on data from the sensory apparatus and input from user settings. Advanced models incorporate AI and machine learning techniques to improve cleaning efficiency over time, learning from past cleaning sessions to optimize their cleaning patterns. The control system also manages the battery usage and power systems, ensuring that the vacuum operates efficiently and returns to its charging dock when necessary. This aspect of the design is critical for user convenience, as it enables the vacuum to operate autonomously without requiring constant human intervention.

The third key component of an autonomous vacuum cleaner is its mechanical and power systems. These systems include the electric motors that drive the wheels and the vacuum mechanism, the battery, and various other mechanical parts such as brushes and filters. The motor selection is crucial for balancing power, efficiency, and noise levels. Brushless DC motors are commonly used due to their efficiency, reliability, and lower noise output compared to brushed motors. The battery, usually a lithium-ion type, is selected for its balance between weight, capacity, and charge cycles, providing enough power for the vacuum to complete its tasks while maintaining a compact and lightweight design. The mechanical design also includes considerations for maintenance, such as easy access to replaceable parts like filters and brushes, ensuring that the vacuum remains effective over its operational lifespan.

In evaluating the performance of vacuum cleaners, a common metric is the comparison of input power across different models. This power rating, however, is just one of several parameters that influence the design and selection of a vacuum cleaner. Other critical factors include the dust pickup factor, which determines the efficiency of the cleaner in removing dirt from surfaces; dust storage capacity, which impacts the frequency of maintenance; cleaning surface, which dictates the type of surfaces the cleaner can effectively handle; and the size, weight, and storage considerations, which affect the practicality and ease of use of the device.

Autonomous vacuum cleaners have become increasingly relevant in industrial and commercial settings, offering numerous advantages. In industrial environments, these devices are particularly valuable for their efficiency and consistency. They are programmed to operate autonomously, which means they can clean large areas without human intervention. This feature is especially beneficial in facilities such as warehouses and manufacturing plants, where the expanse of the area can make manual cleaning time-consuming and labor-intensive. Autonomous vacuum cleaners can be scheduled to operate during off-hours, ensuring that the cleaning process does not interfere with the daily operations of the facility. Additionally, their ability to operate independently reduces the need for a large cleaning staff, which can lead to significant savings in labor costs.

Industrial settings in this study refers to environments associated with manufacturing, production, or large-scale operations. These include factories, warehouses, power plants, and other facilities where goods are produced or processed. These settings are distinguished by their expansive physical spaces, often covering large floor areas essential for housing heavy machinery and equipment. The operations within these environments are primarily focused on handling raw materials, engaging in production processes, and managing assembly lines. Given the nature of these activities, industrial settings are often more hazardous, owing to the presence of heavy machinery, chemicals, or intensive operations.

Table 2. Autonomous vacuum cleaners in industrial and commercial settings:

Aspect	in Industrial Settings	in Commercial Settings
Efficiency and Consistency	Clean large areas autonomously, reducing time and labor especially in warehouses and manufacturing plants.	Minimize disruption, adapt to foot traffic, and maintain cleanliness in high-traffic areas.
Operational Flexibility	Can be scheduled during off-hours to not interfere with daily operations. Reduces the need for a large cleaning staff.	Adjust cleaning schedule or path in real-time based on foot traffic. Contributes to a pleasant environment.
Health and Safety	Address dust and debris hazards; equipped with advanced filtration systems to improve air quality.	Ensure high hygiene levels in areas like food courts and restrooms, reducing contamination risks.
Technological Integration	Equipped with sensors and cameras for efficient cleaning and data collection to optimize cleaning schedules.	Data collection helps understand usage patterns and adjust maintenance strategies.
Environmental Impact	More energy-efficient than traditional equipment, reducing electricity consumption and resource usage.	Enhance business reputation by using eco-friendly cleaning solutions.

On the other hand, *commercial settings* in this study means spaces used for business purposes, but are more public-facing than industrial settings. These include shopping malls, office buildings, educational institutions, hotels, and healthcare facilities. The defining features of commercial settings include areas that are regularly frequented by the public or employees, such as offices, retail spaces, and communal areas. These environments prioritize maintaining a clean, professional, and welcoming appearance to enhance the experience of visitors and employees. The foot traffic in these areas varies, with distinct patterns of peak and off-peak hours.

In industrial settings, the accumulation of dust and debris can be a significant health hazard, potentially leading to respiratory issues for workers. Autonomous vacuum cleaners can be equipped with advanced filtration systems, capable of capturing fine particles and improving air quality. This is particularly important in industries where air quality is a concern, such as woodworking or textile manufacturing. In commercial spaces, maintaining a high level of cleanliness is essential for public health, especially in areas like food courts and restrooms. The consistent and efficient operation of autonomous vacuum cleaners ensures that these areas remain hygienic, reducing the risk of contamination and spread of illness.

Another significant advantage of autonomous vacuum cleaners in these settings is their technological integration and data collection capabilities. Many modern robotic vacuums are equipped with sensors and cameras, allowing them to navigate complex environments and avoid obstacles. This technology not only ensures efficient cleaning but also enables the collection of valuable data about the space, such as high-traffic areas or regions that require more frequent cleaning. In industrial settings, this data can be used to optimize the cleaning schedule and ensure that all areas receive adequate attention. In commercial spaces, the data can help facility managers understand patterns of use and adjust maintenance and operational strategies accordingly.

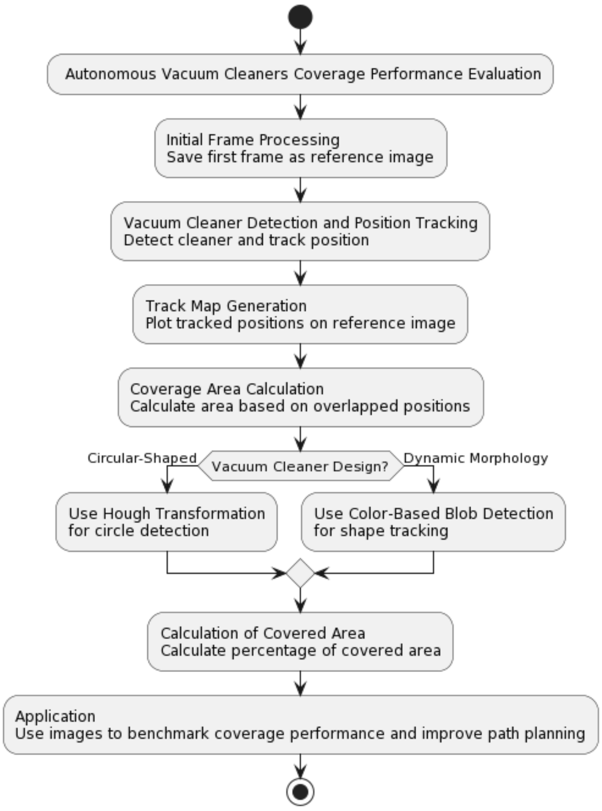
The environmental impact of cleaning processes is an ever-growing concern, and autonomous vacuum cleaners offer a more sustainable solution. They are typically more energy-efficient than traditional, large-scale cleaning equipment, reducing electricity consumption. Additionally, their precision and efficiency mean that they can achieve the same level of cleanliness with fewer resources, such as water and cleaning chemicals. This is particularly relevant in industries that are striving to reduce their environmental footprint. In commercial settings, the use of energy-efficient and eco-friendly cleaning solutions can also enhance the reputation of the business, appealing to environmentally conscious consumers and contributing to a broader corporate social responsibility strategy.

1. Cleaning Efficiency Metrics

Area Coverage: Square footage cleaned per unit of time.

The described process is shown in Figure 1. is formulated for evaluating the area coverage performance of autonomous vacuum cleaners in industrial and commercial settings using image processing techniques. Initially, the process involves initial frame processing, where the first frame from a video sequence is saved as a reference image to generate a track map. This is followed by the detection and position tracking of the autonomous vacuum cleaner, where its position is detected and tracked continuously in each frame. The subsequent step is track-map generation, where the tracked positions of the vacuum cleaner are plotted on the reference image to create a track-map.

Figure 1. autonomous vacuum cleaners in industrial and commercial settings



The coverage area calculation is then performed by calculating the area covered by the vacuum cleaner based on the overlapped positions on the reference image. Specific techniques are employed for different vacuum cleaner designs. For circular-shaped vacuum cleaners, the *Hough transformation* method can be used for circle detection to identify the cleaner's center, and a green circle is drawn on the reference image at these coordinates. For vacuum cleaners with dynamic morphology, a color-based blob detection method can be employed, involving detecting specific-colored markers on the cleaner in each frame (e.g. with green markers plotted on the reference image to represent the cleaner's coverage area). The percentage of the area covered is calculated using following equations that involve identifying the green pixels on the track map on the reference image [2]

$$Percentage\ of\ area\ covered = \frac{Pixel\ area\ of\ the\ robot}{Total\ pixel\ area\ of\ the\ testing\ field} \times 100$$

$$Percentage\ of\ area\ covered = \frac{Pixel\ area\ of\ the\ robot}{Total\ pixel\ area\ of\ the\ testing\ field - Total\ pixel\ area\ of\ the\ obstacles} \times 100$$

The images generated through this process are then used to benchmark the area coverage performance of the autonomous vacuum cleaners, with a future aim to improve global and local path planning for these cleaners in industrial and commercial environments. This method offers a precise and automated way to assess the effectiveness of different autonomous vacuum cleaner models in covering their designated cleaning areas.

Cleaning Quality: Percentage of dirt, dust, and debris removed from surfaces.

Currently, most robotic vacuum cleaners operate without actively identifying the concentration or type of dirt they encounter. This lack of information limits their ability to adapt cleaning patterns based on the specific needs of different areas within a home. If these robots could report the real-time pickup of dirt, it would not only inform the user about the cleanliness levels of various parts of their home but also potentially uncover underlying causes for certain areas being dirtier than others [3]. For example, a user might discover that certain spots in their home accumulate more dust due to external factors like ventilation or foot traffic. This data could also be useful for the robot itself, allowing it to create more efficient cleaning patterns by focusing on areas that consistently show higher levels of dirt accumulation. Essentially, this capability would transform robotic cleaners from blind, path-following devices into intelligent, adaptive cleaning systems.

Table 3. various sensing and measurement technologies for measuring techniques for the dirt pick-up in real time

Technique	Description	Advantages	Disadvantages
Gravimetric Sampling	Dirt collected on a filter, weighed before and after sampling to measure dirt amount.	Highly accurate and robust for measuring dirt concentration; standard for PM2.5 particle measurement.	Time delay in data availability; not suitable for real-time measurement or short sampling periods.
Microphone	Microphone in vacuum cleaner's intake valve records dirt flow noise.	Simple setup and operation.	Susceptible to external noise; difficulty detecting fine dust; microphone contamination over time.
Strain Gauge	Measures weight of picked-up dirt using a strain gauge or load cell.	Easy method for measuring weight.	Inaccurate with varying dirt compositions; cannot differentiate between different types of dirt.
Dust Sensors	Off-the-shelf sensors measuring ambient air dust.	Designed to measure dust in air.	Not suitable for high-velocity, larger dirt particles; sensors can be obstructed by large or stringy dirt.
Light Sensors	Measures dirt intake using light scattering and absorption principles.	Simple technique based on light intensity reduction.	Requires specific setup for effective measurement.

The potential for implementing real-time dirt detection in robotic vacuums invites the exploration of various sensing and measurement technologies [4]. *Gravimetric sampling*, where dirt is collected on a filter and weighed before and after sampling, offers high accuracy and robustness in measuring dirt concentration. It is a standard method for measuring particles like PM2.5. This technique has a significant drawback in its delay in data availability, making it unsuitable for real-time measurement or for short sampling periods. Another approach is using a microphone in the vacuum cleaner's intake valve to record the noise of dirt flow. This method is simple to set up and operate, but it is susceptible to external noise and has difficulty detecting fine dust. Additionally, the microphone can become contaminated over time. Strain gauges or load cells to measure the weight of picked-up dirt offers an easy method for measuring weight. However, they may be inaccurate with varying dirt compositions and cannot differentiate between different types of dirt.

Other techniques include the use of off-the-shelf dust sensors and light sensors. Dust sensors, designed to measure dust in the air, may not be suitable for high-velocity or larger dirt particles and can be obstructed by large or stringy dirt. Light sensors, which measure dirt intake using light scattering and absorption principles, require a specific setup for effective measurement. While this method is simple and based on the reduction of light intensity, it may not be as effective in different environmental conditions or with various types of dirt.

2. Operational Efficiency Metrics

Battery Life: Duration of operation on a single charge.

The battery life of a vacuum cleaner, defined as the duration of operation on a single charge, is used in assessing its performance and convenience. Empirical testing is the most straightforward and reliable method to gauge this parameter. In this approach, the vacuum is operated continuously until the battery is completely depleted. This test is conducted under controlled conditions, which means using standardized flooring types, such as hardwood, carpet, and tiles, and evenly distributed debris, to simulate typical household environments. This standardization ensures that the test results are consistent and replicable. Additionally, if the vacuum cleaner offers variable power settings, it is essential to test the battery life at each of these settings, as the power consumption can vary significantly between them. For instance, a vacuum might last longer on a lower power setting than on a high-power mode, which is critical information for users who may prefer a particular setting based on their cleaning needs.

Another aspect of testing battery life involves analytical modeling, which complements the empirical approach by providing a theoretical estimation of the vacuum's operational time. This model calculates the expected battery life using the vacuum's power consumption rate and battery capacity. The formula used is [5], [6]: $(Battery\ Life = \frac{\text{Battery Capacity (mAh)}}{\text{Power Consumption (mA)}})$

This method may not always account for real-world factors such as the efficiency of the motor or the battery's performance under different load conditions. Therefore, it is essential to compare these analytical results with empirical data to get an accurate understanding of the vacuum's battery life. Moreover, considering the variability in battery performance and potential degradation over time, it is recommended to conduct these tests multiple times and average the results. This repetition ensures that the estimated battery life is more accurate and reflective of the vacuum's performance over its lifespan. Combining both empirical testing and analytical modeling can provide a robust and realistic estimate of the vacuum cleaner's battery life.

Charge Time: Time required to fully charge the vacuum.

The measurement of charge time, which is the duration required to fully charge a vacuum cleaner's battery, is a critical aspect in evaluating the practicality and efficiency of the device. The most direct method to ascertain this parameter is through direct measurement. This involves timing how long it takes to charge the battery from a completely depleted state to full capacity. Such a process, while straightforward, demands precision and consistency in the testing environment. To ensure accuracy, the battery must be fully drained before each charging session, and the charging should be conducted using the vacuum's standard charger under consistent environmental conditions. The direct measurement approach, however, should be repeated multiple times. This repetition is necessary because charging times can vary due to factors like fluctuations in power supply, ambient temperature, or minor variations in the battery's condition. With averaging the results from multiple tests, a more reliable estimate of the vacuum's typical charge time can be obtained.

Alongside direct measurement, analytical estimation offers a theoretical perspective on the expected charge time. This estimation is calculated using the formula [7], [8]:

$$Charge\ Time = \frac{\text{Battery Capacity (mAh)}}{\text{Charger Current (mA)}}$$

This formula assumes ideal charging conditions and provides a baseline estimate under optimal circumstances. This method may not fully account for real-world factors that can affect charging efficiency. For instance, some energy is invariably lost as heat during the charging process, which can extend the actual charge time beyond the theoretical estimate. Additionally, the age and health of the battery play a significant role; older batteries or those that have undergone numerous charge cycles may exhibit increased resistance, leading to longer charging times. Thus, while analytical estimation provides a useful theoretical framework, it is essential to compare these results with those obtained from direct measurement to gain a complete understanding of the vacuum's charging characteristics.

Operational Downtime: Time spent not cleaning due to maintenance, charging, or other non-operational reasons.

Operational downtime refers to the time during which the device is not actively cleaning due to various factors such as maintenance, charging, or software updates. To accurately gauge this downtime logistical analysis can be employed. This method entails tracking the total time spent on various non-operational activities over several cleaning cycles. For instance, maintenance tasks like filter cleaning or replacement are recorded in detail, as these are recurring necessities that contribute significantly to operational downtime. Similarly, the time taken for each charging cycle is documented, acknowledging that charging duration can vary based on factors like battery capacity and charger efficiency. This data collection extends to other forms of downtime, such as those caused by software updates or unexpected repairs. The aim is to gather a view of all the factors contributing to the time when the vacuum is unavailable for its primary function of cleaning.

Predictive modeling involves creating a model based on average maintenance schedules, typical charge times, and other known causes of downtime. Predictive modeling serves as a tool to forecast future downtime, aiding in efficient planning and utilization of the vacuum cleaner. For instance, by analyzing patterns from collected data, it becomes possible to predict when maintenance tasks are likely to be needed, or how often charging should occur based on usage patterns. This foresight can be beneficial for commercial settings where vacuum cleaners are used more intensively, and downtime can significantly impact productivity. Predictive models can also adapt and improve over time with the integration of more data to get accurate predictions that can help in scheduling maintenance and charging activities in a way that minimizes disruption to cleaning operations.

Operational downtime varies significantly based on individual usage patterns and maintenance habits. For instance, a household with pets might require more frequent filter cleanings due to pet hair, whereas a less frequently used vacuum in a smaller space may have considerably less downtime. This variability shows the importance of standardized testing conditions and statistical analysis in the evaluation process. Conducting tests under similar environmental and operational conditions ensures comparability of data, while statistical methods provide a means to analyze and interpret this data, taking into account the variability and drawing more accurate conclusions.

3. Cost Metrics

The adoption of autonomous vacuum cleaners represents a significant range of cost considerations. The initial investment is the first and most apparent cost category as shown in table 4. This includes the purchase price of the autonomous vacuum cleaner, which can vary widely based on the model, brand, and the technology it employs. Advanced features like enhanced navigation systems, superior suction power, and larger dustbin capacities often lead to higher prices. Some models are designed for specific tasks, like pet hair removal or allergy-friendly filtration, which can also influence the cost. Additionally, the installation cost, although generally minimal for most residential autonomous vacuums, can be a factor in more complex commercial setups. This might involve additional expenditures for compatible accessories or modifications to the cleaning environment to optimize the vacuum's performance, such as setting up virtual barriers or docking stations.

Table 4. cost metrics for autonomous vacuum cleaners

Cost Category	Detailed Items
Initial Investment	Purchase Price: Base cost, feature-based price variations, charges for premium models
	Installation Cost: Professional installation fees, additional equipment or modifications
Operational Costs	Electricity: Power consumption costs during operation and charging
	Replacement Parts: Filters, brushes, batteries, brand-specific parts
	Software Updates: Fees for major upgrades, subscription costs for additional features
Maintenance Costs	Regular Maintenance: Routine cleaning of filters, brushes, dustbins, inspections
	Unexpected Maintenance: Repairs for malfunctions, service fees, replacement parts
Labor Cost Savings	Reduction in Manual Cleaning: Estimation of labor hours saved, reduced need for cleaning staff
	Efficiency Increase: Time efficiency, operating outside regular working hours, long-term equipment savings
	Indirect Savings: Reduction in other cleaning tools, increased lifespan of flooring and carpets

Operational costs form the second category of expenses associated with autonomous vacuum cleaners. Electricity consumption, while typically lower than that of traditional vacuums, still constitutes a recurring cost, especially in settings where the vacuum is used extensively or continuously. Replacement parts are another ongoing expense. Parts like filters, brushes, and, eventually, batteries will need to be replaced periodically to maintain optimal functioning. The frequency and cost of these replacements depend on the model and usage intensity. Moreover, software updates – especially in high-end models – might incur additional costs. These updates are crucial for maintaining the efficiency and effectiveness of the cleaning algorithms, and in some cases, for accessing new features that enhance the vacuum's capabilities.

Maintenance costs, both regular and unexpected, are the third significant financial aspect. Regular maintenance, which includes tasks like cleaning filters and brushes or emptying dustbins, is usually straightforward but essential to ensure the vacuum operates at peak efficiency. While this routine maintenance might not incur high costs, it does require consistent attention. Unexpected maintenance encompasses repairs for malfunctions or breakdowns that are not covered by the warranty. Professional service fees and the cost of replacement parts can add up, particularly for more sophisticated models. In addition to these direct costs, the introduction of autonomous vacuum cleaners can lead to significant labor cost savings, especially in commercial or industrial settings. The reduction in manual cleaning labor can be substantial, as these devices operate autonomously and can even be scheduled to clean during off-hours, enhancing efficiency. Over time, these savings can offset the initial investment and operational costs. Again, the regular and gentle cleaning provided by these vacuums can extend the life of flooring and carpets, leading to indirect savings by reducing the frequency of deep cleaning and floor replacement.

4. Productivity Metrics

Cleaning Speed: Area cleaned per hour

Understanding the time dynamics and efficiency of cleaning processes is essential. This understanding becomes particularly important when dealing with large, unoccupied spaces where the efficient use of time and resources can significantly impact overall productivity. To efficiently manage the cleaning of large, unoccupied spaces using a vacuum cleaner, a set of mathematical formulas can be applied, as shown in table 5. The process begins with calculating the total area that needs cleaning, found by multiplying the length and width of the space. Then, the cleaning speed of the vacuum is determined [9], [10]. This speed is calculated based on the wheel radius and the wheels' RPM, converted to a per-minute rate.

The next step involves calculating the time required to clean the length of the room, which is the room's length divided by the cleaning speed. An additional calculation is needed to determine the number of passes the vacuum must make to cover the entire room. This is based on the room's width and the cleaning width of the vacuum. The total cleaning time for the entire room is then found by multiplying the number of passes with the time to clean the length of the room. Finally, the maximum distance that can be cleaned on a full battery is calculated, factoring in the vacuum's cleaning speed and its battery life.

Table 5. determining the time needed to clean an unoccupied space [11]

Formula Category	Symbol	Formula	Description
Estimating Total Area to be Cleaned	A	$A = L \times W$	Calculates the total area the vacuum cleaner needs to clean.
Determining Cleaning Speed	S	$S = R \times (2 \times \pi \times N)/60$	Determines the speed at which the vacuum cleaner operates.
Time Required to Clean a Specific Length	T_L	$T_L = L/S$	Estimates the time to clean along the length of a room.
Calculating Total Number of Passes	P	$P = W/C_W$	Determines the number of passes to cover the entire room.
Total Cleaning Time for the Entire Room	T_total	$T_total = P \times T_L$	Estimates the total time required to clean the entire room.
Distance Cleaned with a Full Battery	D_max	$D_max = S \times R_time$	Calculates the maximum distance cleaned on a full battery.

Note:

- L: Length of room
- W: Width of room
- R: Wheel radius
- N: Wheel RPM
- S: Cleaning speed
- C_W: Cleaning width of the vacuum cleaner
- R_time: Total runtime on a full battery

Autonomous Functionality: Percentage of time the vacuum operates without human intervention.

The concept of autonomy in vacuum cleaners, as delineated by Sheridan's Levels of Autonomy in Decision Making, illustrates a spectrum ranging from complete human control to full automation. At the initial level, the user manually controls every aspect of the vacuum cleaner's operation, embodying a traditional approach where technology acts purely as a tool under human command. At higher levels, the vacuum cleaner begins to play a more active role, initially by suggesting cleaning paths or areas. This gradual transition reflects an increasing reliance on the vacuum cleaner's built-in intelligence, moving from a purely manual device to one that offers guidance and suggestions.

Table 6. Sheridan's Levels of Autonomy in Decision Making in the context of autonomous vacuum cleaners [12], [13]

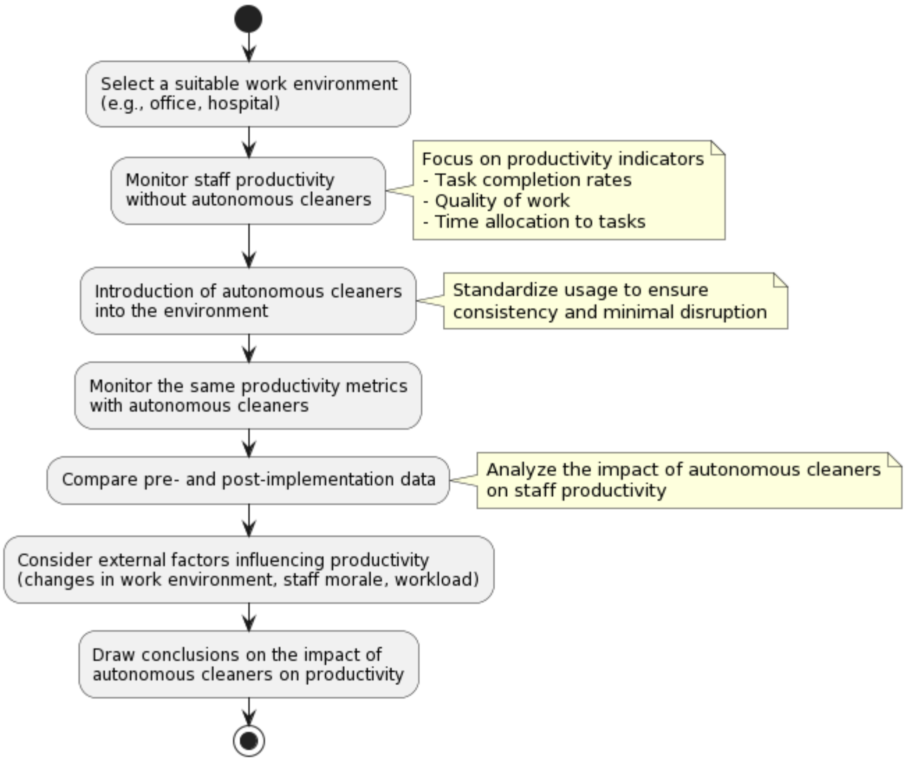
Level	Description
1	100% Human Control: User manually operates the vacuum cleaner, making all decisions.
2	Suggestion of Alternatives: Vacuum suggests cleaning paths or areas, but user manually starts the process.
3	Restricted Alternatives, Human Decision: Vacuum offers limited set of programs or areas, user selects and starts cleaning.
4	Suggested Decision, Human Implementation: Vacuum recommends a specific program or area, user can accept or choose another and start cleaning.
5	Suggested Automated Action, Human Approval: Vacuum selects a program or area and proposes to start automatically, waits for user's approval.
6	Automated Decision, Human Informed: Vacuum autonomously decides and starts a program, but informs user who can stop it.
7	Automated Decision, Informed After Action: Vacuum decides and starts cleaning, informs user after commencement.
8	Automated Decision, Informed if Asked: Vacuum decides and implements program, provides information only if user inquires.
9	Selective Reporting by Computer: Vacuum decides and implements cleaning, decides whether to inform user.
10	Computer Control, Selective Reporting: Vacuum fully controls cleaning, informs user only if it deems necessary.

At the midpoint of the levels, the vacuum cleaner not only suggests but also selects cleaning programs or areas, waiting for the user's approval before proceeding. This represents a significant shift where the device begins to share decision-making responsibilities with the user. In the highest levels of autonomy, the vacuum cleaner completely takes over the cleaning process, making decisions about when, where, and how to clean without requiring human intervention. In these stages, the machine informs the user of its actions either proactively, upon request, or based on its own judgment. This advanced stage of autonomy showcases the vacuum cleaner as an independent agent capable of adapting to its environment and making decisions.

Impact on Human Productivity: Changes in staff productivity due to the implementation of autonomous cleaners.

The assessment of staff productivity changes due to the implementation of autonomous cleaners in a workplace environment. The process begins by selecting a suitable work environment, such as an office or a hospital, where the impact of autonomous cleaners can be feasibly observed. During the initial phase, staff productivity is monitored without the presence of autonomous cleaners. This phase focuses on recording various productivity indicators, including task completion rates, quality of work, and time allocated to different tasks.

Figure 2. assessment of staff productivity changes due to autonomous cleaners' implementation



Subsequently, autonomous cleaners are introduced into the same environment. Their usage is standardized to ensure consistency and minimal disruption to the daily workflow. The same productivity metrics are then measured during this phase. The comparison of data from the pre- and post-implementation phases provides insights into the impact of autonomous cleaners on staff productivity. Factors such as changes in the work environment, staff morale, and workload that could influence productivity independently of the autonomous cleaners. The results of this comparison help in understanding whether the implementation of autonomous cleaners contributes to a significant change in staff productivity.

5. Durability and Reliability Metrics

Incorporating the mathematical aspects of maintainability and reliability, particularly focusing on the Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and the service life of equipment like a vacuum cleaner, alongside the probability of restoring a system within a given time (t), offers a view of equipment reliability and maintenance efficiency.

Mean Time Between Failures (MTBF)

Mean Time Between Failures (MTBF) is a reliability metric representing the average time between inherent failures of a system during operation. Calculated as [14]:

$$MTBF = \frac{Total\ Operational\ Time}{Number\ of\ Failures}$$

Its an indicator of equipment reliability. For instance, a high MTBF value implies that the vacuum cleaner is less likely to fail within a short period, indicating better reliability.

Mean Time To Repair (MTTR)

Mean Time To Repair (MTTR) is a measure of the average time required to repair a system when a failure occurs. It is calculated by [15], [16] $(MTTR = \frac{Total\ Downtime\ Due\ to\ Repairs}{Total\ Number\ of\ Repairs})$

This metric can be understanding the efficiency of maintenance processes and the downtime that can be expected when a failure occurs.

Service Life

Service Life refers to the expected operational lifespan of equipment. It is based on factors like the quality of components, maintenance practices, and environmental conditions. Unlike MTBF and MTTR, service life is less formulaic and more so estimated from historical data, manufacturer's recommendations, and wear-and-tear analyses.

Maintainability and Probability of Timely Restoration

The concept of maintainability (M) the probability of repairing a system within a designated time (t). The formula $(M = 1 - e^{-mt})$ where (m) is the maintenance action rate, gives a probabilistic understanding of whether a repair can be completed within a specific timeframe. This is relevant for understanding the efficiency of maintenance processes.

The maintenance action rate $((m))$ is calculated by the ratio of the total number of units repaired to the total hours required for these repairs. Thus, $(m = \frac{\text{Total Repair Hours}}{\text{Repaired Units}})$. This rate assesses the efficiency of the repair process. An alternative form of the maintainability equation, $(M = e^{-\frac{f}{t}})$, relates the average hours per maintenance action $((f))$ to the maximum allowable time for repair (t).

6. Safety and Compliance Metrics

Autonomous vacuum cleaners are governed by a myriad of standards and regulations designed to ensure their safe and efficacious deployment. Among these are the standards set forth by the National Fire Protection Association (NFPA), which are primarily concerned with the mitigation of risks associated with combustible dust. The main of these standards is NFPA 652, a directive that serves as a unifying benchmark across diverse industries and processes, addressing the management of combustible dust fire and explosion hazards. Notably, NFPA 652 is not legally binding; however, its adherence is crucial, as violations can result in substantial fines and serious safety infringements. This standard stipulates explicit requirements for vacuum cleaners involved in the collection of combustible dust, encompassing various aspects such as construction, operation, and the specifics of integral components like motors, filters, hoses, and accessories. This rigor in standardization underscores the imperative of proactive risk assessment and management in industrial settings for workplace safety and industrial hygiene.

In the European context, the regulatory is shaped by directives from the European Environment Agency (EEA) and the European Commission, which impose restrictions and guidelines formulated towards minimizing the environmental impact of cleaning technologies. A notable regulation by the EEA restricts the power consumption of robotic vacuums, capping it at 900 watts. This regulation is a testament to the increasing emphasis on energy efficiency and environmental protection in the industrial equipment. Complementing this, the European Commission's Directive No 666/2013, aimed at the eco-design of vacuum cleaners, seeks to augment their environmental performance. These regulations are reflective of a broader ecological consciousness, manifesting in policies that promote sustainable and energy-efficient practices in commercial and industrial cleaning operations.

Table 7. Standards and regulations for autonomous vacuum cleaners in industrial and commercial spaces

Authority/Organization	Standard/Regulation	Key Aspects
National Fire Protection Association (NFPA)	NFPA 652	Addresses risks associated with combustible dust; includes specific requirements for vacuum cleaners.
European Environment Agency (EEA)	Energy Labeling Rule	Limits power consumption of robotic vacuums to no more than 900W.
European Commission	Directive No 666/2013	Aims to improve the environmental performance of vacuum cleaners.
Underwriters Laboratories (UL)	Various (e.g., ANSI/RIA R15.06, ANSI/UL 1740, CAN/CSA Z434, ISO 10218, ISO 13482, IEC 61508, IEC 62061)	Certifies safety, reliability, and performance of robotic vacuums; includes standards for robot safety.

The role of Underwriters Laboratories (UL) in certifying the safety of autonomous vacuum cleaners in industrial environments is of significant importance [17], [18]. UL, as a globally recognized authority in safety certification, assesses robotic applications to ascertain their conformity with the highest standards of safety, reliability, and performance. The UL Mark, a globally acknowledged symbol of safety, is conferred upon products that meet specific standards such as ANSI/RIA R15.06, critical for robotic applications that operate in proximity to human personnel. This certification process encompasses safety considerations, adhering to international regulations and standards like ANSI/UL 1740, CAN/CSA Z434, ISO 10218, ISO 13482, IEC 61508, and IEC 62061 [19].

7. Return on Investment (ROI)

The Time to ROI is calculated using the formula $Time\ to\ ROI = \frac{Initial\ Investment}{Annual\ Cost\ Savings}$

In this formula, $Initial\ Investment$ represents the upfront financial commitment required for initiating the project or investment. The $Annual\ Cost\ Savings$ refers to the yearly monetary benefits accrued from the investment. This formula assumes consistent savings each year and the result is typically expressed in years. The ROI Ratio is determined using the formula $\mathrm{ROI\ Ratio} = \frac{\mathrm{Total\ Benefits}}{\mathrm{Total\ Costs}}$, where *Total Benefits* include cost savings and productivity gains, and *Total Costs* are the cumulative expenses incurred over a specified period. This ratio assesses the investment's performance of autonomous vacuum cleaners over time.

8. Flexibility and Adaptability Metrics

Flooring types in industrial and commercial settings vary widely with distinct characteristics and suitability for different environments. In industrial settings, the emphasis is often on durability, resistance to heavy wear, and ease of maintenance. Concrete floors are a staple in these settings due to their robustness and longevity. They provide a solid foundation capable of withstanding the rigors of heavy machinery and constant foot traffic. However, comfort and aesthetic appeal are less prioritized here compared to commercial spaces. Epoxy coatings are frequently applied over concrete to enhance its resilience, especially against chemical spills and stains. This coating also simplifies cleaning processes, a key factor in maintaining large industrial areas. Vinyl Composite Tile (VCT) is another popular choice in industrial environments, known for its durability and ease of maintenance. However, the texture and softness of rubber flooring make it a unique choice in certain industrial contexts (in areas where cushioning and slip resistance are critical).

Table 8. Floor Types and Robotic Vacuum Compatibility

Floor Type	Industrial or Commercial Use	Robotic Vacuums Compatibility
Concrete	Industrial	Good for dry vacuuming. Robotic vacuums work efficiently on smooth concrete surfaces.
Epoxy-Coated	Industrial	Generally good compatibility. Smooth, sealed surfaces allow for easy maneuvering and cleaning by robotic vacuums.
Vinyl Composite Tile (VCT)	Industrial	Good compatibility. Effective cleaning on even, well-maintained VCT surfaces.
Rubber Flooring	Industrial	Moderate compatibility. Challenges may arise due to texture and softness, especially with vacuums having rotating brushes.
Carpet	Commercial (Offices, Hotels, etc.)	Varies widely. Some robotic vacuums are designed for carpet cleaning and handle different pile heights effectively, while others may struggle, especially with thicker carpets.
Vinyl and Luxury Vinyl Tile	Commercial (Healthcare, Retail, etc.)	Very good compatibility. Effective for both dry and wet cleaning, where applicable.
Laminate	Commercial	Good compatibility. Effective cleaning, but caution is needed with wet cleaning features to prevent water damage.
Tile (Ceramic or Porcelain)	Commercial and Industrial	Excellent compatibility. Ideal for both dry and wet cleaning due to the hard, flat surface.
Hardwood and Engineered Wood	Commercial (Boutiques, Restaurants, etc.)	Generally good, especially with vacuums designed for hard surfaces. Caution is needed to prevent scratching and with wet cleaning features.

Commercial spaces, in contrast, often prioritize aesthetics along with durability and ease of cleaning. Carpet flooring is prevalent in offices, hotels, and conference centers, chosen for its noise-reducing qualities and the comfort it offers. These attributes create a more welcoming and comfortable environment, which is vital in spaces where creating a pleasant ambiance for clients and employees is key. Vinyl and Luxury Vinyl Tile (LVT) floors are widely used in sectors like healthcare and retail due to their water resistance and variety in design, providing both practicality and an appealing look. Laminate flooring, mimicking the appearance of wood, offers a budget-friendly alternative to real hardwood, combining aesthetics with easier maintenance. Tile floors, including ceramic and porcelain, are favored in areas like restaurants and retail stores for their durability and ease of cleaning. They offer a clean, professional look, which is highly desirable in commercial spaces.

The advent of robotic vacuums has brought a new dimension to floor maintenance in these environments. Their compatibility varies depending on the floor type. On concrete and epoxy-coated floors, robotic vacuums perform efficiently, especially in dry vacuuming, making them a suitable choice for large industrial spaces. VCT floors also accommodate these vacuums well, provided the surface is even. Rubber flooring, however, presents some challenges due to its texture, which might impede the performance of vacuums with rotating brushes. In commercial settings, robotic vacuums have found a favorable ground. They are particularly effective on vinyl, LVT, and laminate floors, handling both dry and wet cleaning functions efficiently. For carpeted floors, the effectiveness of robotic vacuums can vary significantly. Some models are specifically designed for carpets and can adeptly handle different pile heights, while others may struggle with thicker fabrics. Tile floors, both in commercial and industrial settings, are ideal for these devices due to their hard, flat surface, allowing for effective cleaning. Hardwood and engineered wood floors, though less common in high-traffic areas due to maintenance concerns, can also benefit from robotic vacuums, especially those models that are designed for hard surfaces and have appropriate settings to prevent scratching.

Assessing the adaptability of autonomous vacuum cleaners across different industrial and commercial flooring types, the performance in each criterion can be quantified through a scoring system. Each aspect of a vacuum cleaner's performance – from surface compatibility to sensory feedback and adaptation – can be evaluated and assigned a score, typically on a scale from 1 to 5. This scoring system allows for a standardized and objective way to measure each vacuum cleaner's capabilities.

The score for surface compatibility can reflect how effectively a vacuum cleaner operates on a specific type of flooring, considering both its cleaning efficiency and the potential for damaging the surface. A higher score in this category indicates better compatibility and effectiveness. In terms of navigation ability, a score is given based on how efficiently and effectively the vacuum cleaner maneuvers across various types of floors, navigates around obstacles, and transitions from one surface to another. A high score here signifies a vacuum cleaner capable of operating autonomously with minimal problems.

Debris adaptability can be scored to evaluate how well the vacuum cleaner handles different types of debris typically found on various flooring surfaces. Vacuums capable of picking up a wide range of debris types, from fine dust to larger particles, would achieve higher scores in this category. Maintenance and durability are rated to indicate the frequency of maintenance required for each vacuum cleaner on different surfaces, as well as its overall longevity. A higher score is assigned to vacuums that require less frequent maintenance and demonstrate greater durability. Efficiency in cleaning can be quantified based on the vacuum cleaner's performance in cleaning a designated area within a certain time frame and using a specific amount of energy. Higher scores are awarded to vacuums that clean effectively and efficiently.

The score for sensory feedback and adaptation reflects the vacuum cleaner's ability to adjust to changes in floor texture, incline, and other environmental conditions. Vacuums that can quickly and accurately adapt to varying conditions receive higher scores in this criterion. Aggregating these scores, an overall adaptability score for each vacuum cleaner on different floor types can be derived.

This method will consider aspects such as the vacuum's compatibility with different flooring types, its ability to navigate diverse surfaces, how well it handles typical debris, the frequency of maintenance required, its overall durability, and its cleaning efficiency. Surface compatibility assesses the effectiveness of a vacuum in cleaning specific surfaces without causing damage. The vacuum's navigation ability across different floor types is equally important, including its efficiency in covering areas, avoiding obstacles, and transitioning between floor types. Debris adaptability measures the vacuum's proficiency in handling common debris found on each floor type, such as dust, spills, and fibers.

The method also evaluates maintenance and durability, focusing on the frequency of maintenance required for each vacuum and its longevity. Efficiency in cleaning is another significant aspect, calculated based on the time and energy consumed to clean a standard area on each floor type. Sensory feedback and adaptation are used in determining a vacuum's adaptability. This involves assessing the vacuum's responsiveness to changes in floor texture, incline, and other environmental factors.

Conclusion

In industrial and commercial cleaning automation, there is a notable absence of a unified framework for evaluating the performance of autonomous vacuum cleaners. This gap impedes the ability to objectively compare and assess these technologies across various essential metrics. The framework starts with the assessment of cleaning efficiency, focusing on two primary aspects: area coverage and cleaning quality. For area coverage, the evaluation involves measuring the square footage cleaned per unit of time, using advanced image processing techniques tailored for different vacuum designs. This process allows for an accurate and objective measure of how effectively and extensively the vacuum cleaners cover the designated area. The cleaning quality metric delves into the effectiveness of dirt, dust, and debris removal from surfaces. Technologies like gravimetric sampling and light sensors are proposed for real-time dirt detection, enabling dynamic adaptation to varying dirt concentrations and types. This approach ensures a thorough assessment of the vacuum cleaners’ ability to maintain cleanliness standards in varying environmental conditions.

The second set of metrics evaluates the operational efficiency of the vacuum cleaners, including battery life, charge time, and operational downtime. Battery life is measured based on the duration of operation on a single charge, through a combination of empirical testing and analytical modeling. Charge time, or the time required to fully recharge the vacuum's battery, is assessed to gauge the practicality of the device in continuous operation environments. Operational downtime, which includes time spent on maintenance, charging, and other non-operational activities, is tracked and analyzed to understand the total time the vacuum is unavailable for cleaning. Predictive modeling is employed to forecast future downtime, enabling efficient planning and utilization. This thorough analysis of operational efficiency metrics offers insights into the practicality and readiness of the vacuum cleaners for continuous and demanding use.

Cost analysis includes initial investment, operational costs, maintenance costs, and labor cost savings. The initial investment assessment considers the purchase price and installation cost, providing a baseline for the financial commitment required. Operational costs include ongoing expenses such as electricity consumption and replacement parts. Maintenance costs cover regular and unexpected maintenance needs, crucial for long-term operational sustainability. Importantly, the framework also quantifies labor cost savings, evaluating the reduction in manual cleaning labor and efficiency improvements.

Productivity metrics include cleaning speed and autonomous functionality. Cleaning speed is evaluated in terms of the area cleaned per hour, taking into account various environmental factors. Autonomous functionality is assessed using Sheridan's Levels of Autonomy, reflecting the operational independence of the vacuum and its impact on human productivity. This metric assesses the extent to which the vacuum operates without human intervention, highlighting the shift towards automation. Additionally, the impact on human productivity is examined, looking at changes in staff productivity due to the implementation of autonomous cleaners. This dual approach provides a clear picture of the vacuum cleaners' efficiency and their effect on overall productivity.

The proposed framework also evaluates durability, reliability, safety, and compliance. Durability and reliability are gauged through metrics like Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and service life, providing an understanding of the vacuum's lifespan and maintenance requirements. Safety and compliance are assessed based on adherence to standards and regulations, ensuring the vacuum cleaners meet the necessary safety criteria for industrial and commercial use. This includes certifications and guidelines from organizations like the National Fire Protection Association and Underwriters Laboratories. The evaluation of safety and compliance metrics ensures that the vacuum cleaners not only perform efficiently but also operate within the bounds of established safety norms.

Industrial and commercial spaces are diverse in terms of layout, foot traffic, and the type of debris encountered, which may not be fully encapsulated by standardized testing environments. For instance, the framework's cleaning efficiency metrics, although robust in controlled conditions, might not accurately reflect performance in spaces with unpredictable obstacles or varying floor types. Similarly, operational efficiency metrics like battery life and charge time are tested under specific conditions, but actual usage scenarios, which can include frequent starts and stops, varying surface types, and different levels of debris, might lead to different outcomes. This discrepancy between controlled testing environments and real-world applications can result in a gap between the expected and actual performance of the vacuum cleaners [20].

Another limitation is the proposed framework's reliance on technologies and methods, such as advanced image processing for area coverage assessment and real-time dirt detection technologies. These approaches require significant expertise and resources to implement, potentially limiting the framework's accessibility for smaller manufacturers or facilities with limited technical capabilities. The cost and complexity of setting up such evaluation systems might not be feasible for all stakeholders. This may skew the evaluation towards more technologically advanced and financially robust entities.

References

[1] L. D. Knibbs, C. He, C. Duchaine, and L. Morawska, “Vacuum cleaner emissions as a source of indoor exposure to airborne particles and bacteria,” *Environ. Sci. Technol.*, vol. 46, no. 1, pp. 534–542, Jan. 2012.

[2] P. Veerajagadheswar, “TOWARDS DEVELOPING EFFECIENT AREA COVERAGE APPROACH IN DOMESTIC ROBOTS,” 2019.

[3] L. Harmer, T. Cooper, T. Fisher, G. Salvia, and C. Barr, “Design, Dirt and Disposal: Influences on the maintenance of vacuum cleaners,” *J. Clean. Prod.*, vol. 228, pp. 1176–1186, Aug. 2019.

[4] S. Tina Monteiro, "Real Time Measurement of Dirt Pick-up by a Robotic Vacuum Cleaner using Light Sensing Technology," 2018.

[5] X. Hu, L. Xu, X. Lin, and M. Pecht, "Battery lifetime prognostics," *Joule*, vol. 4, no. 2, pp. 310–346, Feb. 2020.

[6] J. L. Sullivan and L. Gaines, "A review of battery life-cycle analysis : state of knowledge and critical needs," Argonne National Lab. (ANL), Argonne, IL (United States), ANL/ESD/10-7, Dec. 2010.

[7] M. Tomy, B. Lacerda, N. Hawes, and J. L. Wyatt, "Battery Charge Scheduling in Long-Life Autonomous Mobile Robots," in *2019 European Conference on Mobile Robots (ECMR)*, 2019, pp. 1–6.

[8] Z. Cheng, X. Fu, J. Wang, and X. Xu, "Research on robot charging strategy based on the scheduling algorithm of minimum encounter time," *J. Oper. Res. Soc.*, vol. 72, no. 1, pp. 237–245, Jan. 2021.

[9] H. Shakhawat Hossen Prayash, M. R. Shaharear, M. F. Islam, S. Islam, N. Hossain, and S. Datta, "Designing and Optimization of An Autonomous Vacuum Floor Cleaning Robot," in *2019 IEEE International Conference on Robotics, Automation, Artificial-intelligence and Internet-of-Things (RAAICON)*, 2019, pp. 25–30.

[10] A. Eren and H. Doğan, "Design and implementation of a cost effective vacuum cleaner robot," *Turk. J. Eng. Environ. Sci.*, vol. 6, no. 2, pp. 166–177, Apr. 2021.

[11] P. S. Adithya, R. Tejas, V. Sai Varun, and B. N. Prashanth, "Design and Development of Automatic Cleaning and Mopping Robot," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 577, no. 1, p. 012126, Nov. 2019.

[12] M. Vagia, A. A. Transeth, and S. A. Fjerdingen, "A literature review on the levels of automation during the years. What are the different taxonomies that have been proposed?," *Appl. Ergon.*, vol. 53, pp. 190–202, Mar. 2016.

[13] K. Grythe, T. A. Reinen, and A. A. Transeth, "Autonomy levels versus communication in an underwater environment," in *OCEANS 2015 - Genova*, 2015, pp. 1–8.

[14] W. Torell and V. Avelar, "Mean time between failure: Explanation and standards," 2004. [Online]. Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=c81d735b57677b4fc527c7b545b5d0096fcb359f.

[15] Z. Dong, L. Chuan, L. Yongxiang, and G. Zhiqi, "A system's mean time to repair allocation method based on the time factors," *Qual. Reliab. Eng. Int.*, vol. 30, no. 2, pp. 247–256, Mar. 2014.

[16] T. E. Wing and L. H. Crow, "A model for mean-time-to-repair and mean-logistics-delay-time at the system level," in *Annual Proceedings on Reliability and Maintainability Symposium*, 1990, pp. 389–393.

[17] K. Hattori, S. Morford, and D. T. Delaney, "How to obtain maximum underwriters laboratories coverage," *J. Vinyl Addit. Technol.*, vol. 1, no. 3, pp. 170–173, Sep. 1995.

[18] S. Interconnection, “Underwriters Laboratories,” *nrel.gov*.

[19] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, “An atlas of physical human–robot interaction,” *Mechanism and Machine Theory*, vol. 43, no. 3, pp. 253–270, Mar. 2008.

[20] M. Kukde, S. Nagpurkar, and A. Dhakulkar, “Automatic & manual vacuum cleaning robot,” *Research*, 2018.