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The Efficiency Improvement of the Device Based on the Example of a High Building Facade Washer in the Area of Industry 4.0

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Abstract: The publication analyzes aspects of energy efficiency of various types and several technological concepts of facade washing devices. The conducted analyses and tests answered the most essential question of this stage: which, from the technical point of view of solving the problem of stabilizing the track of the washing machine, gives the highest guarantee of effective stabilization of this track in unfavorable wind conditions. The literature analysis showed several solutions to the problem of track stabilization of facade washing machines on the market, of which suction cups stabilize the machine device, a system not attached to the wall of the building, and fans or propellers have been commercialized. However, it pointed out that there are no universal solutions. Detailed analysis of solutions under many criteria led to finding the solution with the fewest defects at this stage of analysis and potentially the greatest chance of success. Thanks to the results of work and research on the effectiveness of technology, it was possible to implement a number of solutions leading to the improvement of work efficiency, safety, and the development of Industry 4.0.

Keywords: energy efficiency; facade washing devices; Industry 4.0; robotics; automation

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1. Introduction

The word "efficiency" comes from the Latin word "effectivus", which means efficiency. The Polish dictionary of terms derived from foreign languages describes this term as a synonym of the following terms: positive result, efficiency, effectiveness, and functionality [1]. Conceptually, efficiency refers to the ability to generate a maximum yield from a given input with the least wastage of time, effort, money, energy, and raw materials. It can be quantified by designing and achieving the ratio of inputs to the results of a company's resources, such as funds, energy, materials, labor, etc. Efficiency is also considered a parameter for calculating efficiency and productivity by comparing a budget product and actual products produced at a fixed price number of inputs. It is also the ability to get the job done in a well-planned manner to achieve the best possible result. Efficiency is an essential component of resource use as there are far fewer resources, and they have alternative usages and, therefore, must be used in the best possible way [2]. An important issue in analyzing the concept of efficiency is to indicate the difference between effectiveness and efficiency. Efficiency refers to the extent to which specific work has been done to achieve a target result. It means the degree of closeness of the achieved goal to the previously established one. Effectiveness is results-oriented, which shows the extent to which the activity that led to the desired result was performed.

The term effectiveness is also called the result of undertaken actions, described by the relation of the obtained effects to the expenditure incurred. It means the best production, distribution, sales, and promotion results are obtained at the lowest costs. The concept of efficiency can be presented from several perspectives. Firstly, it is the difference between the effects and the inputs, defined as the benefit, where the desired result should be greater than zero, which means the advantage of the obtained effects over the costs incurred. Another approach is to present efficiency as a ratio of inputs to effects. In this case, efficiency is defined as economy, where the desired result is less than one, which means that the inputs are less than the results obtained. Efficiency can also be defined as the ratio of the difference between effects and inputs to inputs. In this case, it is defined as the rate of return on investment, where the result is expressed as a percentage [3].

It is worth pointing to the concept of efficiency in the context of the device's effectiveness. At this point, special attention is paid to the very fact of managing and managing efficiency. This measure includes activities that guarantee the effective achievement of the objectives. Performance management may consist of activities both within the organization's structures and concerning a specific device—planning its operation and comparing potential effects with planned expectations. Performance management can also be implemented as a periodic evaluation system or control by objectives system. In any case, it is essential to monitor each area and the progress of the goals.

Appropriate management of the effectiveness of the device operation can lead to the achievement of several profits for a given unit. First of all, it will be an increase in financial profits. It is correct to say that you can expand sales, optimize costs, determine the real profitability of implemented projects, or define new, more efficient goals through efficiency management. Another benefit will be the reorganization of management controls. In this case, using a performance management system helps to systematize better work and document and check the compliance of processes with the law and production assumptions [4]. It is worth paying attention to the fact that the devices are designed in such a way as to waste as little energy as possible. It means that as much of the input energy as possible should be used to achieve the goal or be transferred to useful energy stores. Correctly transferring input energy to useful output energy is called efficiency. It can be seen that a very efficient device will waste very little input energy, while a very inefficient device will waste most of the input energy.

When analyzing the concept of efficiency concerning devices, it is worth paying attention to energy efficiency. It is the ratio of the outputs, services, goods, or energy obtained to the energy input. Efficient energy use aims to reduce the energy needed to deliver products and services. The cited definition is quite complicated, but in the simplest terms, energy efficiency can be defined as the ratio of the amount of energy used, for example, for heating/cooling a building before a specific modernization, to the amount of energy used after the modernization.

In the course of the analysis, with regard to the concept of device operation efficiency, it also becomes appropriate to pay attention to the efficiency of maintenance because it is inseparably related to the effectiveness of the device sensu scricto. Maintenance is defined, inter alia, as systematic work consisting of carrying out one-off or periodic actions in accordance with the system of inspections and repairs. The purpose is to control and reduce the degree of degradation of the technical condition of devices to prevent failures and remove them when they occur. The very concept of preventive maintenance and servicing of machines and devices was created 150 years ago and is derived from the analysis of simple maintenance activities. Significant progress has been made in industrial enterprises in terms of maintenance expenditure. It is worth noting that the knowledge and tools supporting the effective implementation of activities for which the device was intended have been significantly developed.

The result of the described facts was the creation of many programs, systems, and strategies offering various paths to effective maintenance. It is believed that maintenance should be treated as an element of operational excellence known from the theory of enterprise management. Given the definition of efficiency and the primary goal of maintenance, the concept of effective maintenance can be defined. It is work performed according to a specific plan in order to prevent or reduce the consequences of an accident while at the same time carrying out the work in the most economical way possible.

An interesting issue is to indicate the elements that allow you to improve the efficiency of the device. First, clearly defined goals relating to the avoidance of machinery failure or the mitigation of the consequences of failure are important. It is also essential to define the consequences of machine failures and to be aware that all parties involved in maintenance and responsible for the efficiency of the machine must understand its essence and feel responsible for achieving the goals associated with it. When planning the device's effectiveness, a formal plan to achieve the set goal is also important; for example, this could be a specific strategy. Control measurements of efficiency and progress in achieving goals are also becoming important issues.

2. Definition of an IT Solution and the Industry 4.0 Area

The concept of IT solutions broadly refers to everything related to computer technology, for example, networks, hardware, software, the Internet, or people working with these technologies. It should therefore be noted that many companies now have IT departments to manage their operations' computers, networks, and other technical areas. IT jobs include computer programming, network administration, computer engineering, web development, tech support, and many other related professions. As we live in the "information age", information technology has become part of our daily lives. IT solutions, for instance, are a set of related programs and services sold as a single package. IT vendors, value-added service providers, and resellers sell their software packages and service packages under the brand to promote the idea that purchasing a product will help the customer solve a problem or deal with a complicated situation successfully. Many vendors, especially developers, refer to all of their products as software solutions. For example, a vendor might call their antivirus a solution because it helps solve a specific problem [5].

Industry 4.0, also known as Intelligent Industry, focuses on automation. The domain of this system is an attempt to replace human thought processes with automatic systems, which is why the above actions are often called the digital revolution. Information and communication technologies are integrated into the entire production process rapidly. This pace is maintained from the beginning of the project to distribution. Organizations, machines, and other production resources are increasingly digitized. The result is the so-called intelligent factories. Processes, people, and machines are constantly and integrally connected, getting work done faster and more intelligently. Industry 4.0 affects the entire manufacturing industry.

The introduction of Industry 4.0 solutions can be treated as another industrial revolution, which in most manufacturing industries strongly contributes to achieving environmental effects and increasing ecoefficiency. It is well illustrated by the diagram below (see Figure 1), which shows the Industry 4.0 process as a continuation of earlier advances in the industry.

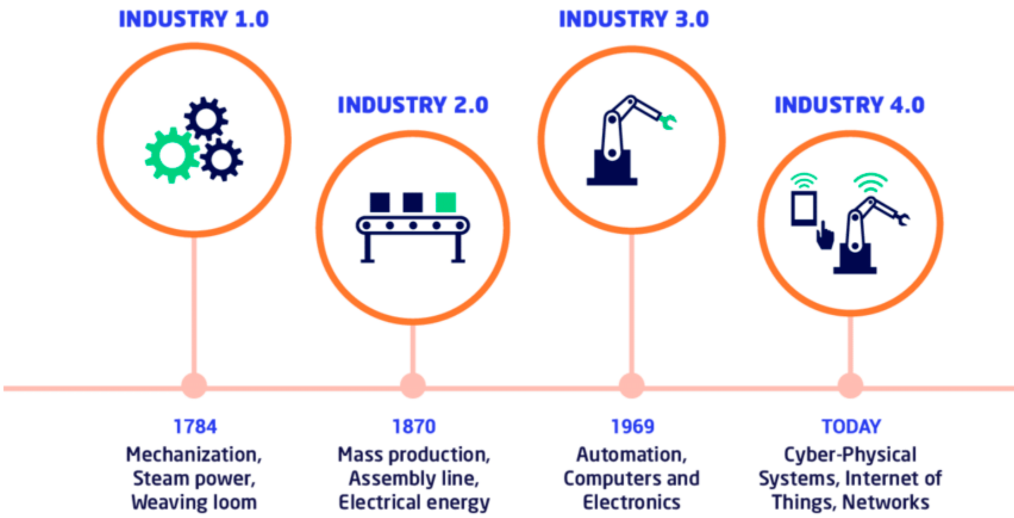

Figure 1. From Industry 1.0 to 4.0 [6].

Efficiency in the context of Industry 4.0 is defined as an approach to managing the production process and providing services at competitive prices in a manner tailored to the needs of the buyer and increasing his quality of life, with the assumption of limiting the impact on the natural environment throughout the life cycle of a product or service [7,8]. Such a concept has been proposed as one of the main tools to promote the transformation from unsustainable development to sustainable development. It was based on creating more goods and services while using fewer resources and producing less waste and pollution [9].

Managers of modern enterprises should regularly analyze the efficiency of work and operation of devices to reduce the consumption of materials and the amount of waste and emissions, which will allow for material savings, reducing the scale of pollution as a result of reducing production costs and increasing the level of competitiveness [10]. In addition, care for the natural environment results in marketing advantages and better perception by consumers. The benefits of implementing and analyzing ecoefficiency are also the increasing morale of employees, increasing attractiveness for investors, higher acceptance of the local community, and the sense of value of the management staff.

The implementation of industry 4.0 solutions to activities related to networking and data exchange significantly improves the quality of work in enterprises. Manufacturers can work more economically and respond faster to individual customer needs. The time spent on adapting machines to new requirements is reduced to a minimum, and at the same time, the flexibility of their operation is increased. In turn, the improvement in flexibility and speed brings several additional advantages for the enterprise. A good example is the increase in customer-oriented product customization. Another advantage in this respect is the use of efficient and scalable production processes that are based on open standards with a high degree of modularity. Another advantage is the easy production management of many production variants thanks to integrating production systems. It is also worth describing the advantages of Industry 4.0 applications in the context of efficiency. They certainly result in the advantages of optimization measures concerning production processes and the benefits of high production availability that is based on intelligent data analysis. Production tools can modify their operation themselves. Thanks to this, they adapt to new tasks because it is enough to apply the appropriate command of the program for machine operation. The command also automatically enables modules needed to execute a given process and disables those that are no longer required. Thanks to this, manufacturers can realize low-serial orders and even produce single items at the cost of standard serial production. It leads to increased production efficiency as any efficiency losses and wastage are detected through greater transparency in the value chain, which in turn enables the manufacturer to gain a decisive competitive advantage.

While pointing to the numerous advantages and benefits of introducing Industry 4.0 solutions, it is worth mentioning that new, innovative production systems not only show a higher degree of functional integration, but the data that are generated by these systems also become more accessible and, therefore, more valuable. Thus, Industry 4.0 allows you to create new business models. The challenge is to spot these new models, deploy them as quickly as possible, and focus on harnessing their economic benefits. It is also essential to connect the virtual world with the real one. In the ideal model of this problem, people, machines, and objects are connected by ICT—i.e., Information and Communication Technology, and they communicate dynamically in real time. During this time, they optimize all necessary processes. As part of these intelligent production systems, all factory components must be connected—from procurement to transport. It is also worth paying attention to the issue of automation because distributed, intelligent automation components are components equipped with their data processing systems and software. Drives using this technology only need commands from the control system to perform a specific movement or sequence of actions. They have the ability to independently control all movements. It can also be seen that the more functions are transferred to the software, the more flexibly the actuators can adapt to new requirements. The adaptation of machines to new conditions no longer takes place with the help of manual tools as it used to. Nowadays, everything can be programmed [11].

3. Basic Assumptions of the Operation of the Machine for Washing the Facades of Tall Buildings

In the course of the analysis of this concept, it will be appropriate to approximate the idea of a machine for washing the facade in a general manner. At the outset, however, it should be pointed out that in the past, the facades of skyscrapers were probably simpler and easier to clean. It was possible simply by opening the windows and, indeed, cleaning the facade before 1950 primarily involved window cleaning, carried out by a specialized workforce. They clung to leather harnesses and latched on the sides of skyscrapers' windows. Although the windowsills they stood on were relatively narrow, they felt safe. Washing the brick facade did not take place or was performed extremely rarely. The situation changed dramatically with the arrival of the 1950s, because with the advent of the glass curtain wall, the windows effectively became an integral part of the façade. However, the problem was that the facade was stationary. It was impossible to open, so cleaning the windows required access from the outside and thus became more complex. Buildings had to be constructed with flat roofs to accommodate fixed or mobile window cleaning equipment to facilitate access to the facade. Various mechanisms have been developed to allow window cleaning platforms to be suspended from rails or tracks on the roof of the building and to move up or down [12].

With the advancement of technology, buildings with glass curtain walls could break away from the obligatory silhouette with a flat roof. As a result, cornices and numerous niches that were visible in designs during the first three decades of the 20th century (e.g., Chrysler Building or Empire State Building) began reappearing in skyscraper designs at the end of the century. As a result, new types of facade access devices have been developed to serve these buildings, including arms that can act as cranes for both window cleaning and window replacement. Currently, window cleaning remains at the center of the building's regular maintenance routine. Most windows will be cleaned twice a year, except overground commercial and hall entrances, which are done much more frequently (see Figure 2).

However, practice shows that the infrastructure solutions proposed by building architects do not meet the approval of employees who perform the hazardous work of washing the facade at heights. There may be several reasons for this. Building maintenance systems (BMU) require specialized training, which is expensive, and the constant optimization of costs and pressure from property managers to lower prices mean that trained climbers prefer to use their qualifications to work on more profitable orders, e.g., wind turbine service, assembly in construction, etc.

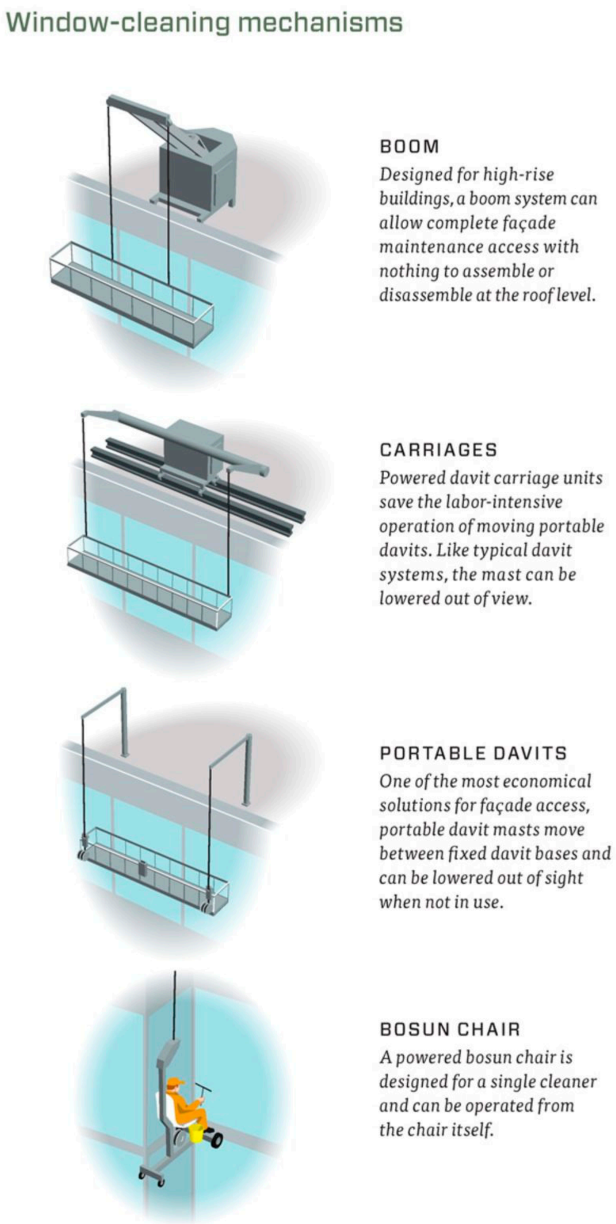

Figure 2. Types of window cleaning solutions [12].

The second aspect is security, which may seem like a paradox at first glance. The facade systems were designed to ensure safe work at height, yet the specialists who carry them out do not want to use them for safety reasons. Interviews with specialists working in the industrial mountaineering profession indicate that concerns largely stem from the complexity of the design and the high failure rate of these systems, which translates into a lack of confidence in these devices. For example, an industrial climber takes care of his equipment by working with it daily, knows all aspects of its operation, and can quickly evacuate the building in an emergency. In the case of using the elevation system that is activated extremely rarely (lack of skill in operation) in the event of a change in weather, power failure, or another hazard, the employee is transported on the platform at a height. The evacuation takes place very slowly because it is limited by safety reasons, including the limited operating speeds of winches, the presence of sensors, etc. In addition, these systems do not allow agile movement of the facade, thus reducing productivity, which is often billed per square meter in this industry. The high investment cost of facade service systems concerning their efficiency and frequency of use has recently become the subject of analysis. It should be noted that BMU systems were not designed to improve the efficiency of facade maintenance but to enable their maintenance and replacement of windows at all. The continuous "improvement" of safety standards makes improving their efficiency of moving on the facade difficult. Due to the emergence of other options for replacing windows and the possibility of performing minor repairs from rope access, the effectiveness of the BMU in this respect may be subject to discussion. The aspects mentioned above and the fact that the technology of replacing facade windows from inside the buildings is already available mean that some investors resign from installing BMU systems on new buildings, equipping the building only with safety systems for industrial climbers [13].

Today, the number of buildings with large glazed or flat facades is increasing worldwide. These types of facades must be periodically cleaned, which generates not only high costs, but also risk for employees. In addition, waiting by employees for weather windows can extend the cleaning of very tall buildings up to several months, which sometimes causes dissatisfaction on the part of tenants, residents, and the property manager. The cost of cleaning depends mainly on several factors, such as the characteristics of the facade, the degree of soiling, rope access difficulties, the periodicity of cleaning, or the total area to be cleaned. The cleaning costs of non-porous facades in Europe are EUR 0.5–5 per square meter. A typical building with an area of 20,000 m^2 implies a total facade cleaning cost of around EUR 15,000–40,000, and it should be noted that this task is usually performed at least once a year for glazed buildings. Hence, attempts have been made for a long time to develop a system for cleaning facades in a full or semi-automatic manner [14].

It is estimated that using an automatic or semi-automatic system for cleaning can lead to about 60% savings compared to manual cleaning [14]. Furthermore, automation and robotics technologies allow for environmentally friendly cleaning of the facade, helping to reduce the costs of these tasks. Until 2012, only one system was and still is in continuous practical operation. An automatic system for cleaning a vaulted glass hall at the Leipzig Trade Fair, Germany, was developed by the Fraunhofer Institute IFF, Germany [15].

An interesting issue in the course of the analysis of this concept is the comparison of the issues of surface cleaning efficiency with the use of specialized equipment with the economy. It should be pointed out that the use of innovative solutions leading to an increase in the efficiency of the device operation directly affects the economic results of the equipment operation. The described solution of the machine for washing the facades of high buildings is so innovative that it is in vain to look for the results of similar research on improving their efficiency. So, by analogy, we can briefly describe the process of cleaning surfaces used in the auto detailing industry.

The processes and dependencies on the efficiency ecology line functioning within its framework can be implemented accurately in the facade cleaning process description. In this case, the activities across the last few decades also looked similar. Just as washing the facade 50 years ago required an increased amount of human input and a significantly greater consumption of materials and, above all, water, it was the same for washing cars. Cleaning varnished and glass surfaces consisted of washing with sponges, with a large amount of environmentally hazardous chemicals, possibly using a low-pressure spraying hose, which would not remove dirt satisfactorily anyway. Moreover, water from the water intake had a lot of scale in its composition, which hurt the cleaned surfaces. Summing up the average consumption, up to 400 L of water was wasted during one wash. The situation changed dramatically with the introduction of self-service washers, also known as touchless. Using the aforementioned infrastructure allowed for the reduction of water consumption to about 100–150 L. Thanks to using a stream of water under very high pressure, washing efficiency has been increased while reducing the amount of water used and the number of detergents introduced into the environment. In addition, the time needed to complete the task was shortened, meeting another premise of the device's effectiveness [16].

4. Research Methods Used to Improve the Efficiency of the Device

The essence of using mechanization and automation of simple activities is to increase the efficiency of the process and/or safety. In the case of facade washing machines, efficiency determines the washing costs and profitability of a project consisting of the purchase of a machine for a building or the provision of facade cleaning services by specialized entities. The basic measures to improve the efficiency of the washing machine for washing the washing facade may be increasing the working width, increasing the rotational speed of the brush or other washing module, increasing the speed of the machine moving along the facade, reducing technological downtime, shortening the time of assembly and disassembly, or the use of a specially prepared washing medium [17–19].

More advanced methods may range from optimization of steering, obstacle detection and avoidance, contamination detection, aerodynamics improvement, and conduit logistics to autonomous operation. The "Holy Grail" of improving the efficiency of facade washing machines is efficiency optimization at which the production price of the device will allow for its commercialization at a price affordable for stakeholders [17].

Currently, in many regions of the world, research is being carried out on semi-automatic and automatic machines for washing the facades of tall buildings. However, most of them are so advanced and expensive that the cost of their purchase is not economical at the current prices of handicrafts, and others turn out to be ineffective. This article presents an excerpt from the research work on improving the effectiveness of stabilizing the washing machine on the façade to increase washing efficiency and safety of working at a height in adverse wind conditions. Adverse wind conditions are the most significant barriers to cleaning glazing in high-rise buildings by machine robots for cleaning of facades. In the case of manual work performed by industrial climbers, the range of limitations extends to strong sunlight and rain [20]. The most critical factor, however, is wind, as it is the most frequent and longest limiting factor in the year. The initial research position of the described case was the behavior of the washer before it was subjected to changes. The simulation analysis was carried out, i.e., the mathematical models of the washer were verified, and measurements were carried out in controlled and actual conditions. At the start of the project, the washer was characterized by the following properties (Table 1):

Table 1. Characteristic properties of the facade washer before modernization [21].

Own weight:	270 kg
Side area:	0.89 m^2
Cable weights:	electric: 0.275 kg/m water: 0.357 kg/m
Water in the water line:	0.133 kg/m
Rope over the machine:	0.254 kg/m + 0.5 kg hook
The method of correcting the vertical washing path:	none
How to prevent deviations in the washing path:	Generation of the pressure force of the guiding wheels on the facade by high-power industrial fans

Figure 3 shows the facade washing machine before modernization.

It is worth describing the situational analysis at this point. To determine the current possibilities of maintaining the track, the theoretical pressure force generated by fans based on nominal data was tested. It was also checked computationally and experimentally to determine the value of lateral forces that causes the machine displacement.

As a result of the conducted analyses, it was found:

- ✓ Maximum pressure generated by fans: 137 N.
- ✓ Wind speed that does not significantly alter the machine's trajectory: 15 km/h.

✓ The maximum deviation of the wash track recorded in practice: 10 m in highly variable wind conditions on a 100 m line.

To determine the effect of wind on the behavior of the washer, we decided to check how the force of wind pressure on the side surface of the machine changes depending on the parameters of the atmosphere, such as air temperature and pressure and wind speed.

Figure 3. Facade washing machine before modernization [21].

As is known, the air density $\rho\left[\frac{kg}{m^3}\right]$ depends on its pressure p [Pa], temperature (in absolute scale) T [K], and the gas constant for dry air $r = 287.05$ [J/kg·K] [21]:

$$\rho = \frac{p}{r \cdot T} \tag{1}$$

The dependence on wind pressure is linear. The pressure force decreases with increasing temperature and reducing pressure. This dependence can be traced in the example charts (see Table 2).

Table 2. Influence of temperature and pressure on the force of wind pressing against the machine [21].

The Lateral Surface Area of the Machine—0.89 [m²]				
	Ambient Temperature [K]	Air Pressure [Pa]	Wind Speed [km/h]	Wind Force Pressing against the Side Wall [N]
1	293.15	101,300	10	4.13
2	293.15	101,300	20	16.53
3	293.15	101,300	30	37.20
4	293.15	101,300	40	66.14
5	293.15	101,300	50	103.34
6	293.15	101,300	60	148.81
7	293.15	101,300	70	202.54

The first graph (see Figure 4) shows the dependence of the pressure force on air pressure and temperature for a wind speed of 10 km/h, and the second one for a rate of 70 km/h (see Figure 5).

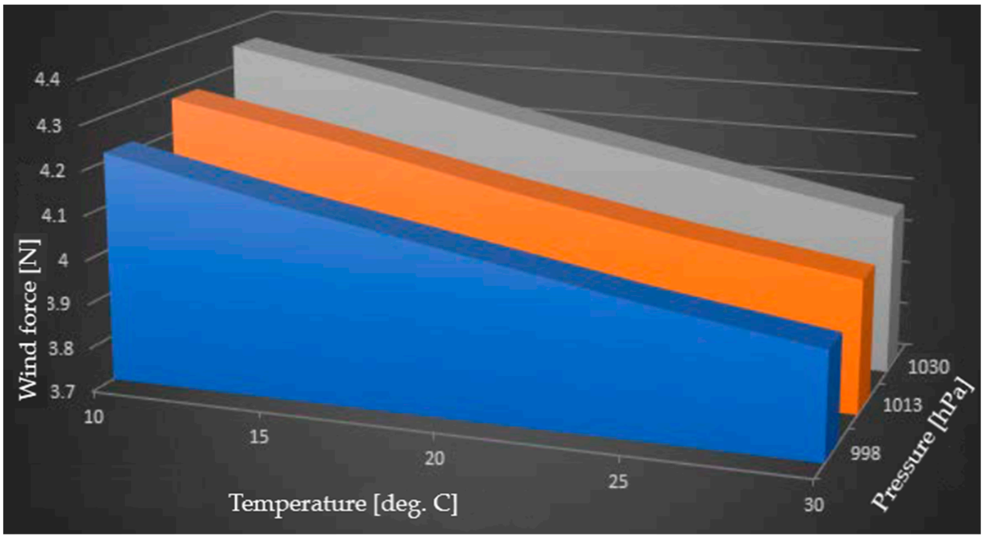

Figure 4. Dependence of wind strength on temperature and pressure for a speed of 10 km/h [21].

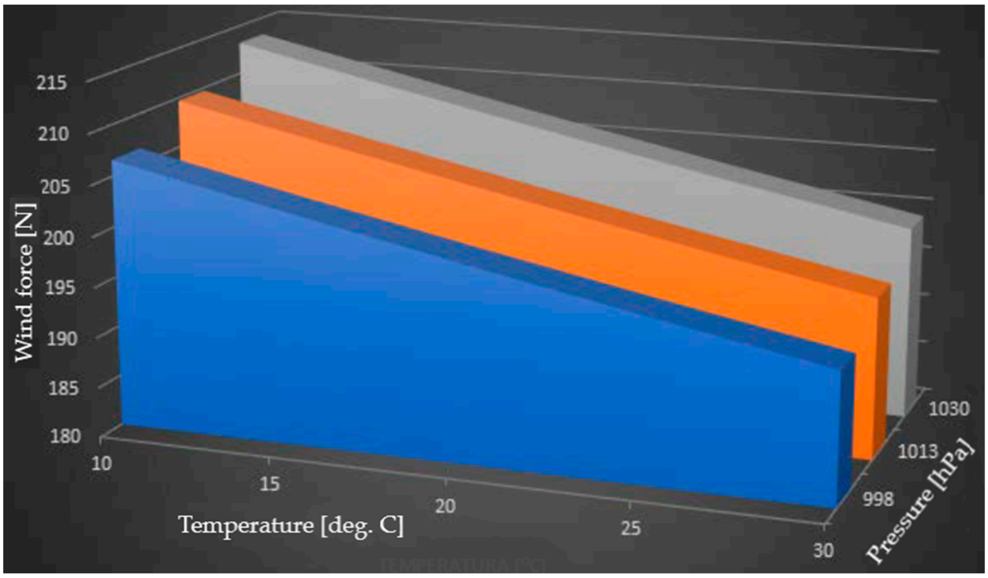

Figure 5. Dependence of wind strength on temperature and pressure for a speed of 70 km/h [21].

The largest measured value is 213.2 N at an air pressure of 1030 hPA and a temperature of 10 degrees Celsius (283.15 K).

This means that to maintain the position of the washer against a force of 137 N, the friction coefficient would have to be greater than one. Analyzing the technical possibilities and safety and taking into account the statistical number of days with wind of a certain speed, the limit wind speed was set at 40 km/h.

Wind pressure affects the position of the washer. Therefore, the deflection experienced by the machine under the influence of the wind is an important parameter indicating not only the need for correction but also the scale of this correction necessary to maintain the proper trajectory of the washer, which is extremely important for work efficiency. The estimated amount of deflection was made based on theoretical considerations, in which the washer was treated as a physical pendulum with the center of gravity coinciding with the center of wind pressure, which is influenced by the force of wind pressure (see Figure 6).

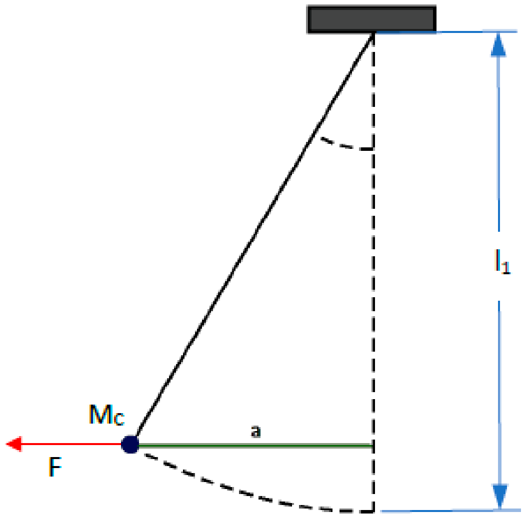

Figure 6. Diagram of the pressure force analysis due to gravity in solutions with pressure fans [21].

The table below (Table 3) shows the dependence of the deflection of the facade washing machine on the vertical (measured by the horizontal displacement of the machine under the influence of wind) depending on the wind force and also on the length of the rope on which the facade washing machine is suspended.

Table 3. Table of the dependence of the deviation of the machine for washing the facade from the vertical (measured in meters) depending on the wind force and the length of the rope on which the machine is suspended [21].

The Lateral Surface Area of the Machine—0.89 [m^2]				
Temperature—291.15 [K] (18 °C); Pressure—1013.25 [hPa]				
The Height of the Building is 240 [m]				
	Rope Length [m]	Wind Speed [km/h]	Machine Weight [kg]	Moving the Machine from the Vertical [m]
1	10	10	300	0.0141
2	20	10	300	0.0283
3	50	10	300	0.0707
4	100	10	300	0.1414
5	150	10	300	0.2121
6	200	10	300	0.2829
7	10	20	300	0.0566
8	20	20	300	0.1131
9	50	20	300	0.2829
10	100	20	300	0.5657
11	150	20	300	0.8486
12	200	20	300	1.1314
13	10	30	300	0.1273
14	20	30	300	0.2546
15	50	30	300	0.6364

Table 3. *Cont.*

The Lateral Surface Area of the Machine—0.89 [m^2]				
Temperature—291.15 [K] (18 °C); Pressure—1013.25 [hPa]				
The Height of the Building is 240 [m]				
	Rope Length [m]	**Wind Speed [km/h]**	**Machine Weight [kg]**	**Moving the Machine from the Vertical [m]**
16	100	30	300	1.2729
17	150	30	300	1.9093
18	200	30	300	2.5457
19	10	40	300	0.2263
20	20	40	300	0.4526
21	50	40	300	1.1314
22	100	40	300	2.2629
23	150	40	300	3.3943
24	200	40	300	4.5258
25	10	50	300	0.3536
26	20	50	300	0.7071
27	50	50	300	1.7779
28	100	50	300	3.5357
29	150	50	300	5.3036
30	200	50	300	7.0715
31	10	60	300	0.5091
32	20	60	300	1.0183
33	50	60	300	2.5457
34	100	60	300	5.0915
35	150	60	300	7.6372
36	200	60	300	10.1829
37	10	70	300	0.6930
38	20	70	300	1.3860
39	50	70	300	3.4650
40	100	70	300	6.9301
41	150	70	300	10.3951
42	200	70	300	13.8601

As shown by the simulation results obtained at a temperature of 291.15 K (18 °C) and a pressure of 1013.25 hPa, the maximum deflection occurs at the maximum length of the rope (200 m) and the maximum wind speed (70 km/h) and is almost 13.9 m.

For the indicated application speed of 40 km/h and the rope length of 200 m, the machine deflection reaches 4.5 m. The dependencies in the table are presented in the chart below (see Figure 7).

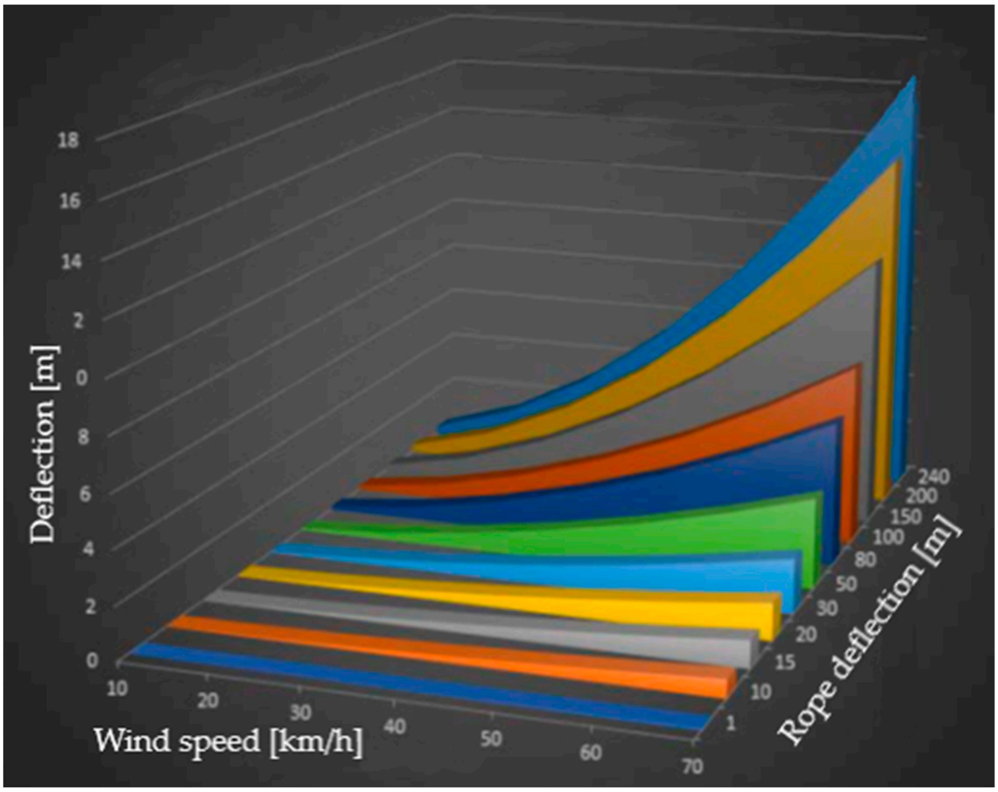

Figure 7. Influence of the rope length on the horizontal displacement of the machine [21].

It is worth describing the extended model here. At the source of the model is the conclusion that the essential elements affected by the wind are the ropes attached to the machine. Hence, taking this into account, the following forces acting on the washer in the horizontal axis should be noted (see Figure 8):

RM—the force with which the washer resists the force of the wind. It consists of the forces of wheel friction, brush friction, and the tangent component of gravity.

RA—reaction of the upper attachment point of the washer.

RL1—tangential component of gravity (lifting rope).

RL2—tangential component of gravity (lines under the washer).

FT—the force with which the cables at the base resist the force of the wind.

F1—the force of the wind pushing against the side surface of the washer.

F2—the force of the wind pressing against the carrier rope.

F3—the force of the wind pressing against the cables under the machine.

Due to many unknowns, the model is also a simplification of the actual situation. The most crucial approximation is the uniformity of the wind along the entire building height, which is inconsistent with the actual situation; however, it is not technically possible to know this distribution as part of the project due to the need to place anemometers every few meters along the entire height of the building. It is necessary due to the variability of the wind gusts. The course of measurements with one anemometer moved along the facade of the building would be as unreliable as the assumption of a constant force of this wind. The latter is so much better that it gives the results of limiting the thrust force on the ropes from the top, i.e., they give, at most, a greater thrust force than in reality.

While analyzing the research on the effectiveness of the device, it becomes essential to compare the operation with the weather conditions occurring during the investigation. The obtained data were compared with the data from the wind recorder placed on the facade washing machine. The recorder recorded the wind speed every 10 s. For the compilation, the maximum value recorded in a given minute was taken into account and compared with the data from the observation of the machine. Due to a large amount of measurement data, only selected results are presented in this study.

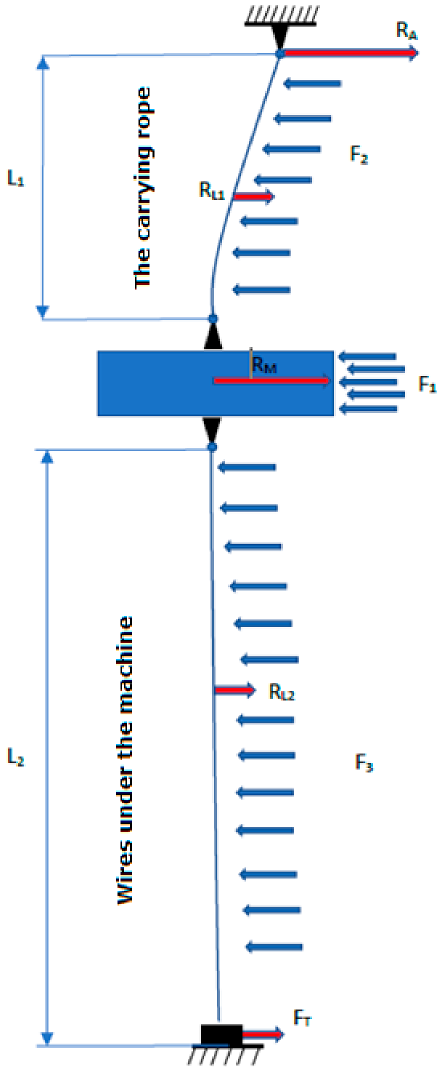

Figure 8. The system of forces in the developed model [21].

Measurements of the wind's impact on the machine's stability in wind were carried out on the 210 m SkyTower building in Wroclaw, Poland. The weather forecast was updated to 2 h.

A Navis WL11X/WS anemometer was installed on the facade cleaning machine to record the wind speed. The measurement was performed continuously. The recorder collected data every 2 s and recorded the readings every 10 s, showing the current value and the maximum value during the last 10 s.

Measurements were carried out on a building with a height of 210 m in various places of the facade over several days. The building has a sloping attic. Therefore, the hoist suspension height depended on the measurement location (170–205 m). Furthermore, measurements were carried out in real conditions, i.e., the washing process was carried out using demineralized water to obtain the friction resistance of the brush and wheels of the machine against the facade.

During the machine's operation, deviations from the set work path caused by gusts of wind were noted.

Lateral displacement in meters and the length of the rope on which the machine was suspended at the time of removal were recorded. The data were matched with the data from the wind recorder placed on the machine. For the compilation, the maximum value recorded in a given minute was taken into account and compared with the data from the observation of the machine. Due to a large number of records, only selected results are presented in this study.

The observations and analysis of the results showed (Table 4) that the gusts of wind do not always correlate with the machine's displacement. There were cases of stronger gusts of wind, to which the machine reacted with a more minor deflection than other smaller ones lasting longer. In addition, machine displacements were observed even in the case of slight gusts, which at other times did not generate machine displacement. The reasons here are in particular measurement conditions. Around tall buildings, there are turbulences in the air flowing around the building (especially SkyTower, which has an oval shape) and air chimneys caused by the convection of heated air at the facade. The facade is washed with water at a temperature of about 13–15 °C, and the facade is cooled down to this temperature during washing. Therefore, there are two large elevation planes with different temperatures next to each other: a dry elevation heated to, e.g., 40–80 °C, and a wet elevation with a temperature of 15 °C, which may cause additional air turbulences disturbing the measurements. In addition, there are horizontal air currents at different heights, which are not detected by the anemometer mounted on the machine and affect the 8 mm wire rope (if present above the device) or the media supply lines to the device (if present below the machine suspended at height). In this case, the wires or the rope generate a machine offset even though the wind recorder does not record variations in the wind speed. The above may cause measurement errors and/or ambiguous measurement results, which were observed during the measurements [21].

Table 4. Measurements of the influence of gusts of wind on the lateral displacement of the machine [21].

Measurement Time	Max Speed [km/h]	Machine Tilt [m]	Rope Length [m]	Temperature [K]	Weight of Hanging Cables under the Machine [kg]	The Weight of the Rope above the Machine [kg]
10:02	12.6	0.8	70	288.15	116.5	17.78
10:19	17.6	0.4	150	288.15	23.3	38.1
10:23	7.6	0.3	120	288.15	58.25	30.48
10:24	22.3	1.2	110	288.15	69.90	27.94
10:25	22.3	0.8	115	288.15	64.07	29.21
10:26	22	0.7	105	288.15	75.72	26.67
10:27	10.1	0	105	288.15	75.72	26.67
10:29	8.3	0	100	288.15	81.55	25.4
10:30	11.2	0.2	95	288.15	87.37	24.13
10:31	16.9	1	90	288.15	93.20	22.86
10:32	10.8	0	81	288.15	103.68	20.574
10:33	17.6	0.5	75	288.15	110.67	19.05
10:34	19.8	0.7	65	288.15	122.32	16.51
10:35	7.2	0	58	288.15	130.48	14.732
10:36	6.8	0	58	288.15	130.48	14.732
10:38	8.3	0	50	288.15	139.80	12.7
10:39	13.3	0	40	288.15	151.45	10.16
10:46	8.6	0	40	288.15	151.45	10.16
10:47	10.3	0	20	288.15	174.75	5.08
10:48	14.4	0	20	288.15	174.75	5.08

Based on numerical analyses and measurements in actual conditions, the limit values of the forces acting on the machine during side gusts of wind were determined, and specialized BLDC drives were selected for use in uncrewed aerial vehicles (industrial drones) that can meet the requirements of stable operation, i.e., without shifting by more than 10 cm in increased wind gust conditions up to 40 km/h speed [21].

The key to achieving this criterion was the system for locating the position of the machine in space, identifying the minimum horizontal change in the position of the machine caused by gusts of wind, and the automatically reacting side stabilization system consisting of high-power propeller drives.

Thanks to the use of specialized sensors, satellite antennas, and dedicated software, a system for automatically stabilizing the machine's position was created. In addition, the system is equipped with an on-board energy storage, allowing the device to be safely lowered to the ground in the event of a power failure. In addition, the automatic system can be turned off with one button to switch to manual control that allows you to bypass a small obstacle while working at a height, e.g., an open window on the 30th floor, or diagnose a threat by the operator.

This solution is a significant improvement in the efficiency of the facade washing machine and a process innovation when working on a tall building.

The next stage of work on improving the efficiency was the analysis of the possibilities of improving the efficiency of the drives through their appropriate positioning in relation to the machine structure and their readiness for immediate reaction. Many variants of the direction of the rotational axis of propeller drives and their take-off power were analyzed to optimize air flows through and around the machine structure. Selected results of the simulation of the flow analysis are presented below.

One of the analyzed issues was the maximum shortening of the reaction time of the engine responsible for preventing the machine's oscillation. The original concept assumed that the corrective drives would work 5% in the windward direction to minimize their activation time (see Figure 9).

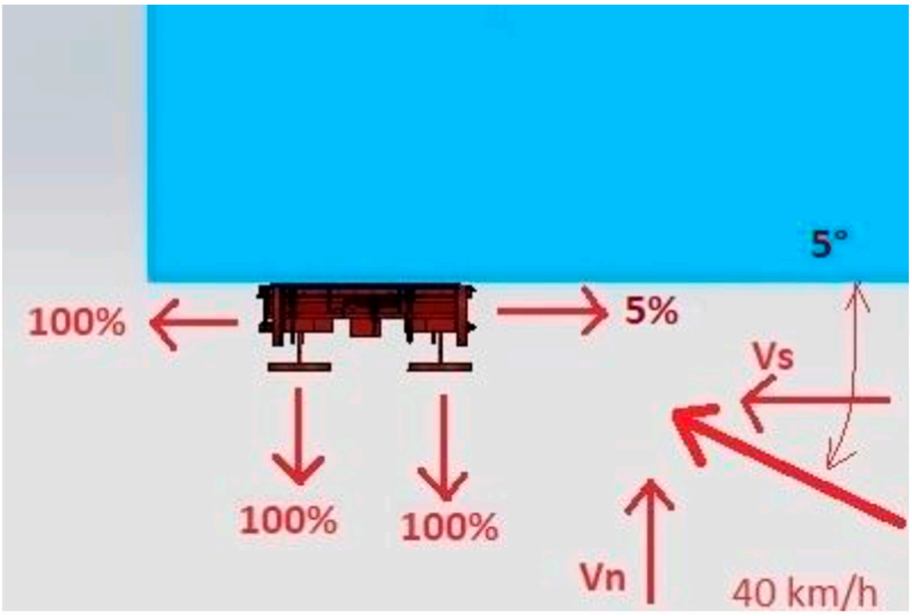

Figure 9. The tested system of setting the drive power in the 5% variant on the windward side [21].

The flow analysis showed that the procedure adversely affects the aerodynamics of the system and the efficiency of the other drives. Then, turbulence occurs in the device's immediate vicinity, which significantly impacts the wind speed measuring system installed on the facade washing machine. Such turbulence will interfere with correct wind speed weather station measures by giving inaccurate wind speed and direction data (see Figures 10–12).

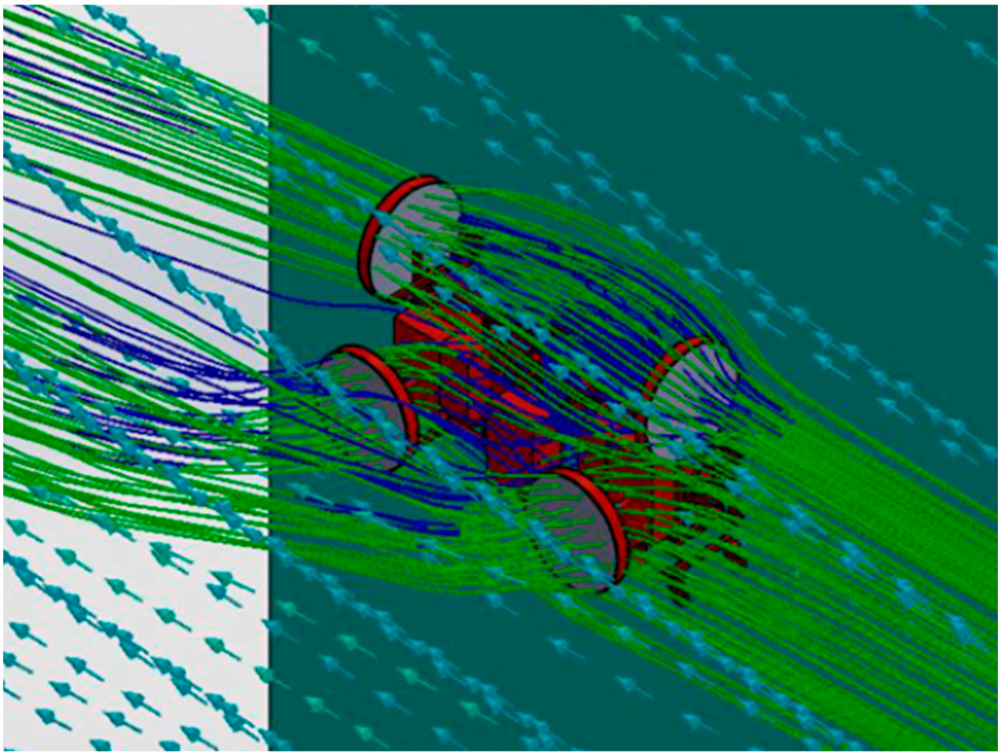

Figure 10. Turbulence around the device with streams generated by propeller drives [21].

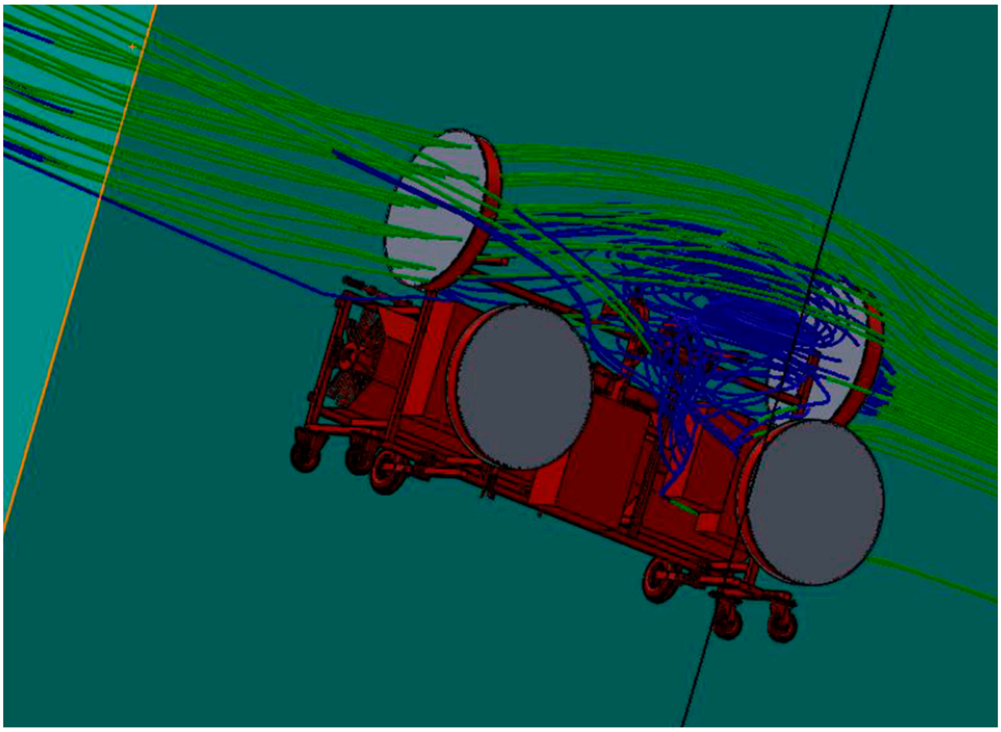

Figure 11. Air streams flow through stabilizing propeller drives [21].

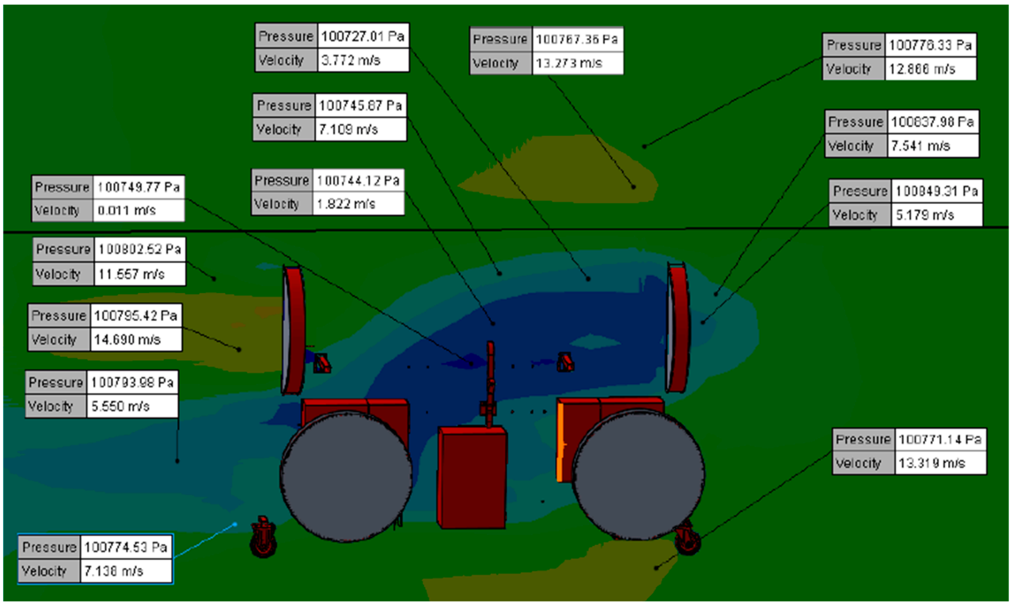

Figure 12. Velocity field in the axis of stabilizing drives [21].

Below are the results for the system in which the windward drive does not idle, which slightly delays the response time, but has a positive effect on the work of other drives and the aerodynamics of the system. With such a large mass of the system, the difference in activation time turned out to be less critical than the disturbances in the air flow, as shown in Figures 13–16.

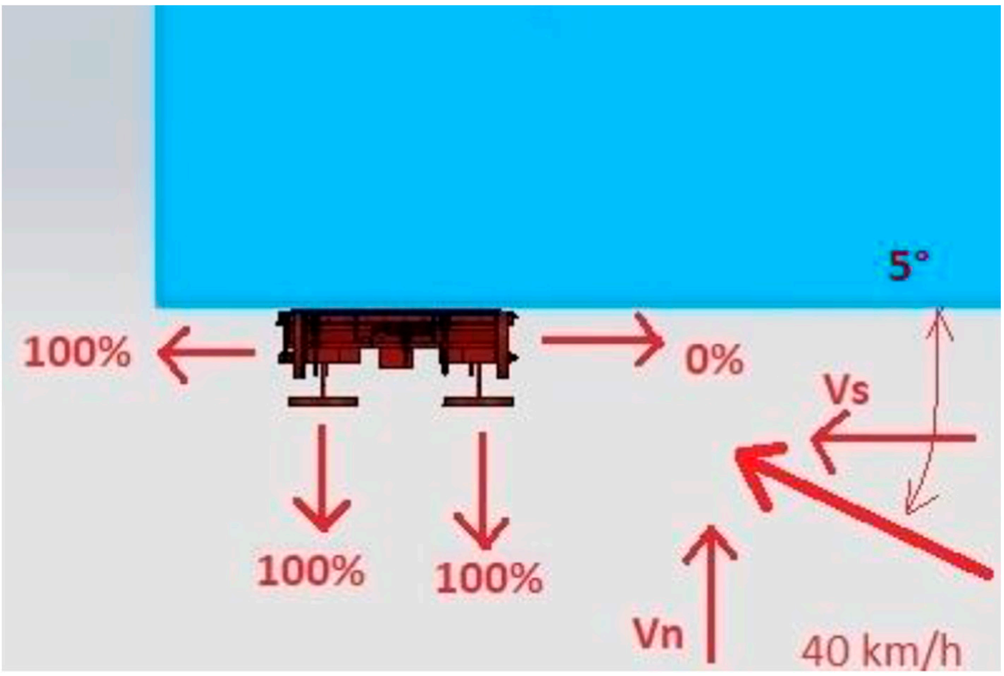

Figure 13. The tested system sets the drive power in the variant 0% on the windward side [21].

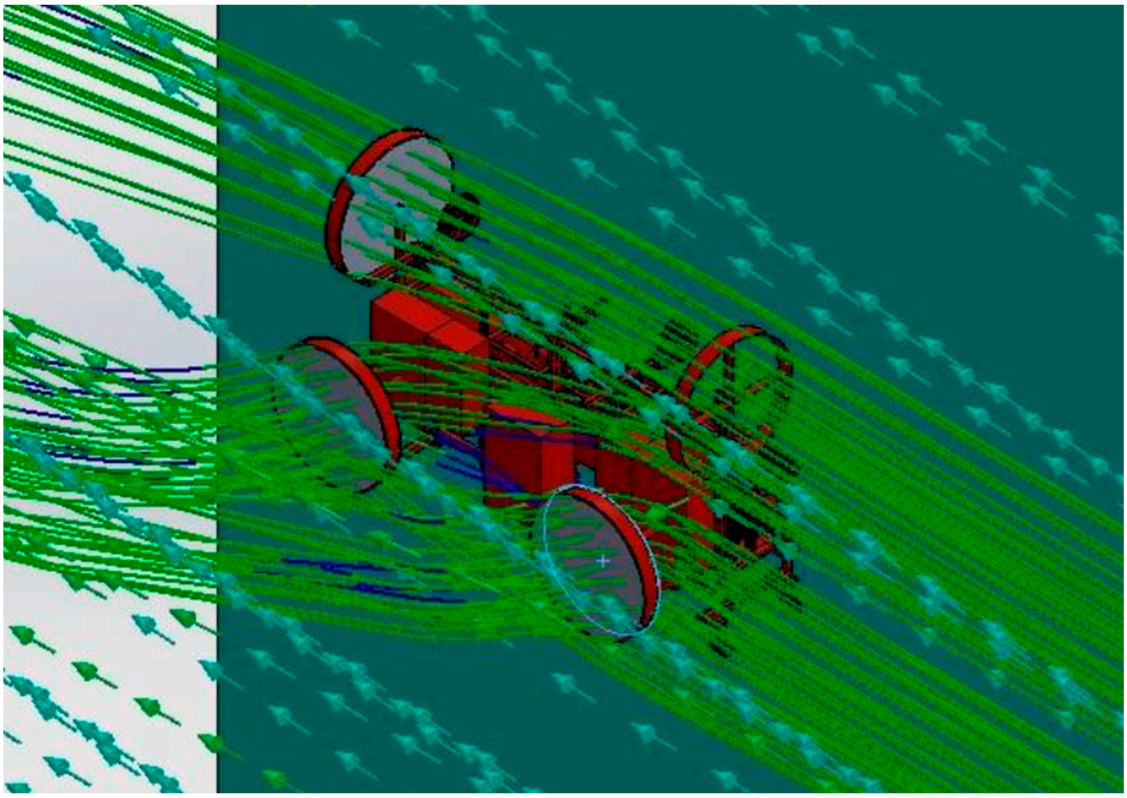

Figure 14. Air streams flow through stabilizing propeller drives [21].

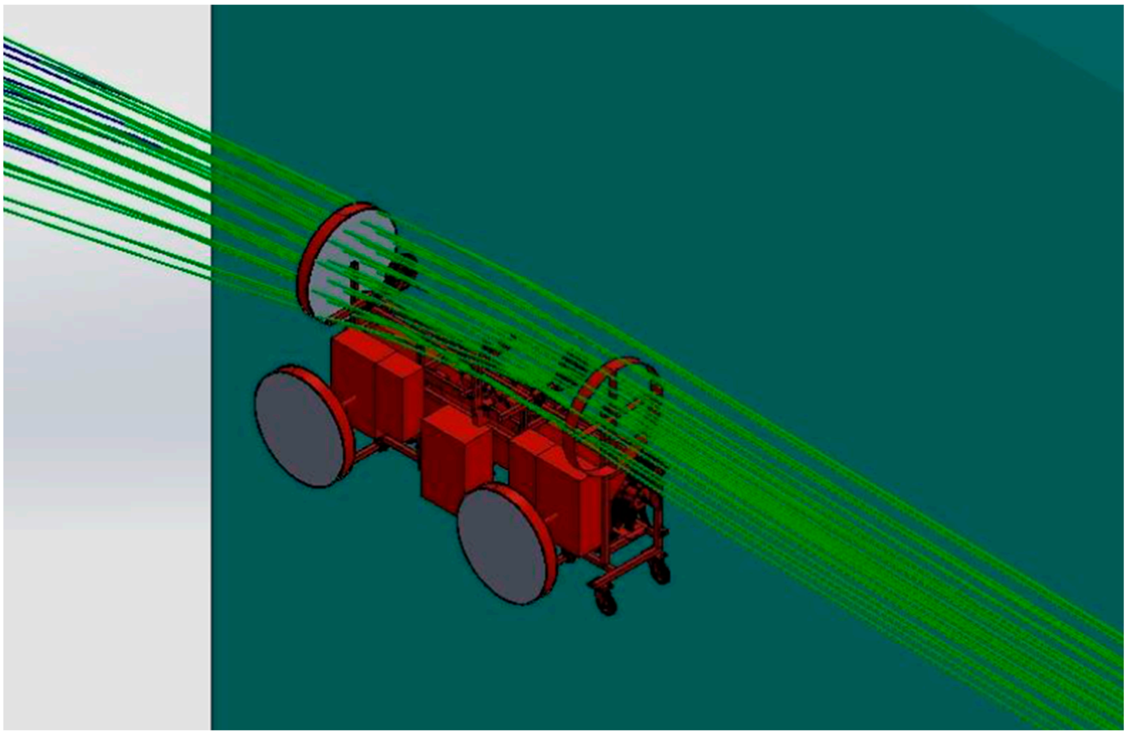

Figure 15. Air streams flow through stabilizing propeller drives [21].

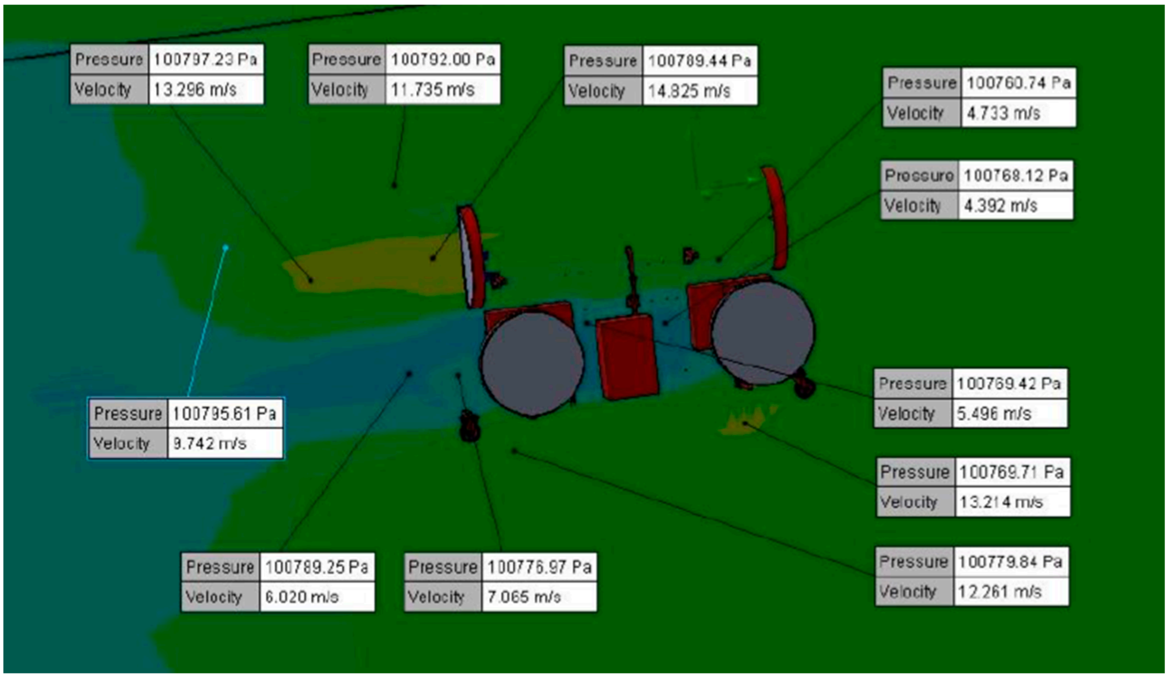

Figure 16. Velocity field in the axis of stabilizing drives [21].

The subject of research on improving the efficiency of the facade washing machine was also the analysis of the influence of the alignment of the thrust vector axis of the drives used to stabilize the facade washing machine on the building in the wind.

The following is an analysis of the dependence of the effect of the deflection angle of the drives (clamping and stabilizing) on the turbulence around the machine structure (see Figures 17–21).

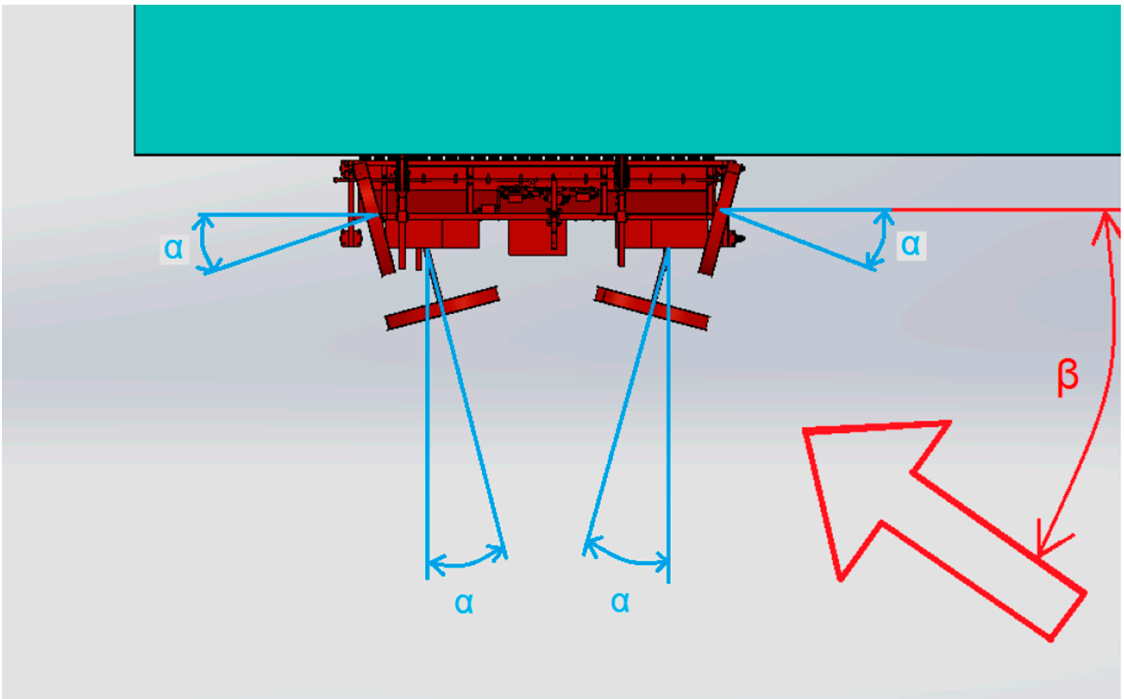

Figure 17. The analysis of the dependence of the deflection angle of the pressing and stabilizing drives on turbulence around the machine structure [21].

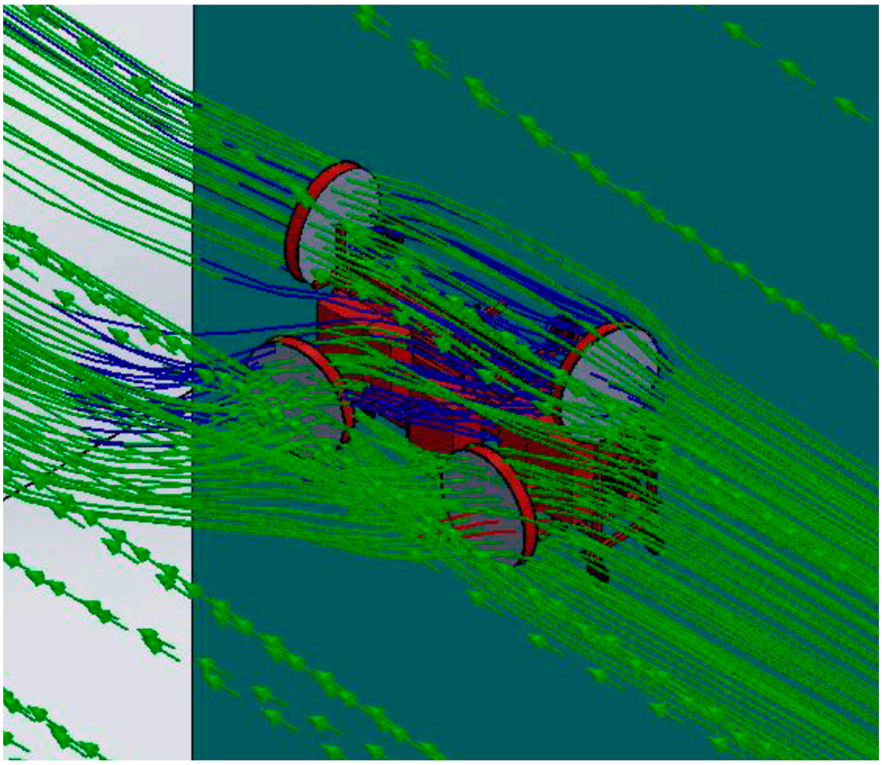

Figure 18. The analysis of the dependence of the deflection angle of the pressing and stabilizing drives on turbulence around the machine structure (Alpha angle = 5°, Beta angle = 5°, wind speed 40 km/h) [21].

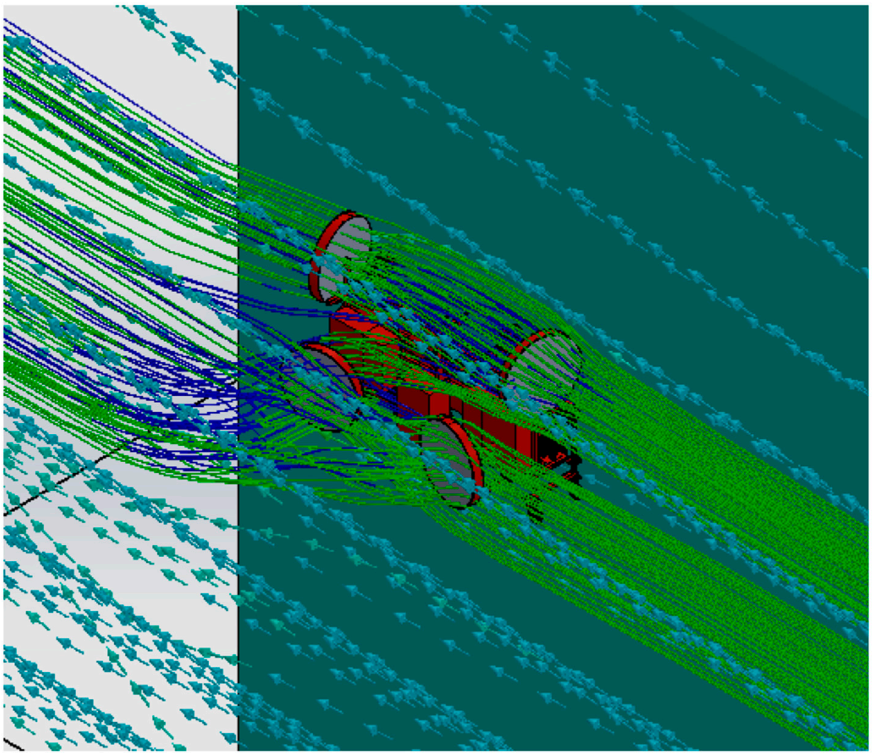

Figure 19. The analysis of the dependence of the deflection angle of the pressing and stabilizing drives on turbulence around the machine structure (Alpha angle = 10°, Beta angle = 5°, wind speed 40 km/h) [21].

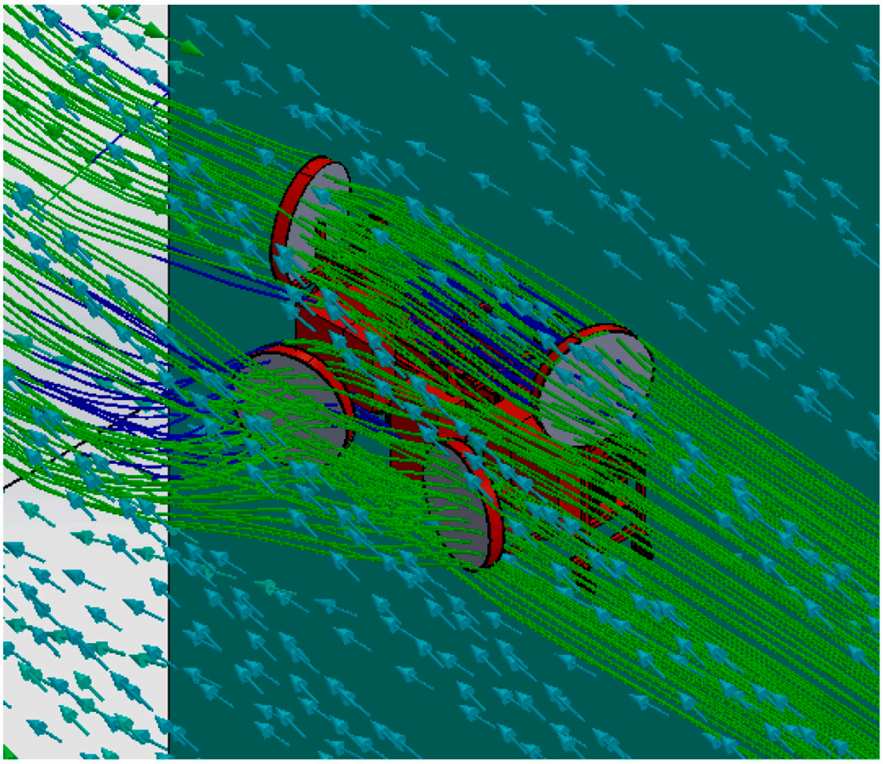

Figure 20. The analysis of the dependence of the deflection angle of the pressing and stabilizing drives on turbulence around the machine structure (Alpha angle = 15°, Beta angle = 15°, wind speed 40 km/h) [21].

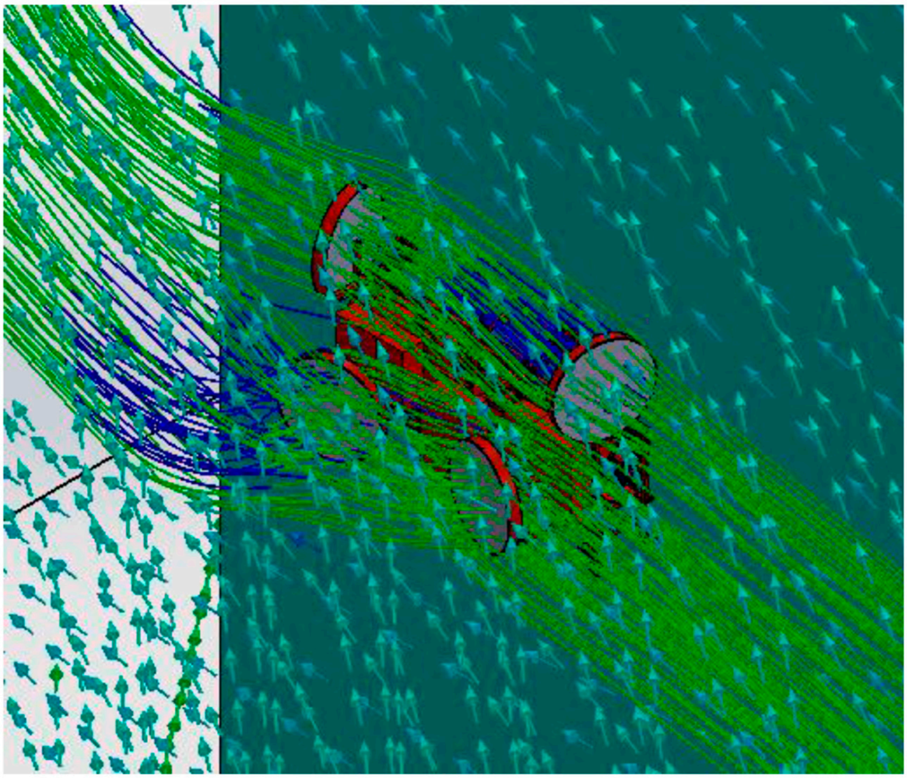

Figure 21. The analysis of the dependence of the deflection angle of the pressing and stabilizing drives on turbulence around the machine structure (Alpha angle = 15°, Beta angle = 45°, wind speed 40 km/h) [21].

A detailed analysis of solutions under many criteria has led to finding a solution with the smallest number of defects at this stage of the analysis and potentially the greatest chance of success. The solution with these advantages is BLDC drives with controlled thrust, compensating for side gusts of wind because the solution abstracts from the facade of the building, which is taken into account only in such a way that it eliminates gusts of wind from its side and sets limits for the position of the facade cleaning machine [21]. The most important parameter determining the applicability of the solution is the value of the forces that can be generated by the propeller drive compared to the forces acting on the machine. The analyses of the forces that may affect the facade washing machine, as well as the forces that may affect the machine laboratory tests and measurements carried out in real conditions, indicate the possibility of using such a solution.

5. Summary and Conclusions

Analysis of the flows showed that a slight change in the axis of operation of the machine's pressure drives favorably affected the efficiency of the windward pressure propeller generating additional force to assist the machine's return to the wash track. This is a beneficial effect, especially due to the possible (and observed in real conditions) phenomenon of the machine pulling away from the windward side of the hill during strong wind gusts. The increased efficiency of the propeller on the windward side has a beneficial effect on stabilizing the machine at the elevation. The results of calculations at different angles of deflection of the drives' axis of rotation in relation to the angle of incidence of the airflow did not give conclusive results. However, a relationship was observed that the least turbulence occurs when the axis of rotation is deflected by an angular value (alpha) close to the angle of incidence of the wind. Due to the unsteady wind conditions on the facades of tall buildings and the phenomenon of wind slipping over a large area of the facade, the alignment of the axis of rotation of the pressure propellers in the 5–10-degree ranges were adopted for the construction of the early prototype.

The decisive criterion was to maximize the efficiency of the windward thrust drive to prevent the machine from being pulled away from the facade and to generate an additional force with the resultant vector directed opposite to the blowing wind (before the lateral drive works).

An advantageous solution would have been the possibility of parallel alignment of both thrusters, but it would have required the operators to change this frequently depending on the machine's orientation with respect to the wind. Moreover, it would generate additional failure risk and production costs.

Several technological concepts were taken into account in the modernization work aimed at improving efficiency. The analysis of the advantages and disadvantages of individual solutions indicated that the solution with the greatest chance of success is a machine enriched with propeller drives responsible for compensating for the influence of side gusts of wind. This choice was made based on the criteria analysis. In this assessment, parameters such as the complexity of the structure, the possibility of correcting the machine trajectory along the facade, the dependence of the operation on contact with the façade, and the effectiveness of adhesion on a wet surface were taken into account. The technical complexity of the solution and scalability were also taken into account. Weights were selected for each criterion, taking into account the importance of a given parameter to assess the action of thought enriched with a given solution stabilizing its path during the impact of the wind. The system based on BLDC drives, despite the relative complexity of the detection and control system, gained a decisive advantage due to the full possibility of position correction and the lack of dependence on the contact with the facade, which also resulted in the highest rating for effectiveness on a wet surface. The high score for the solution's scalability only completed the overall assessment. An early prototype of the solution is shown in Figure 22 below.

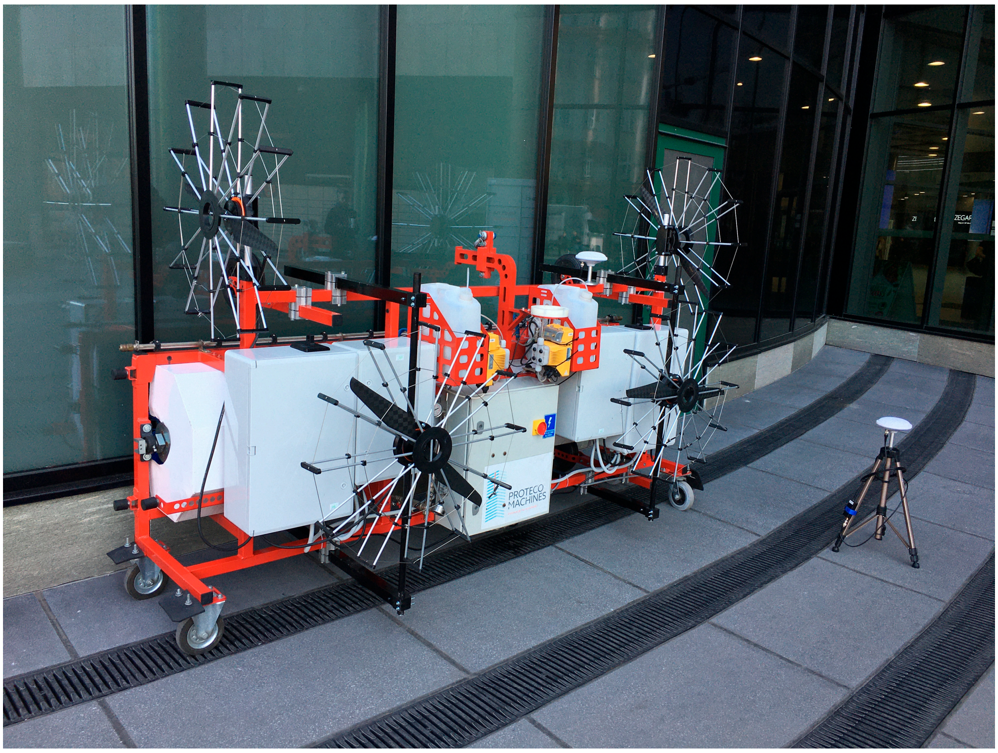

Figure 22. An early prototype of the stabilization system in the washing machine [21].

The main advantage of this solution is that the effectiveness of the solution is independent of the type, structure, and materials used on the building facade. The effectiveness of all other solutions depended, to a greater or lesser extent, on the facade of the building [17].

Summarizing these considerations, the conducted analyses and research gave an answer to the most essential question of this stage: from the technical point of view, which solutions to the problem of washing machine track stabilization give the highest guarantee of effective stabilization of this track in unfavorable wind conditions? The conducted literature analysis showed several solutions to the problem of stabilizing the path of facade washing machines on the market, from which suction cups stabilizing the device, the system of unfastened cables on the building wall, and fans or propellers were commercialized. However, it also indicated that there are no universal solutions. Most of the applied solutions will work in specific conditions (which should be understood as "on specific buildings"), but not in all. In many situations, it is also not possible to use the near-surface effect (negative pressure in the housing) or suction cups because the facade is heterogeneous, and there are many fragments of the facade in the form of openwork louvers. A similar situation may take place in the case of the use of suction cups. Therefore, their effectiveness increases with the number of suction cups distributed over a large area, which significantly increases the cost of manufacturing the machine and the complexity of the system. In search of a possibly universal solution, many systems were considered.

However, much depends on a specific technical solution, such as the place of installation of the control propellers, the drive system control system, the structure of ropes and cables, the detection system, etc. It is also worth noting that this system fits perfectly into the innovative concepts in Industry 4.0. In summary, thanks to the results of the work and research on the effectiveness of the technology, it was possible to implement several solutions leading to the improvement of work efficiency and safety and the development of Industry 4.0.

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