

Shaping an ergonomic hand disinfection station: Design, structural analysis, and universal accessibility validation of a modular research prototype

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ABSTRACT

Fragmented disinfection systems in public spaces reduce prevention effectiveness and increase transmission risk. This research presents a comprehensive design and validation study of a lightweight, modular device casing for multifunctional disinfection and monitoring, combining Prince2 governance with iterative Human-Centered Design and rapid prototyping. Four design variants were developed between 2021–2023, with Version 4 selected for detailed evaluation. The ultra-lightweight stainless steel laser-cut frame ensures accessibility across diverse users: wheelchair users, children, and adults across the 10–90th anthropometric percentiles per ISO 7250-1:2017. Finite element method analyses confirmed structural robustness: under impact loading (400 N), von Mises stress reached 110 MPa with 2.5 mm deformation – well below critical thresholds. Wind load analysis demonstrated exceptional resilience across typical (40 MPa) and extreme hurricane-force conditions (128 MPa at 35.8 m/s). Full-scale ergonomic studies verified comfortable accessibility for wheelchair users across aperture heights of 73.5–98.5 cm. The ballast foundation employs glass fiber-reinforced concrete (GRC), eliminating site preparation while providing exceptional durability and fire resistance (DIN class A1). Rapid service access to critical components prioritizes maintenance during high-risk epidemiological periods. This research demonstrates that designing a modular casing system for a multifunctional device, based on a hybrid methodological approach and aligned with universal design standards and structural resistance requirements, provides an effective research and design direction for disinfection devices in the public health sector.

Keywords: structural materials, mobile disinfection device, modular architecture, ergonomic architecture, lightweight design.

INTRODUCTION

The primary objective of this article is to methodically present the design process of the external casing for a multifunctional device intended for disinfection and health monitoring of individuals in public spaces. The main limitations of currently used disinfection systems lie in

the lack of integration between their individual functions, which necessitates the use of multiple separate devices often located in different areas. Such a fragmented approach increases the risk of viral transmission and reduces the overall effectiveness of preventive measures. The paper includes an analysis and discussion of four selected design variants of disinfection enclosures that

represent the final configuration options. One of the key assumptions in the design process was to ensure a modular structure, enabling replication of the solution and its flexible adaptation to the needs of different user groups, including individuals with functional limitations – both physical and cognitive. An additional requirement concerned the development of a lightweight structure that would not require interference with the existing ground surface. Strength tests and numerical simulations (including finite element method analyses, FEM) were also conducted to design a vandal-resistant frame and an enclosure that meets the normative requirements for the protection of internal components (IP55 protection rating). The comprehensive research project covered an extensive range of studies, including ergonomic, material, structural, and microscopic analyses conducted to assess the bactericidal and virucidal properties of the selected materials. However, the microscopic analyses are presented in detail in publication [28].

One of the strategies for counteracting the spread of epidemic threats involves the use of specialized devices for hand and body disinfection available in public spaces. However, devices located in key public areas often serve merely a psychological rather than a practical role in preventing the transmission of viruses and bacteria. In response to the growing technological demand, an interdisciplinary research team from Wrocław University of Science and Technology, in collaboration with Metaloplastyka Marian Ostrowski, a company specializing in metal processing, undertook the development of an integrated multifunctional device designed for antiviral disinfection combined with health monitoring of individuals moving through public spaces. The research prototype was implemented within the framework of the National Centre for Research and Development (NCBR) competition, project POIR 1198/00. The main objective of the research was to design an ergonomic, mobile casing equipped with a chamber for hand misting using bactericidal agents, with an optional integration of a thermal imaging camera for monitoring public spaces. The studies were preceded by professional ergonomic analyses based on 10th-, 50th-, and 90th-percentile anthropometric models of European men and women. The research work led to the development of several variants of external device casings featuring precise

openings for hands, dedicated placements for the thermal imaging camera, and alternative disinfection systems employing UV chambers. One of the major research outcomes was the development of a misting system based on specialized ultra-low-volume (ULV) nozzles supported by a dedicated hydraulic supply system. Between 2021 and 2023, multiple spatial and modular versions of the disinfection station casing were designed simultaneously.

This article presents four selected casing variants to illustrate the key material, structural, and ergonomic principles underlying the project. Furthermore, a detailed study was conducted on one selected disinfection device casing, chosen for its specific characteristics: (1) use of a lightweight, mobile enclosure enabling rapid relocation of the device; (2) an original internal framework concept employing a modular, laser-cut stainless-steel truss; (3) adjustable height and module dimensions ensuring accessibility for the full range of users, in line with the principles of universal design.

The research innovations encompass both methodological and structural solutions, focusing on the development of an interdisciplinary approach to the design process that integrates materials engineering, ergonomics, architecture, and project management into a coherent research framework. At the methodological level, the key contribution lies in the adoption of a hybrid research approach that combines the Prince2 methodology with an iterative design cycle including the stages of observation, induction, deduction, testing, and evaluation. The research process was further enhanced through the implementation of universal design (UD) and human-centered design (HCD) principles, as well as finite element method (FEM) simulations to validate structural performance.

At the technological level, the novelty of the research concerns the development of a lightweight, modular construction system made of laser-cut components, which ensures rapid assembly, high manufacturing precision, and resistance to mechanical damage and vandalism. The article presents an analysis and discussion of four selected variants of disinfection device housings, representing the final design configurations. In addition, one variant of the device is discussed in detail, selected for its functional characteristics, modular configuration, and compliance with universal design principles.

STATE OF RESEARCH

The COVID-19 pandemic and preventive measures

The COVID-19 pandemic highlighted the crucial role of nonpharmaceutical interventions (NPIs) in public spaces, such as physical distancing, the use of protective masks and appropriate ventilation, as well as hand hygiene and disinfection [1]. A meta-analysis conducted by Chu et al. (2020) demonstrated that maintaining a physical distance of ≥ 1 m between individuals in public areas significantly reduces the risk of viral transmission, while wearing protective masks (including medical and N95/FFP2 types) combined with eye protection further decreases the likelihood of infection. However, discomfort and skin damage were observed among individuals using external protective measures [2]. Similar studies by Ford et al. (2021) confirmed the correlation between mask use and reduced infection risk among mask wearers, emphasizing that mandatory mask policies effectively lower the population-level disease burden [3]. From the perspective of infection prevention, proper hand hygiene and integrated infection prevention and control (IPC) practices are also of critical importance. Special attention should be given to the efficacy of disinfectants against SARS-CoV-2, as well as to the growing interest in electronic monitoring of compliance with hygiene and preventive recommendations, alongside educational initiatives. Research by Xiao et al. (2022) indicated that one of the major challenges in designing disinfection chambers and implementing preventive measures during the COVID-19 pandemic was selecting a disinfectant solution with appropriate properties and composition to ensure the efficient operation of misting nozzles [4]. Lotfinejad et al. (2020), in an editorial commentary, emphasized that low compliance with hand hygiene standards remains a major global concern despite extensive interventions and public health campaigns. The authors noted that alcohol-based hand rubs (ABHR) containing at least 60% ethanol are effective for hand hygiene. At the same time, healthcare workers are encouraged to adhere to the WHO's "My 5 Moments for Hand Hygiene" guidelines: (1) before touching a patient, (2) before clean/aseptic procedures, (3) after exposure to body fluids or risk thereof, (4) after touching a patient, and (5) after touching the patient's surroundings [5].

Research has also focused on the disinfection of surfaces using virucidal and bactericidal agents. Kampf et al. (2020) reported that coronaviruses such as severe acute respiratory syndrome coronavirus (SARS-CoV), Middle East respiratory syndrome coronavirus (MERS-CoV), and endemic human coronaviruses (HCoV) can survive on inanimate surfaces - including metal, glass, and plastic - for up to nine days. Nevertheless, effective inactivation can be achieved within one minute using standard disinfection procedures based on ethanol (62–71%), hydrogen peroxide (0.5%), or sodium hypochlorite (0.1%). The authors further stressed that early prevention of SARS-CoV-2 spread is essential for breaking the chain of infection [6]. Similarly, van Doremalen et al. (2020) discussed the aerosol and surface stability of SARS-CoV-2, noting the persistence of viral particles in aerosols and on surfaces such as plastic and stainless steel [7]. In 2020, during the course of the pandemic, the World Health Organization (WHO) issued comprehensive guidelines for healthcare personnel and patients aimed at preventing SARS-CoV-2 transmission. These recommendations included hand and respiratory hygiene, appropriate use of personal protective equipment (PPE), environmental cleaning, and safe waste management practices [8].

Research on disinfection devices

Studies also indicate a growing interest in electronic systems for monitoring hand hygiene and preventive practices. Kelly et al. (2021) extensively examined Electronic Hand Hygiene Monitoring Systems (EHMS) and compared their performance to traditional manual auditing methods [9]. The COVID-19 pandemic significantly increased the demand for rapid, touchless disinfection systems. Bista et al. (2025) compared the effectiveness of manual disinfection with that of an automated robot in two hospitals dedicated to COVID-19 treatment in Nepal. According to their findings, both manual and robotic disinfection reduced the presence of pathogens from 12 bacterial families classified as global priority pathogens (GPPs). However, robotic disinfection demonstrated higher efficiency, reducing microbial load in 58.3% of samples compared to 25% for manual methods. The superiority of robotic disinfection is primarily attributed to the elimination of human error and the precise dosing of disinfectant agents [10]. Martins et al. (2022) conducted a

systematic review of disinfection methods effective against SARS-CoV-2. The authors analyzed strategies applied to environmental surfaces, skin and mucous membranes, air, and personal protective equipment (PPE). The findings indicated that the most effective disinfectants include alcohols (62–80%), sodium hypochlorite ($\geq 0.1\%$), hydrogen peroxide ($\geq 0.5\%$), and UV-C radiation. The study emphasizes that a comprehensive approach combining multiple disinfection strategies is essential for effective prevention of SARS-CoV-2 transmission [11]. During the COVID-19 pandemic, numerous design concepts for disinfection devices emerged, particularly from India and China. One such innovation was presented by Samal et al. (2020), who developed an automated hand hygiene device integrating a touchless disinfectant spraying mechanism, body temperature measurement, and internet of things (IoT) connectivity for real-time monitoring [12]. Another prototype, proposed by Kumar et al. (2020), introduced a portable device for surface and air disinfection. The project aimed to create an easily transportable, cost-effective solution suitable for widespread use in public spaces. The study presents prototype testing results, including aerosol generation performance and disinfection efficiency in enclosed environments [13].

Patents related to disinfection devices

Before and during the COVID-19 pandemic, a number of patents were filed concerning multifunctional disinfection devices. One notable example is the Korean patent KR101751677B1 (2016), which describes an innovative system combining hand disinfection with user body temperature measurement. The solution is intended for public spaces such as schools, kindergartens, and office environments, where hygiene and health monitoring are essential. The system consists of a mirror equipped with a hand sanitizer dispenser located in its lower section, and a thermal imaging camera installed in the upper section, which automatically activates when the sanitizer is used [14]. In 2016, Altitude Medical, Inc. developed the patent “Device to Promote Hand Sanitization” (US9255423B2), which introduces a solution aimed at improving hand hygiene by integrating a disinfection mechanism with door-handling components. The device combines a handle, lever, push panel, or door latch with a disinfectant dispenser. When a user opens

or closes the door, the mechanism automatically dispenses a portion of disinfectant onto the user’s hands. The sanitizer can be delivered through a perforated handle surface, porous material, or fluid-dispensing nozzles. This solution can also be integrated into other objects that come into direct contact with the user’s skin in public spaces, including healthcare facilities [15]. A significant number of patent inventions in this field originate from the Chinese market. One example is the 2021 patent titled “Method and Apparatus for Hand Disinfection and Disinfection Quality Control”, which describes a method for hand disinfection combined with automated quality control. The invention enables automated verification of hand disinfection effectiveness, potentially reducing the incidence of healthcare-associated infections (HAIs). The method involves adding a light-reflective compound to a standard disinfectant formulation. This allows differentiation between areas of the hands adequately covered by the disinfectant and those insufficiently treated. The control device includes an imaging chamber in which the hands are illuminated by light sources of specific spectra (UV, IR, or visible). The results are displayed to the user in real time (e.g., on a screen), allowing immediate correction of inadequately disinfected areas [16]. Another relevant patent, “Portable Disinfection Device” (2020), concerns the development of a lightweight personal disinfection unit utilizing UV-C radiation within the 200–280 nm wavelength range. Owing to its portability and structural durability, this device is suitable for both daily personal use and applications in environments with limited access to conventional sterilization methods [17].

A review of the available scientific literature and patents shows that the topic of hand disinfection in public spaces is an intensively explored area of research, particularly in the context of the COVID-19 pandemic and future epidemiological threats. Numerous patent filings covering a wide range of hand and body disinfection devices, as well as theoretical review and conceptual papers, confirm an important trend toward integrating disinfection functions with other components such as temperature measurement, UV sterilization, hygiene quality control, or mechanisms supporting process automation. However, an analysis of existing studies and solutions reveals a significant gap between the theoretical and prototypical stages and practical implementation in public spaces. Most works focus on the laboratory or design phase,

rarely presenting results of user tests conducted under real-world conditions, including long-term device durability, user ergonomics, or social acceptance. Consequently, there is a clear need for application-oriented and experimental research aimed at validating prototypes in real conditions and developing integrated disinfection systems.

METHODOLOGY

Design approach

The development of a multifunctional device for antiviral disinfection and health monitoring in public spaces was conducted by an interdisciplinary team combining expertise in materials engineering, ergonomics, architecture, and industrial product design. The research process, structured according to the Prince2 methodology, was divided into industrial, developmental, and pre-implementation stages. Due to the complexity of the task, a hybrid research model was adopted, integrating technological, ergonomic, and design aspects. The design process followed an iterative cycle of Observation, Induction, Deduction, Testing, and Evaluation [18], complemented by

the principles of human-centered design (HCD) (Figure 1). In line with ISO 9241-210:2019, HCD ensures a strong link between design decisions and user needs through iterative testing, user participation in validation, and the inclusion of ergonomics and safety at all stages. All activities related to functionality, usability, component accessibility, and visual identification were based on universal design principles. Elements of the design thinking methodology were also applied, focusing on user empathy, variant generation, and rapid prototyping [19], [20]. The process incorporated rapid prototyping techniques and testing of physical and digital models under laboratory and near-real conditions using additive manufacturing [21].

The development of external casing variants followed the principles of UD and HCD, emphasizing inclusivity for users with diverse physical, perceptual, and cognitive abilities [22] (Figure 2). According to the United Nations Convention on the Rights of Persons with Disabilities (2006), universal design refers to creating products, environments, and services usable by all people, to the greatest extent possible, without the need for adaptation or specialized solutions [23]. Ergonomic studies were carried out in several stages.

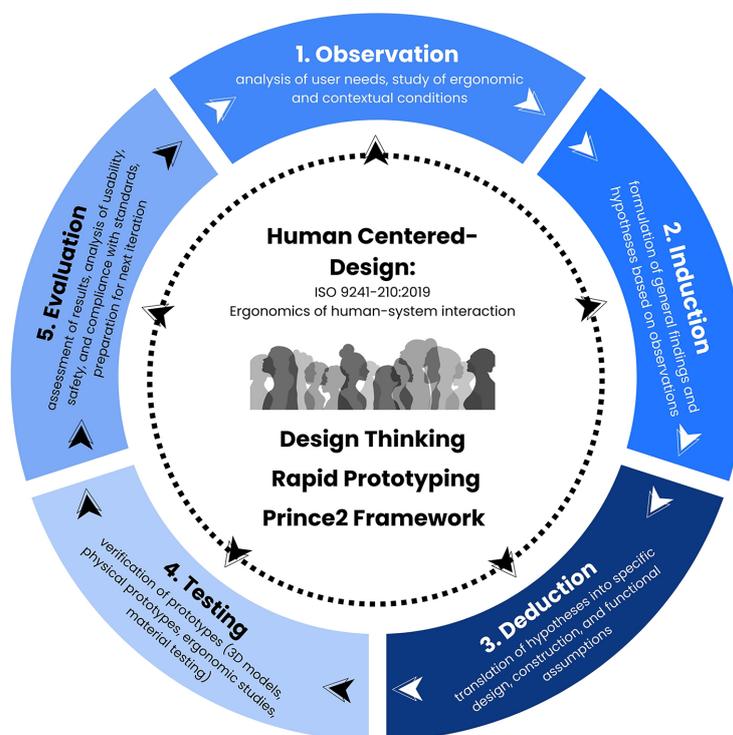


Figure 1. Diagram of the adopted research methodology presenting a hybrid model that integrates the iterative product design process with the approaches of Human-Centered Design, Design Thinking, and Rapid Prototyping, based on the Prince2 project methodology. Illustration: author’s own elaboration

In the initial phase, 2D and 3D virtual simulations were conducted in CAD environments using anthropometric models based on ISO 7250-1:2017 [24], covering the 5th to 95th percentile range. This approach enabled the identification of critical accessibility zones and reach parameters for different user groups, including adults, children, older adults, and individuals with limited mobility. The resulting design guidelines were verified through full-scale (1:1) laboratory and quasi-real testing to confirm access to key interface components and evaluate ergonomic performance. After validating accessibility, the casing design was iteratively refined to optimize component layout and ensure full compliance with universal design principles as described by Kroemer Elbert et al. (2018) [25].

3D modeling of mechanical component

As part of the research conducted between 2021 and 2023, the team developed approximately 20 spatial modular housings for disinfection

stations. Due to the need to design multifunctional device components, the research was associated with several technological challenges, including:

- Ensuring a lightweight, modular housing, which required precise laser cutting of stainless steel sheet panels. The materials of sheet panels were selected on the basis of previous work [28], where extensive material tests were carried out.
- Using an appropriate disinfectant fluid mixture with virucidal and bactericidal properties capable of supporting high-performance misting nozzles, which necessitated reducing glycerin content due to its high viscosity.
- Enabling easy and rapid relocation of the device to subsequent sites, which required minimizing internal components that could increase the housing volume and consequently the overall weight of the device.

These constraints influenced the dimensions of the housing and required reducing the number of components, resulting in the selected

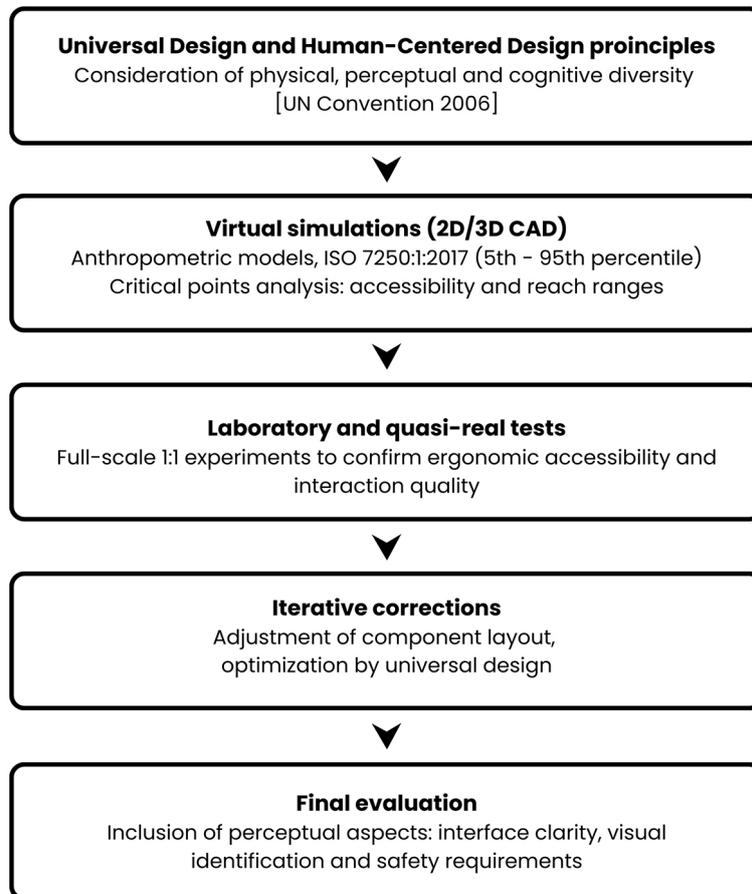


Figure 2. Diagram illustrating the ergonomic research process of the disinfection device as one of the stages of the iterative design procedure

version for further research having diminished disinfection capabilities.

The first stage of designing the device's external housing involved 2D and 3D computer simulations of various design options. In addition, the structural integrity of the modular housing and its key joints was preliminarily verified using FEM numerical simulations to identify potential stress concentrations and validate the assumed geometry/material configuration under representative handling and operating loads. This approach is consistent with FEM-based strength assessment workflows reported in the literature; for an example of a detailed FEM stress analysis procedure, see Decker et al. [26]. One of the applied research methods included 3D simulation of device components combined with an experimental approach consisting of developing a series of spatial solutions that adhered to ergonomic principles and universal design guidelines.

The preliminary assumptions for the component housings included:

- The use of side panels made from materials allowing inspection access;
- The application of antibacterial materials in housings of sensitive elements such as the ozonator;
- The use of hydrophobic and aseptic materials in areas intended for contact with organic tissue;
- Independent construction and housing of individual components to facilitate their replacement without compromising the integrity of the entire system;
- Adjusting the internal geometry of the component housings to match the form of the main external housing through the use of curvilinear shapes.

As part of preparing the workstation for component testing, a series of 2D and 3D models was developed, constituting preliminary research experiments related to the construction and form of the component housings. (Table 1). The table below provides a summary of four types of device housings for disinfection units that were thoroughly examined in accordance with the developed research methodology.

Next, two 3D versions of the disinfection device were selected as the basis for producing models using 3D printing technology. The developed 3D models were saved as stereolithographic (*.stl) files and subsequently exported

for 3D printing using software compatible with a Makerbot Replicator Z18 printer, employing PLA filament (odorless, biodegradable polylactide). The next step in the research process involved properly preparing the workstation for cleaning the printed models and assembling individual components. As part of the 3D printing activities, two working models with a height of 15 cm were produced and subsequently analyzed in terms of visual characteristics, usability, and spatial suitability within various urban contexts of the built environment.

As part of the small-scale model studies, preliminary 3D models were created, forming the basis for preparing the printed prototypes. Version no. 3 received intellectual property protection as a utility model entitled "Housing for a Hand Virucidal Disinfection Device" (registration no. W.131878, issued by the Polish Patent Office) and constitutes a separate development; therefore, its technical solutions are not discussed in this article. Further research presented in this study focuses on version no. 4, which also represents one of the final product variants of the disinfection device.

The device prototype – version no. 4

The housing of the disinfection device (version no. 4) is dedicated to a unit determined primarily by a component designed for dispensing protective masks. The hand-disinfection module is mounted at a height of 1200 mm, while the upper section accommodates a thermal imaging camera and an LCD display. The lower section provides space for a liquid tank and a pump unit. The device width of 400 mm ensures the possibility of installing all components and enables replicating clusters in any configuration. Within the research analyses, the stages of individual tasks were prepared with particular attention to optimizing the fabrication of specific parts and unifying the production process.

The next phase of the research involved analyzing the external housing element mounted on a frame made of C-shaped structural profiles, combined with a powder-coated stainless steel cladding. The element is intended to be produced in two variants:

1. Variant 1: A curved, bent element with a radius of R150 mm; all edge elements will be rounded to ensure user safety in both outdoor and indoor environments. All bent edge elements will be unified to optimize the production line.

Table 1. A comparative summary of the four selected versions of the disinfection device, accompanied by a discussion of key aspects of component accessibility

No.	Device type (width, depth, height)	Disinfection compartment	Ozonation compartment	Mask dispenser	Thermal imaging camera	Linear scheme
1.	Modular version with the option of suspension on a vertical surface; adapted for use by people with mobility impairments and for disinfection access height suitable for children; module dimensions: 550 × 350 × 1100 mm	Disinfection chamber located at h = 500 mm; height measured from the bottom of the casing; with adjustable height by suspension at any level of the wall surface	No ozonation chamber provided	No mask dispensing chamber provided	No thermal imaging camera with LCD display provided	
2.	Curvilinear version in a triangular arrangement; access from 2 or 3 sides to device components (1110 × 900 × 2000 mm)	Two or three disinfection chambers located at h = 1000 mm	Ozonation chamber located at h = 1000 mm	Mask dispensing unit at h = 550 mm; chamber with a rectangular cross-section	Thermal imaging camera with the lens located at h = 1700 mm; possibility of installing an LCD screen	
3.	Free-standing version with the option of mounting on a ballast foundation or suspended on a vertical surface; upper and lower zones as a bent casing adapted to radius R = 275 mm; module dimensions: 550 × 350 × 1800 mm	Disinfection chamber located at h = 1000 mm; height measured from ground level at the bottom of the ballast foundation	No ozonation chamber provided	No mask dispensing chamber provided	Thermal imaging camera with the lens located at h = 1700 mm; possibility of installing an LCD screen	
4.	Curvilinear version with modular connection capability to adapt to user needs; dimensions of a single module: 350 × 900 × 2200 mm	Chamber in a profiled zone at h = 1200 mm or h = 800 mm (installation of mist nozzles in the curved section of the casing)	Ozonation chamber provided at h = 750 mm with a rectangular cross-section	Mask dispensing unit provided at h = 450 mm; chamber with a rectangular cross-section	Thermal imaging camera provided with the lens located at h = 1700 mm; possibility of installing an LCD screen	

From an ergonomic perspective, the rounded elements will protect users from striking sharp edges of the device.

2. Variant 2: Bent, straight, folded elements. This represents an iterative attempt to redesign the external housing, particularly the edge components. Iteration no. 2 addresses the challenge of bending to a specified radius of R150 while also attempting to eliminate sharp edges; minimal rounding will be applied along the bending lines. This approach corresponds to folding-structure solutions (Figure 3, Figure 4). The device housing consists of modules mounted on a steel frame of the C50 type (50 × 20 × 2 mm), composed of flat (FP) and bent (BP) enclosure panels. The bending radius of the BP panels at the device corners was adopted

as a constant 150 mm in each corner, ensuring user safety and smooth edge transitions. Each module (A1, B1, C1) includes peripheral bends with identical radii, allowing for production standardization and component repeatability. On the left side, a 1:1 scale silhouette of an adult user is shown, enabling an assessment of proportions and operational heights.

Additionally, user ergonomics were analyzed. With the configuration in which the mask-dispensing component determines the spatial arrangement, placing the hand-disinfection module at approximately 1200 mm would make it accessible only to adults, excluding children and wheelchair users. Therefore, an alternative scenario was analyzed, involving rotating the unit by

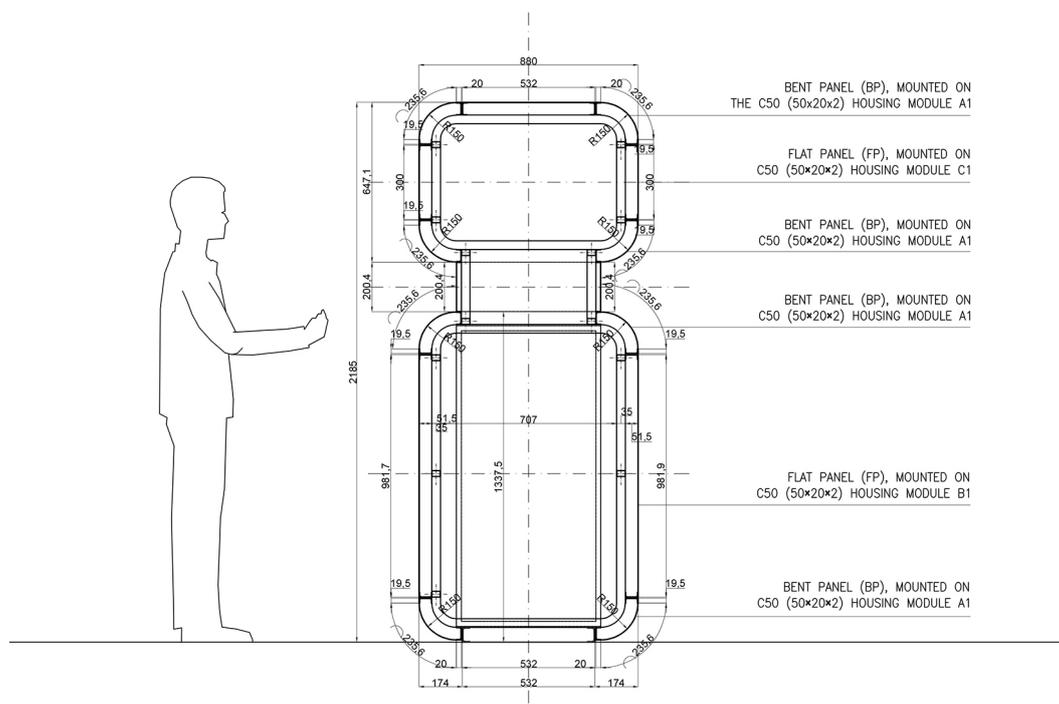


Figure 3. Version no. 4 illustrating the shaping of the modular housing: functional solutions of the freestanding model. The drawing presents the front elevation of the modular disinfection device, with key dimensions indicated for the assembly process and ergonomic analysis. The device housing consists of modules mounted on a steel frame of the C50 type (50 × 20 × 2 mm), composed of flat (FP) and bent (BP) enclosure panels. On the left side, a 1:1 scale silhouette of an adult user is shown, allowing for the assessment of proportions and operational heights. Illustration: author.

180 degrees to ensure access to the disinfection function for wheelchair users and children. The device in version no. 4 is equipped with the following functional components integrated into the modular housing system:

1. Thermal imaging module with LCD interface: this component enables continuous monitoring of the body temperature of individuals approaching the device. The LCD display provides real-time instructions on the correct positioning distance and presents the measured temperature accompanied by an indication of whether the value falls within the acceptable threshold.
2. Hand disinfection module: the disinfection unit incorporates high-efficiency ULV misting nozzles, ensuring effective aerosol dispersion of the virucidal solution. The ergonomic geometry of the opening enables intuitive and stable hand placement, improving user interaction and reducing operational error.
3. Mask dispensing and ozonation module: the two-column mask dispenser uses a Magic Gripper mechanism combined with a mechanical feed system that ensures reliable

distribution of protective masks. An additional ozonation module enables disinfection of small personal items, activated in an independent operational cycle. All components may be installed independently, although appropriate insulation of units containing disinfectant fluids is recommended to maintain system safety and performance.

The primary structural framework of the device consists of a lightweight steel skeleton made from laser-cut, closed-section profiles. The external enclosure is formed by modular, laser-cut sheet-metal panels finished with a durable powder-coated surface. The structural configuration provides a high level of vandal resistance. The housing underwent FEM analysis (Section 3.5. finite element analysis), confirming its mechanical integrity under typical operational loads. The external panels have a modular bent-sheet configuration, and the color finish may be selected from the full RAL palette according to user requirements. Owing to the modular design of all components, the device allows rapid assembly and efficient replacement of individual modules

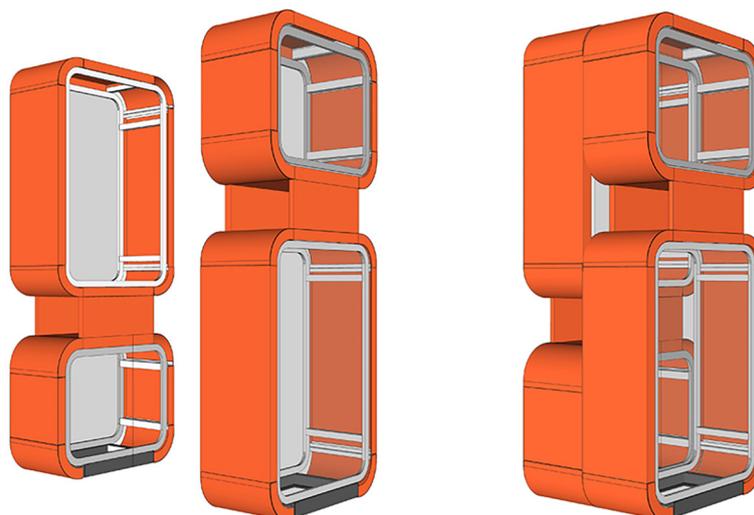


Figure 4. Modelling of configuration variants for device version no. 4, adapted to different user needs

during maintenance or system reconfiguration. Additionally, ergonomic principles were applied to coordinate the height of individual components with the height and reach ranges of users, and iterative 2D and 3D versions of the housing were developed to refine the device's usability and spatial configuration (Figure 5, Figure 6).

Structural design

The development of the modular housing for the disinfection device was carried out in multiple stages. Research on material selection for the housing and 2D and 3D modeling proceeded simultaneously, enabling the adaptation of design solutions based on material testing results.

A key aspect of the external housing research was the creation of internal component housings with inspection access to critical device elements. The basic assumption was to allow inspection access to individual component elements without compromising structural integrity. One of the research methods employed was 3D simulation of the device components, combined with an experimental approach involving the creation of a series of spatial solutions that incorporated ergonomic principles and universal design.

1. Preliminary assumptions for the component housings included:
2. Side panels made from materials allowing inspection access;
3. Critical housings, such as those containing the ozonator, made from antibacterial materials;
4. Areas in contact with organic tissue constructed from hydrophobic, aseptic materials;

5. Independent construction and housing of components, allowing removal without compromising structural integrity;
6. Internal housing shapes adapted in a curvilinear manner to the main external housing.

As part of the preparation for component testing, a series of models was created, constituting preliminary research experiments related to the design and shape of component housings. The objective of the modular construction research was to design a housing that allowed unobstructed and rapid service access, which is particularly necessary during periods of increased infectious disease incidence.

Another critical factor was maintaining environmental resistance (IP55), vandal resistance, user safety, and hygiene requirements. Parallel research focused on a high-efficiency misting process. The construction was designed according to the DfMA (Design for Manufacturing and Assembly) approach, aiming to minimize material waste and reduce assembly time.

An important aspect was ensuring inspection access to device components while maintaining user safety through the absence of sharp edges (radii $R \geq 1$ mm). A crucial element of the prototyping process was the execution of FEM simulations.

Ergonomic analysis

Following the 3D simulations, working research stations were prepared in a laboratory environment to conduct ergonomic studies on the

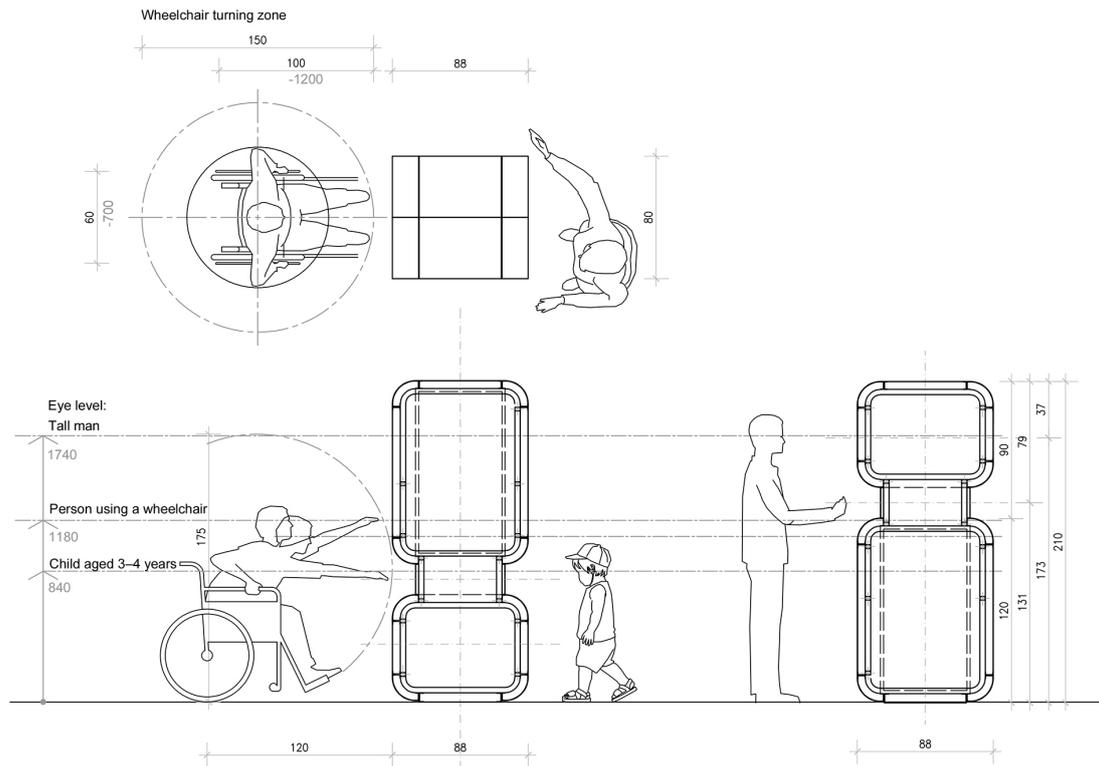


Figure 5. 2D ergonomic analyses conducted as part of the preliminary design and research work for version no. 4

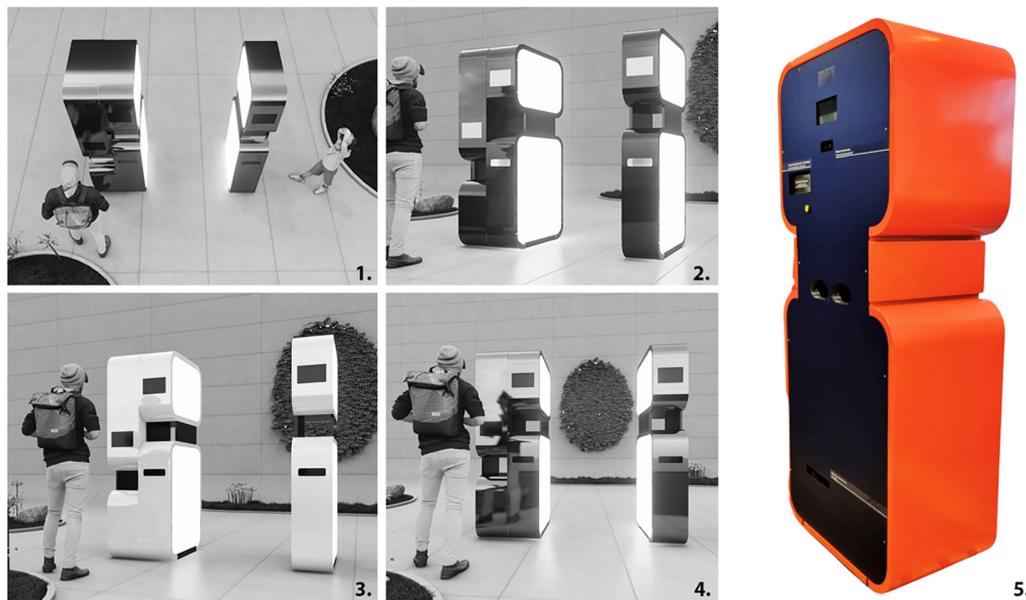


Figure 6. As part of the design work, a series of iterative solutions was developed for each housing version through 2D and 3D modelling. Figures 1–4 present selected iterative visualizations for device version no. 4. Figure 5 shows the final prototype version produced for research purposes

accessibility of critical components of the disinfection device. Ergonomic analyses included assessments of users' reach and arm span in both standing positions and seated positions using a wheelchair. Ergonomic research is essential for the further development of the device housing

and for determining the placement of individual components. According to the definition proposed by the International Ergonomics Association (IEA), ergonomics is a scientific discipline concerned with the study of interactions between users and other elements of a system [27].

A table of measurements was developed, including arm reach, elbow and knee joint height, and eye level. During the first stage of the study, experiments were conducted for both standing and seated positions using an electric wheelchair for individuals with limited mobility.

The following sensitive elements were analyzed, for which an acceptable range of access was defined:

1. Accessibility for hand disinfection for adults in a standing position (analyzed separately for European males and females at the 10th, 50th, and 90th percentiles);
2. Accessibility for hand disinfection for children aged 5–15 years in a standing position (analyzed separately for European males and females at the 10th, 50th, and 90th percentiles);
3. Accessibility for users in a wheelchair with mobility impairments;
4. Accessibility for facial assessment using the thermal imaging camera for adults and children, both male and female, European origin, at the 10th, 50th, and 90th percentiles;
5. Accessibility for additional components, including the mask-dispensing chamber and the ozonation chamber.

The studies were conducted using 2D and 3D simulations for selected housing versions. Additionally, the simulation assumptions were verified by creating mock-ups of the selected housings and analyzing accessibility using the foldable electric wheelchair AT52304 Antar.

The aim of the study was to determine accessibility and the ergonomics of user interaction with the disinfection component in relation to mounting height and upper limb reach. Extreme anthropometric points (eye level, elbow and knee height, maximum horizontal and vertical reach) were verified in two mobility modalities: standing and seated on an electric wheelchair for users with functional limitations. Pilot studies involved participants without medical contraindications.

The research apparatus and workstation included:

1. A full-scale 1:1 workstation with adjustable mounting of the disinfection component across 10 height planes (50 mm intervals; range 600–1150 mm to the lower edge of the operational opening);
2. A prototype configuration of the disinfection component (sleeve opening, protective collar, hand presence sensors);

3. Electric wheelchair AT52304 Antar (factory configuration);
4. Data recording equipment (perspective-calibrated video camera, video recordings, and photographic images).

Experimental scenarios were developed to assess accessibility in a laboratory setting using the full-scale 1:1 workstation. Two example scenarios are presented below: a user in a wheelchair and a standing user of varying height.

Moreover, the device has been tested under real-world field conditions in public spaces (see Figure 7), which confirms its ability to operate under practical usage scenarios.

During a one-month field-testing period, the device was deployed in selected public spaces and operated under everyday usage conditions involving diverse user groups. The tests were conducted in both open-access environments and inside building, exposing the device to regular public interaction and variable environmental conditions.

Overall, the device demonstrated stable and reliable performance throughout the testing period. Only minor operational issues were observed, none of which affected the core functionality or safety of the system. These included occasional superficial contamination of external surfaces, and temporary reductions in visibility of informational labels due to weather exposure.

Importantly, no structural damage, functional failures, or safety-related issues were recorded. The observed minor issues were easily mitigated through standard maintenance procedures and are considered typical for devices operating in public spaces.

Finite element analysis

The selected version (No. 4) was subjected to numerical calculations to assess the impact of key operational and environmental loads. The following load cases were considered:

- Impact (U): a concentrated force applied over a surface with a diameter of 150 mm with a value of 400 N. Since the device is intended to withstand an impact from a 30 kg sledgehammer, a dynamic force safety factor of 1.33 was applied, resulting in the adopted value: $400 \text{ N} = 30 \text{ kg} \cdot 10 \text{ m/s}^2 \cdot 1.33 = 400 \text{ N}$
- Wind load (W): $v = 20 \text{ m/s} \rightarrow q = 0.25 \text{ kPa}$. This corresponds to a Class II wind, characterized as a “gale” (capable of causing

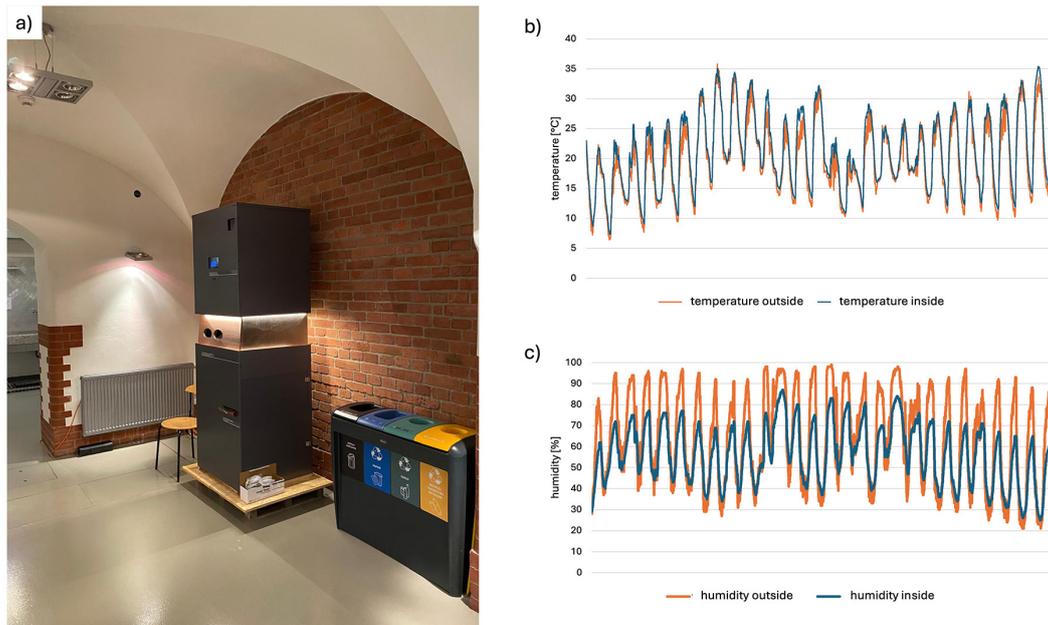


Figure 7. Testing of the device under real-world field conditions, a) next generation of device in public space, measurement of the temperature (b) and the humidity (c) inside and outside the device

building damage, tearing off roof tiles, and breaking entire trees).

- Extreme wind load (WW): $v=35.8 \text{ m/s} \rightarrow q = 0.8 \text{ kPa}$. This wind exceeds Class V (hurricane or tornado conditions – causing destruction, devastation, and potentially fatal accidents) and is assigned to Class V-1 (strong hurricane or severe tornado, commonly referred to as hurricanes, cyclones, or typhoons). At this wind speed, all mechanical devices, such as open-pit mining equipment (conveyors, excavators), would be rendered inoperable.

The aerodynamic wind pressure (q) was calculated using the formula, where v [m/s] represents the wind velocity:

$$q = \frac{v^2}{1600} \left[\frac{kN}{m^2} = kPa \right] \quad (1)$$

The coatings were assigned a thickness of 3 mm and attributed the material properties of steel. A detailed summary and description of the structural and cladding materials used in the project, as well as the methodology of the material tests, are presented in Widomski et al., 2025 [28].

The models shown in (Figure 8a) were initially obtained as volumetric solids. Subsequently, all decorative elements (panels), internal equipment (pumps, compressors, feeders, and other auxiliary devices) were removed, leaving only the

load-bearing structure forming the device frame. Surface models of the frames were then prepared.

During the creation of the surface models, the overall dimensional envelope was preserved, and the modeled surfaces were positioned at the mid-thickness of the sheet metal. This ensured that when thickness was later applied, it was distributed symmetrically on both sides of the surface and aligned with the actual volumetric model of the examined solution.

The model was then discretized for FEM analysis using surface elements with six degrees of freedom (Figure 8b). The average finite element size was 40 mm, while the maximum discretization error (the distance between any finite element and the discretized surface) was 1 mm. Additionally, the finite element mesh was refined at radii to more accurately represent the analyzed components.

Boundary conditions, including constraints and loads, were assigned to the prepared models. For the constraints, six degrees of freedom (3 translational, 3 rotational) were fixed at the surfaces in direct contact with the ground. The analyzed components were assigned the material properties of steel. The computational model (discretized model with boundary conditions) illustrating the application of constraints and loads is shown in Figure 9. Next, thickness was assigned to the coatings based on the provided volumetric model.

Numerical strength analyses (FEM) supported the design of a vandal-resistant frame and

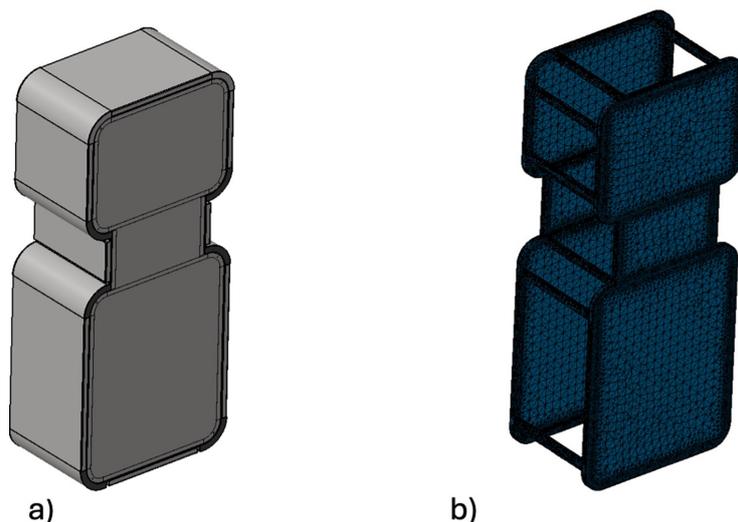


Figure 8. 3D models of the device reconstruction: a) volumetric model, b) after the discretization process

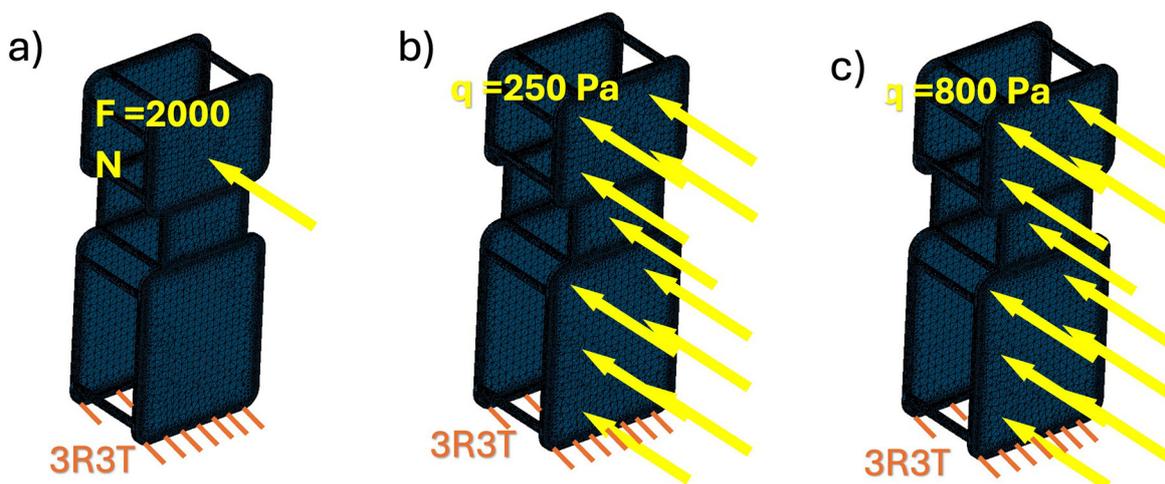


Figure 9. Computational model illustrating the application of constraints and loads for the considered cases: a) impact (U), b) wind load (W), c) extreme wind load (WW)

housing that meet IP55 requirements for the protection of internal components. In the final stage of the research on the device, a process for data reporting and synchronization from the key components of the device was developed (Figure 10).

RESULTS

Ergonomic analysis

Scenario No. 1 (limited mobility): The participant, seated in an AT52304 Antar electric wheelchair, approaches the workstation; the component is set at a randomly selected height from the 10 available planes. Task: insert the hands into the component and maintain the position for

5 seconds; record accessibility, time, subjective ratings, and comments.

Scenario 2 (full mobility): The participant approaches the workstation with the disinfection device component positioned on one of twelve height planes. The participant then inserts their hands into the disinfection component to perform analyses of the anthropometric extreme points in relation to height.

Due to the need to adapt the device to the principles of universal design and barrier-free product design, particular emphasis was placed on conducting the analysis from the perspective of individuals using wheelchairs. Table 2 presents a summary of the analyses for scenario no. 1 (limited mobility).

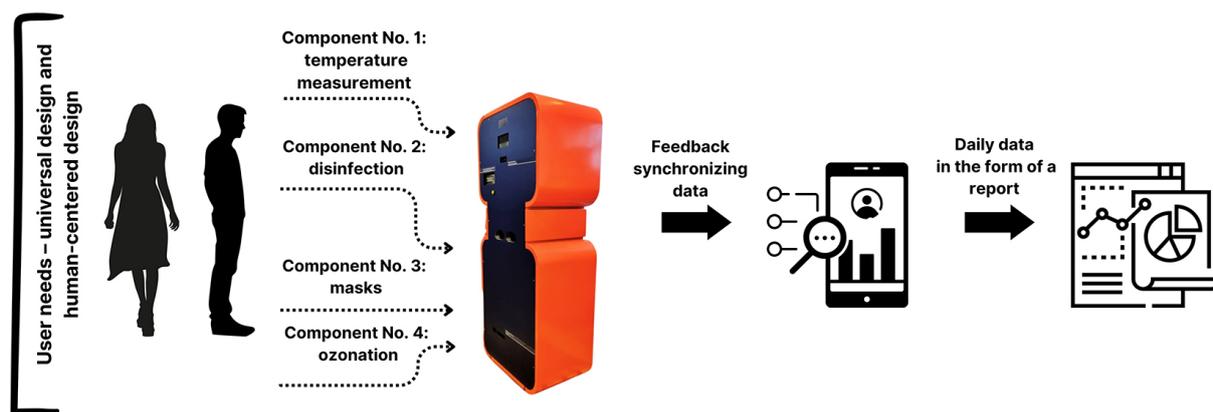


Figure 10. Schematic representation of the data acquisition and reporting process from the functional components of the disinfection device

Table 2. Presentation of critical points for ergonomic analyses for two example participants in a seated position using the specialized AT52304 Antar electric wheelchair. The color scale is defined as follows: Red indicates not met (height inaccessible or significantly hindered), Yellow indicates partially met (height conditionally accessible or requiring additional support), and Green indicates met (height fully accessible in accordance with universal design principles)

Participant No. 1 subjected to the laboratory experiment: seated position						
Position no.	Height of the shelf with the disinfection component [cm]	Height to the elbow joint [cm]	Height to the knee joint [cm]	Height to the shoulder joint [cm]	Eye level height [cm]	Perceived comfort in the given position
1.	58.5	71.0	60.0	95.0	113.0	Red
2.	63.5	76.0	60.0	98.0	113.0	Red
3.	73.5	80.0	60.0	98.0	113.0	Yellow
4.	78.5	87.0	60.0	98.0	113.0	Green
5.	89.0	90.0	60.0	98.0	113.0	Green
6.	93.0	96.0	60.0	100.0	113.0	Green
7.	98.5	98.0	60.0	102.0	113.0	Red
8.	103.5	102.0	60.0	103.0	113.0	Red
9.	108.5	105.0	60.0	104.0	113.0	Red
10.	113.5	107.0	60.0	105.0	113.0	Red
Participant No. 2 subjected to the laboratory experiment: seated position						
Position no.	Height of the shelf with the disinfection component [cm]	Height to the elbow joint [cm]	Height to the knee joint [cm]	Height to the shoulder joint [cm]	Eye level height [cm]	Perceived comfort in the given position
1.	58.5	73.0	65.8	95.8	113.3	Red
2.	63.5	77.3	65.8	94.7	113.3	Red
3.	73.5	83.0	65.8	95.2	113.3	Yellow
4.	78.5	84.1	65.8	97.1	113.3	Green
5.	89.0	87.4	65.8	98.3	113.3	Green
6.	93.0	91.5	65.8	97.4	113.3	Green
7.	98.5	95.7	65.8	98.0	113.3	Red
8.	103.5	97.0	65.8	98.3	113.3	Red
9.	108.5	113.3	65.8	100.4	113.3	Red
10.	113.5	103.4	65.8	101.7	113.3	Red

Note: The green color indicates the arm reach ranges that allow comfortable use of the hand disinfection component for the two selected participants in the experiment.

Out of approximately 20 housing variants developed between 2021 and 2023, four versions were selected and discussed in this article. One of the most promising versions, No. 4, was chosen, including obtaining a utility model. These versions are considered the most promising in terms of functionality, ease of relocation to other sites, and suitability for the full spectrum of users.

2D and 3D simulations conducted in accordance with ISO 7250-1:2017, as well as full-scale (1:1) pilot studies, confirmed the accessibility of components in both standing and seated positions for wheelchair users. The pilot study identified extended comfort zones for both mobility modalities, which informed the iterative adjustment of component placement.

Finite element analysis

The prepared models were used to perform numerical simulations using the finite element method. The first analyzed load case (U) was an impact on the upper part of the housing with a force of 400 N, which caused a maximum sheet deflection of 2.5 mm. Detailed results are presented in Figure 11 in the form of contour plots of von Mises reduced stresses (values in MPa) and displacement vectors (values in mm). As can be observed, the maximum stress reached a value of 110 MPa.

The second analyzed case (W) was wind loading at a velocity of 20 m/s, generating a surface pressure of 0.25 kPa. The results of the

calculations are presented in Figure 12. The maximum stress was 40 MPa, while the deflection of the housing reached 0.6 mm. These values are significantly lower than in the first case, with the greatest deflection occurring in the lower part of the housing.

In the third case, an extraordinary load (WW) was assumed, corresponding to hurricane-force wind with a velocity of 35.8 m/s, generating a surface pressure of 0.8 kPa. Numerical calculations (Figure 12) showed that the displacement reaches a maximum value of 2 mm, which is lower than in the first analyzed case, while the stress reaches 128 MPa, the highest among all three cases.

For a clearer illustration, the maximum values of the obtained stress and displacement results for each load case are presented in Table 3.

During physical implementation, particular attention should be paid to the welding of the closed-profile frame sections, as they will act as stress concentrators under loading, especially in the impact load case (U). Additionally, the number of attachment points for the front and rear panels to the housing frame should be increased. It is recommended to use no fewer than 20 attachment points.

For the calculations, the front and rear panels were assumed to be part of the frame, meaning that the fasteners must be able to transfer operational loads under the following conditions: U – impact, W – wind, and WW – extreme wind. The fasteners cannot serve solely

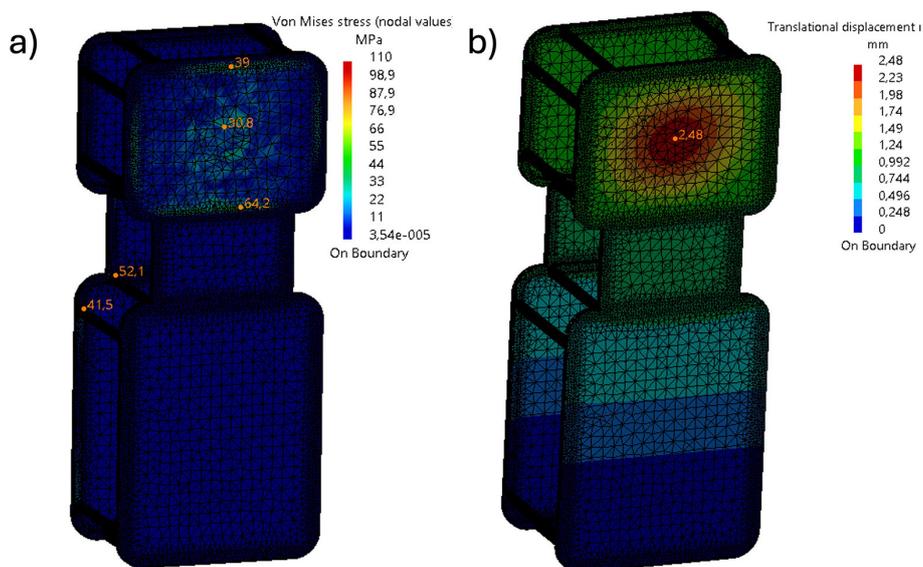


Figure 11. Calculation results for the load case U (impact): a) contour plots of von Mises stress (values in MPa); b) displacement (values in mm)

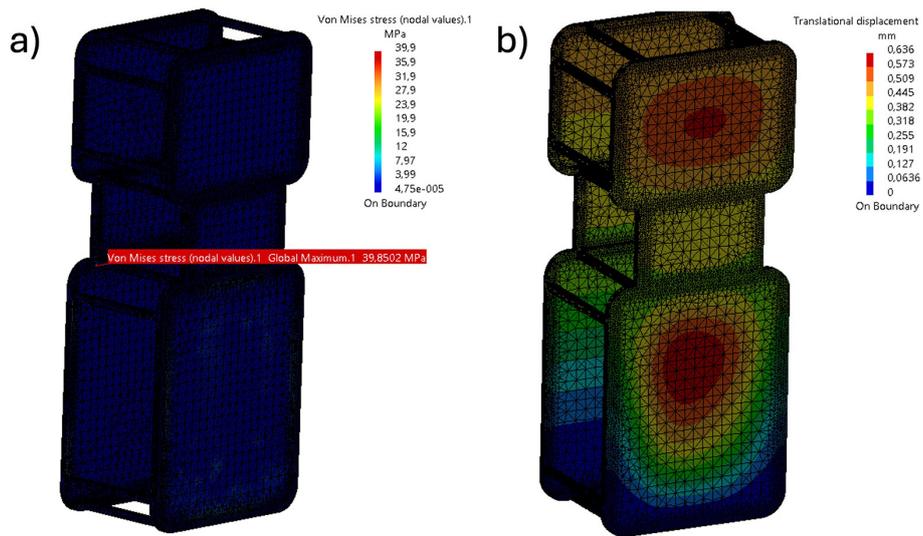


Figure 12. Calculation results for the wind load case W: a) contour plots of von Mises stress (values in MPa); b) displacement (values in mm)

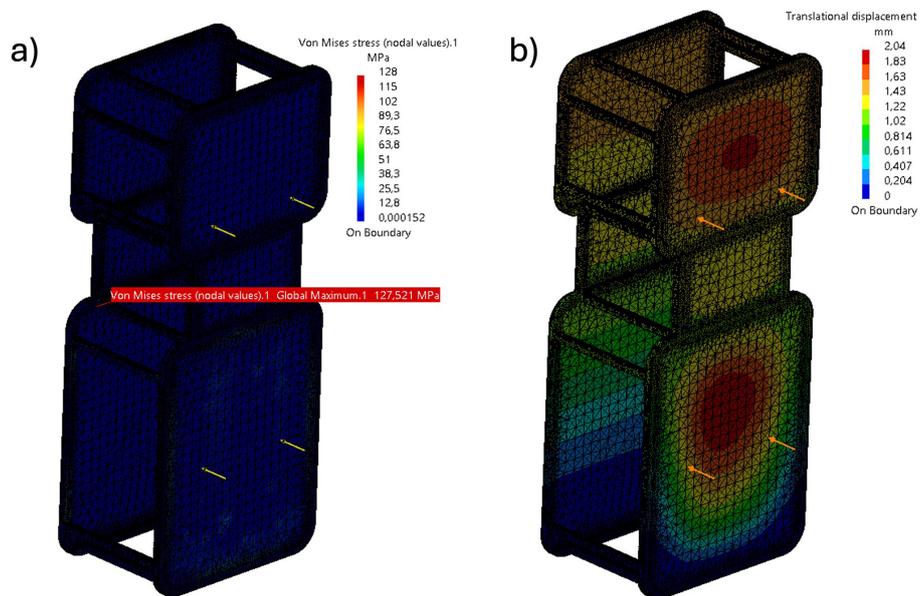


Figure 13. Calculation results for the extreme wind load case WW: a) contour plots of von Mises stress (values in MPa); b) displacement (values in mm)

to attach the panels to the frame; they must be sufficiently strong to prevent the panels from shifting relative to the frame under the specified operational loads.

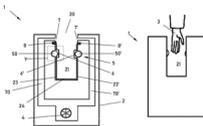
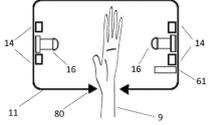
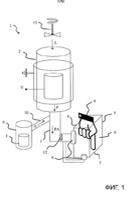
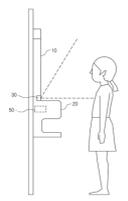
Table 3. Calculation results – summary

No.	Adopted load case	Stress [MPa]	Displacement [mm]
1.	Impact(U)	110	2.5
2.	Wind (W)	40	0.6
3.	Extreme wind (WW)	128	2.0

FUTURE RESEARCH

Future research will focus particularly on multi-faceted prevention of infectious disease transmission in public spaces. Currently, there is a noticeable relaxation of mandatory hand disinfection requirements in public buildings, which may, in the long term, contribute to the renewed spread of viruses. The development of high-quality, modular and lightweight disinfection devices with strong aesthetic and functional qualities can become an important component of preventive and

Table 4. Comparison of the state of the art of current disinfection devices

Lp.	Existing patented solution	Description of the existing patent	Diagram of the existing patent	Technological advantage of the designed device
1.	Hand dryer with UV disinfection device [29]	The patent concerns a hand dryer equipped with a housing featuring a cavity where hands are placed for drying by an airflow and disinfection with UV radiation. The device includes a lamp emitting ultraviolet light in the range of 200–380 nm, with the radiation intensity in the 228–380 nm range not exceeding 20% of the total intensity. This solution enables simultaneous hand drying and disinfection in a manner that is safe for the user.	<p>2021-09-14 Publication of US11116856B2</p> 	The device surpasses traditional UV dryers through its multifunctionality and interdisciplinary design. In addition to hand disinfection, it enables temperature measurement, mask distribution, and object ozonation, integrating these functions within a modular, mobile, and vandal-resistant structure.
2.	Method for disinfection and disinfection quality control of a user's hand and device for carrying out the method [30]	The patent concerns an automated method for hand disinfection and quality control of the disinfection process. It involves applying a disinfectant containing a light-reflectance-modifying substance, followed by imaging the hands in a dedicated chamber using a light source with a defined spectral range and a camera that records both sides of the hands. The system analyzes the captured images, distinguishing areas thoroughly covered with the disinfectant from those that remain untreated.	<p>2021-07-27 Publication of CN110100268B</p> 	The designed device is a multifunctional station for disinfection, temperature measurement, mask distribution, and object ozonation. Its modular and mobile structure allows for easy transport, quick assembly, and flexible adaptation to various public spaces. Made of lightweight, laser-cut steel panels, it meets IP55 standards, ensuring resistance to vandalism and environmental conditions.
3.	Hand disinfection device having plasma and aerosol generator [31]	The patent concerns a plasma surface disinfection device in which a disinfecting plasma gas stream is combined with a stream of water aerosol and directed into an enclosed disinfection area. The invention also includes a method of plasma surface disinfection using a mixture of plasma gas and water aerosol particles.	<p>2018-12-13 Publication of RU2674764C2</p> 	The designed device surpasses the patented solution through its enhanced functionality and user safety. While the patent focuses solely on surface disinfection using plasma and water aerosol, the device described in the article integrates multiple functions into a single system: hand disinfection, temperature measurement, mask distribution, and object ozonation.
4.	A hand sanitizer dispenser with body temperature measurement [32]	The patent concerns a hand disinfection system integrated with a body temperature measurement device. It consists of a mirror with a built-in hand sanitizer dispenser and a temperature sensor that automatically measures the user's body temperature during the disinfection process.	<p>2017-06-28 Publication of KR101751677B1</p> 	The designed device surpasses the patented solution through its broader range of functions and more advanced construction. While the patent is limited to combining hand disinfection with body temperature measurement in a mirror, the device described in the article integrates four functions within a single system: hand disinfection, temperature measurement, mask distribution, and object ozonation. Additionally, the project features a modular and mobile structure that allows for easy transport and configuration in various public spaces, as well as vandal resistance (IP55).

health-promoting strategies. The research area related to disinfection devices remains broad and may include, among others, material adhesion and durability testing, UV/chemical/thermal exposure studies, development of component cleaning cycles and logistics (including transport), design of advanced user interfaces and communication systems, as well as full standardization of modules together with the preparation of deployment scenarios for various types of facilities and user flows.

DISCUSSION

The investigation of the designed structure, carried out through ergonomic analysis and mechanical property assessment, provided extensive insights. The three load cases adopted for the study, representing conditions potentially occurring during real-life operation, allowed us to evaluate the structural resistance of the device. Based on the conducted FEA, it can be concluded that the selected design variant exhibits sufficient strength, as the yield strength of the material was not exceeded for any of the analyzed load cases.

According to the requirements, the housing should not deform by more than 5 mm. In none of the analyzed cases was this value exceeded, and the material's yield strength was not surpassed either, which means that the observed deformations are not permanent in nature. The largest deformation, amounting to 2.5 mm, occurred in the first scenario, where an impact on the upper part of the housing was simulated using a 30 kg steel striker imparted with 150 J of kinetic energy.

In contrast, the highest von Mises reduced stress - 128 MPa, was observed in the third scenario, which simulated the effect of a hurricane with wind speeds reaching 35.8 m/s. The occurrence of maximum deformation in a different load case than that producing the maximum stress results from the type of loading in the first scenario, where the most probable impact on the upper part of the housing, characterized by a smaller contact area, was assumed.

From a methodological perspective, the hybrid research process, combining the PRINCE2 methodology with an iterative Observation–Induction–Deduction–Testing–Evaluation cycle and the principles of HCD, enabled effective feedback between ergonomic, structural, and material studies. Short-loop iterations (simulations → prototypes → full-scale tests) minimized the risk of

design errors and shortened the time required to reach target configurations.

To ensure device mobility, reduction or relocation of components was necessary (e.g., the removal of certain functions for Versions 3 and 4). A key objective of the research was to ensure device accessibility for all users in accordance with HCD and UD principles. Pilot studies confirmed that appropriate shaping of the housing can accommodate various functional scenarios of the device. Local height adjustment in Version 4 currently represents the most effective adaptive mechanism toward inclusive ergonomics. As part of the discussion, a table (Table 4) was presented comparing several patented disinfection devices available on the market, along with an overview of the technological advantages of the designed multifunctional disinfection device. Although many commercial implementations of such devices exist, the authors chose to present patented solutions due to the scientific and research-oriented nature of the study.

CONCLUSIONS

This research demonstrated that a modular design approach for the disinfection station's external casing enables integration of key functions while maintaining accessibility for diverse user populations. Device versions 3 and 4 successfully met primary design criteria: stability and impact resistance while achieving lightweight and adaptive characteristics.

FEM analysis confirmed structural integrity across three critical load scenarios. Under impact loading (U case: 400 N force simulating a 30 kg sledgehammer strike), the frame exhibited maximum von Mises stress of 110 MPa with total deformation of 2.5 mm – well below the 5 mm safety threshold and significantly under the steel yield limit. For typical wind conditions (W case: $v = 20$ m/s, $q = 0.25$ kPa), stress reached only 40 MPa with 0.6 mm displacement. Notably, even under extreme wind conditions exceeding Class V hurricane parameters (WW case: $v = 35.8$ m/s, $q = 0.8$ kPa), the structure maintained integrity with von Mises stress of 128 MPa and deformation of 2.0 mm, demonstrating robust vandal-resistance and environmental durability suitable for high-risk deployment zones.

Ergonomic validation studies employing AT52304 Antar footprints confirmed universal

accessibility across diverse user groups. For wheelchair users, pilot studies identified a comfortable operational height range of 73.5–98.5 cm for the disinfection aperture, while 2D/3D simulations based on ISO 7250-1:2017 verified accessibility for children aged 5–15 years and adults spanning 10th to 90th anthropometric percentiles of European populations (both male and female). The adjustable height suspension mechanism in Version 4 represents an effective adaptive solution toward inclusive ergonomics, enabling seamless accommodation of standing users, seated wheelchair users, and pediatric populations.

The hybrid methodology combining Prince2 structured governance with iterative HCD/UD cycles and rapid prototyping proved effective in reducing development risk and accelerating convergence to target configurations. Short feedback loops (simulations → prototypes → full-scale tests) minimized design errors while parallel materials research enabled optimization of ultra-lightweight stainless steel lattice frames with laser-cut joints (± 0.5 mm tolerance). The innovative ballast foundation employing glass fiber-reinforced concrete (GRC) eliminates site preparation requirements while providing superior durability across thermal, chemical, and UV exposure conditions (fire resistance class A1 per DIN standards).

The developed lightweight, modular architecture with rapid, non-intrusive access to critical components – particularly the disinfectant reservoir for refilling – addresses key operational deployment objectives. The modular construction enables quick service interventions during high-risk epidemiological periods when frequent maintenance is essential. These findings support implementation of such systems in high-traffic public spaces to enhance compliance with WHO hand hygiene protocols and strengthen prevention strategies against infectious disease transmission. Recommended future work includes field validation studies under real-world conditions, long-term durability testing of spray mechanisms across variable temperature/humidity ranges, and development of standardization protocols for varied institutional contexts (hospitals, schools, transit facilities, commercial centers).

The authors consider testing operational parameters (disinfectant concentration, exposure time, and coverage percentage of ULV nozzles) as the main research area and the subject of further investigation under real-world field conditions.

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