A New Approach for Handling Element Accessibility Problems Faced by Persons with a Wheelchair

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Abstract:
The built environment accessibility evaluation is required if the person physical capacities no longer correspond to the habitat requirements, which generally occur after an accident. For the person with disabilities, the inner accessibility of habitat is a highly important factor that allows him to live and work independently. This paper presents a new approach to determine the accessibility of handling elements like doors, windows, etc. inside the habitat for the wheelchair user. Thus, allowing housing professionals to assess the needed changes in terms of accessibility. The idea is to involve a new computer approach to evaluating the performance of these elements against wheelchair user capacity. The presented approach simulated wheelchair user behavior when he/she is operating a handling element in order to determine the dimensions/positions of wheelchair clearance space and handle grip optimal heights while considering wheelchair arrival direction and respecting joint limits constraints of person upper body and wheelchair nonholonomy constraints.

Keywords: *accessibility, handling element, wheelchair, person with disability, wheelchair wheelchair clearance space, environment rehabilitation, inverse kinematics*

1. Introduction

The accessibility represents the objects, the apartments, the information and the technologies which the persons with physical limitations can use. It is an important factor for people with disabilities to enable them to live and work independently and to minimize the cost of personal care.

For wheelchair users (the subject of our proposed approach), the rehabilitation represents tools, process and systems adaptation in order to customize and to aid them to overcome the obstacles. For this category of persons, environments may create obstacles if they are not incompatibles with persons technical aids used, like wheelchair which cannot execute maneuver to cross a door, etc., or may facilitate the inclusion if their designs are more flexible. For that, the environments must be well adapted to the wheelchair users, not only in terms of the quality of ground surfaces which must be flat and smooth, but also at the level of navigation which must allow to the wheelchair users to navigate freely within. Universal design principle cannot consider each handicap needs in the same time. So, to increase autonomy of wheelchair users in their house and reducing accident risk. In this presented word we aim to propose a new numeric simulation tool, used by professional designers to assess the accessibility of handling element (doors, windows, etc.) considering the person capabilities and wheelchair designs. The accessibility test is done by computing the required wheelchair maneuvering clearance at the handling element, dimensions and the optimum handle height, which ensure easy and smooth navigation for those persons.

2. Related Works and Context

There is not at present a consensus of numerical methodology to be used for accessibility assessments of interior habitat. In most industrialized countries, standards or recommendations are available for building professionals to be guided in the design of new buildings.

Among these assigned laws, we can take up the disability discrimination act (DDA) of the United Kingdom (2005) [1]. In France(2005), a certified handicap law [2], aimed to make products and the built environment accessible and usable for people with disabilities. In the United State (1997), the Americans with disabilities act accessibility guidelines (ADAAG) [3], contain "prescriptive" specifications for determining the existence of a valid wheelchair accessible route as well as other objectives for disabled access.

In recent years, this accessibility field has experienced a new progress in the proposed numerical approaches. According to the results of the old laws of accessibility assessment, we note that they do not comply strictly with people disabled requirements. Here, we quote some research intended to develop numerical approaches using the capacities of virtual reality (VR) and virtual prototyping which includes 3D modeling and simulation systems as simulation tools. The HM2PH Project (Habitat Modular and Mobile for Persons Handicap) is developed by experts. Its objective is to specify the living environment mobile functionality, open to the outside for disabled persons, with major concern for an access to an enhanced autonomy by an appropriate devices (technical aids, domotic… etc.) [4], [5]. In [6] and [7] the authors proposed new tools based on VR, to determine the accessible circulation zones of the wheelchair users within a domestic habitat which ameliorate a user action capability within domestic environment.

In [8], authors have proposed a method to determine if there is a usable wheelchair accessible route in a facility using motion-planning technique, to predict the performance of a facility design against requirements of a building code. In [9], the authors have presented approaches to assess the accessibility of the interior of an environment for wheelchair users. In [10], authors proposed a new approach to determine the human reach envelope, which help designers to determine the zones with different discomfort levels. This capability is a powerful tool for ergonomic designers. In [11], the authors proposed an approach to designing way finding aids to fit people needs to facilitate environmental knowledge acquisitions for people and improve their way finding performance. In [12] we find a new study about a usage and accessibility problems faced by disabled (whether in pain or not) users of assistive devices and physical barriers that limit their mobility, and recognize the socio-cultural practices excluding them from the design process of such devices. In same field of research there is a study of Theresa Marie Crytzer *et al.* [13] toilet seat, bath bench, car seat, which describes the results of focus groups held during Independent Wheelchair Transfer (IWT) workgroup. The idea is consisted in connecting three focus groups composed of experts in the field of assistive technology by Live web-based conferencing using Adobe Connect technology to study the impact of the built environment on the wheelchair transfer process within the community to participate in daily activities, wheelchair users' needs during transfers in the built environment, and future research directions. Recent study (2014) proposed by Myriam Winance [14], the authors suggest a way of changing the concept of the Universal Design in order to take into account uniqueness and diversity, in order to allow the shaping of abilities.

In the following section, the interest of this approach, the problem addressed and the contribution that we have provided to the field of accessibility for people with reduced mobility, will be presented.

Generally, all accessibility assessment prescription adopted in many countries are manually approaches, based on norms or recommendations. Whatever, the manual prescription can be ambiguous, and unduly restrictive in practice. In order to compensate the measurements error of these approaches, we will propose a software numerical tool to assess the accessibility inside habitat.

The objective of this present work is the accessibility assessment of handling elements indoor living space for wheelchair users such as doors, windows etc. and the problematic that we are going to address, is how we can simulate virtual movements, physically feasible by wheelchair user, within 3D virtual environment.

3. Person-Wheelchair Kinematic Model Definition

To describe human movement, we use an open loop molded by links and joints such as those used in robotic field. Numerical and kinematic model of the upper part of the body used in our simulation is that proposed by [15] that contains 21 degrees of freedom (DOF), from bottom of the spine to the right hand which seems the most suitable for our application (see Figure 1). Each joint variable is bounded by lower and upper constraints limits. All joints are modeled by rotary joints and each contributes to the movements in one or several plans.

The position vector of the joint model of the body upper part described in terms of joint coordinates is:

$$X = f(\theta) \qquad (1)$$

With the set of joint variables $\theta = [\theta 1 \dots \theta n]^T \epsilon R^n$ is called $(n \times 1)$ joint vector. These joint variables uniquely determine the configuration $f(\theta)$ of the open articulated structure with n DOF and are called the generalized coordinates. Then the position vector of a point of interest attached to the frame $\{n\}$ of the hand can be written with respect to the global frame $\{0\}$ using the homogeneous transformation matrix $(4 \times 4)\ {}^{i-1}DH_i$ defined by Denavit and Harterberg [16].

The wheelchair is a non-holonomic vehicle, characterized by a non-holonomic constraint imposed on its displacements. This constraint indicates the tangent direction along the entire feasible trajectory, and the limit of curvature of the trajectory. Generally, the non-holonomic vehicle position (vehicle rolling without sliding) is defined by two parameters (x, y) and one parameter of orientation θ_0(see Fig. 1). The non-holonomic constraint indicates that the path displacement tangent and the vehicle direction have the same trajectory.

In our simulation, only the obstacle avoidance and non-holonomic (position and orientation) constraints are considered. In order to respect the constraint of a non-holonomy, we distinct two allowed displacements, go straight and turning.

In addition to the 3 DOF of the wheelchair (x, y, θ_0), we obtain a model with 24 DOF which we used in the simulation, described in Fig. 1.

4. Definitions

4.1. Feasible Displacement of a Non-holonomic Mobile Base

The term used in this text "a wheelchair feasible displacements" is equivalent to the trajectory planning in the field of robotics. In robotics, a non-holonomic mobile base moves in a Euclidean space *W* (work space), represented as R^N (*R* is the set of real numbers, and *N* the spatial dimension). In the case of wheelchair, the displacement assumes a two-dimensional space where $N = 2$. The space W populated with obstacles represented as $B_1, B_2, \dots, B_q$. The moving feasibility is based on the generation of a configuration space from the geometric properties of the wheelchair, obstacles Bi, work space W and geometric properties of handling elements. Computing the feasible displacements of a wheelchair consists on ensuring the successive displacements without colli-

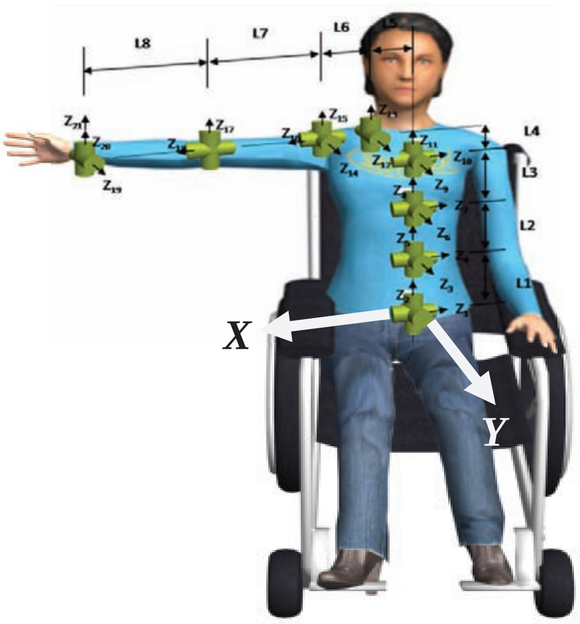

Fig. 1. 24-DOF of person-wheelchair couple used in simulation

sion during the operations for the handling elements (doors, windows, etc.) in a configuration space C for a 2-dimensions space W, the dimensional m of the configuration space C is 3. The wheelchair moves in the xy-plane Cartesian space ($W = R^2$) and has three degrees of freedom: translations in x and y directions and orientation θ_0. The obstacles Bi are changed into CB_i in the C space by applying a transformation by the Minkowski sum proposed by [17] and Minkowski difference proposed by Svetlana [18], [19], for each orientation of the wheelchair. The definition of the configuration space transforms the problem of obstacle avoidance to the problem of a point moving feasibility.

4.2. The importance of Maneuvering Area at a Revolving door: Size and Position

Revolving doors are among the most used. They consist in one or two leaves which are pivoted on a vertical axis (the hinges). The opening direction is fixed relative to the bulkhead or wall. Pull revolving doors denote pivoting door that are pulled toward the user, while push revolving doors denote pivoting door that are pushed away from the user. In the following we will use the two terms to distinguish them. The disadvantage of this type of door is that it requires a large area of deflection but in the open position, the passage is completely free. Depending on the building type and the type of door used, wheelchair clearance space is necessary to both sides to enabling to wheelchair user to open, cross and close a door independently. This space is required in front of any door, gate, and any door opening on the common areas, any door of a local collective, and any erasing door-opening or hinged-leaf door of a public establishment, collective residential buildings or individual houses.

4.3. Accessibility of a Handling Element in Relation to a Wheelchair User

According to the Center of Expertise and Education on the Risks, the Environment, Mobility and Development (CEREMA) [20], the handling element is accessible by wheelchair user if it is able to handle it independently. According to ADDAG [3], the handling element can be reached if there is a space around it containing a continuous path, unobstructed and connected allowing to manipulate it.
Manipulation is a generic term that concerns the grip with objective of performing a movement function. For a door, we need to grasp it, push it, pull it or slide it depending on the type of the opening. This aspect is valid regardless of the type of handling element to manipulate.

Both definitions adopted in France and the United States take only into account wheelchair in simulation while a handling operation requires the intervention of the upper body of the person (arms and trunk). Generally, handling elements are accessible if the person is able to manipulate it freely in a continuous space, unobstructed and connected.

5. Our Approach

Our approach is oriented specifically towards accessibility evaluation of handling elements inside individual or public apartment for wheelchair user. The main objective of our algorithm is to generate successive configurations of the wheelchair-user couple that describe the handling operation respecting join limits (see Table 3) and non-holonomic constraints, respectively. Our application is part of a 3D human movement simulation and analysis field. However, in our application only the joint limit constraints of the person upper body are taken into account. Our objective is to assess the accessibility of handling elements, by computing dimension and position of wheelchair clearance space which is required at these elements to propose the appropriate modifications inside the habitat. Because we believe that if the upper body articulated structure postures are executing within the joint limits constraints, they are physically feasible by the person. We will generate only the postures considering joint limit and non-holonomic constraints. We suppose that handling elements are without weight, so dynamic constraints like muscular energy, external loads etc. are ignored [21], [22], [23].

The judgment of our results is done by taking in consideration only the joint limit constraints of a person upper body and non-holonomic constraints of the wheelchair.

To resolve our problematic, we developed a simulation tool using Visual Studio C++. This tool is divided in three blocks. The first one is used to modeling a wheelchair mobility space, a person upper body, a wheelchair (section 3) and the 3D environment. The second one is used to fix constraints of simulation, the upper body joints limits and the non-holonomy. The last block, includes the algorithm and different sub-blocks of the computation. This last block is considered as an interface between block one and block two, which are the inputs of the third block.

5.1. Wheelchair Mobility Space

The wheelchair user moves parallel to the ground with three degrees of freedom (x, y, θ_0), which θ_0 is the orientation of the wheelchair relative to the universal framework and (x, y) describing its position. The wheelchair mobility space or configuration polygons determine all displacement areas of wheelchair reduced to a point. This technique, well known in the field of mobile robotics and motion planning such as that proposed by Latombe [24] and that proposed by Pruski [25] for accessibility assessment, corresponds to computing the Minkowski sum and difference.

In our application, the mobile device is a wheelchair which is considered as a rectangle and the reference point selected is the center of the mass. The Minkowski sum and difference are applied to the polygon which can be an obstacle to avoid or an envelope polygon corresponding to world space in which the wheelchair can move. The mobility space corresponds to the space wherein the wheelchair, reduced to a point, can move and to a single value of its orientation θ_0. In our case, the polygon envelope, integrating the handling elements, is modified over time. The handling elements corresponding to moving obstacles affect the overall shape of the displacement space. So, dynamic mobility space is defined according to the orientation of the chair and the position as well as the orientation of handling elements.

The blue space (see Fig. 3a) represents the dynamic mobility space Cd, within the wheelchair can move for a given orientation of the wheelchair, and different positions of the revolving doors.

Figures 3b, 3c and 3d show the dynamic mobility space corresponding to the opening of a revolving door for different orientations of the wheelchair. The passage from the configuration b to d requires a feasible displacements of the wheelchair and a permanent contact between the hand of the person and the door

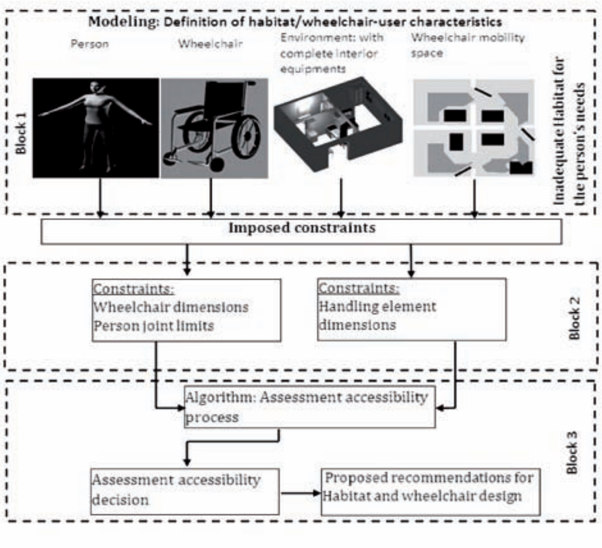

Fig. 2. Simulation tool

handle. In Figure 3, the wheelchair adapts its direction to follow the rotation of the door which causes a change in the dynamic mobility space. Path-planning between the configurations of the wheelchair corresponding to $P_{initial}$ to P_{final}, using the generalized polygon configuration technique is not necessary in our application. Because of we are not trying to compute the trajectory connecting two configurations but only to check if it exists. We consider a handling element is accessible if the person is able to position his/her wheelchair in minimum space to manipulate the element regardless of the direction of arrival.
To simulate the handling operation we developed the following algorithm.

5.2. Algorithm

The proposed algorithm is used to assess the accessibility of handling elements, presented inside individual or public buildings. Its main principle consists on simulating feasible wheelchair-user configurations used to manipulate handling element within 3D environment. Table 1 shows the inputs and the outputs of algorithm.

5.3. Algorithm Operations

The complete algorithm is shown below:

1. Initialize randomly: the joint variables , the counters: Cter1, Cter2, Hn, Hi.
2. Do for each point Hn
  2.1. Cter1 = Cter1+1
  2.2. Define the inverse kinematic in relation to the target point Hi of the dynamic path of the hand (call to the IAA algorithm)
  2.3. If (the target point Hi is not reachable) then write, target point is not reachable and move to the next hand path point (move to line 2.1)
  2.4. Else (the target point Hi is reachable)
    2.4.1. Define the wheelchair configuration
    2.4.2. If (the wheelchair configuration in the world frame is not feasible and the wheelchair displacement is not feasible) then write, target point is not reachable and move to the next hand path point (move to line 2.1)
    2.4.3. Else if (the wheelchair configuration in the world frame is feasible and the wheelchair displacement is feasible)

1. Cter2=Cter2+1.
2. 2.4.3.1.If (Cter1 >Hn)
3. Move to the next hand path point (move to line 2.1)
4. 2.4.3.2.Else (Cter1 <Hn)
5. 2.4.3.2.1.If (Hn == Cter2)
6. Dynamic element is accessible, Write to output file
7. 2.4.3.2.2.If($H_n \neq$ Cter2)
8. Dynamic element is not accessible, Write to output file

3. While (stop conditions not verified)

Hn represents number of hand target points, Cter1 is a counter of tested target points and Cter2 is a counter of reachable target points (feasible configurations of a wheelchair-user).

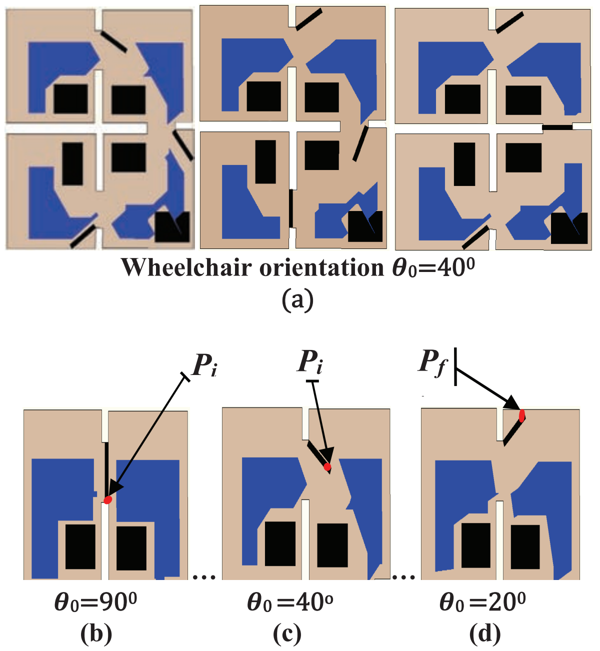

Fig. 3. Dynamic mobility space: Example of opening a pull/push revolving door

Wheelchair-user configuration kept only if target point is reached by hand of person, and configuration/displacement of the wheelchair in the frame work is feasible. The algorithm is fast and has no local minimum. The appropriate configurations of the upper body are computed from the hand (21^{st} joint) to the 1^{st} joint (see Fig. 3). The wheelchair configurations are computed according to the position/orientation of hand by direct kinematics which increases the speed of convergence.

In the algorithm operations, we considered that the handling element is accessible if all hand path points are accessible. In fact, we divide the path created by the handling element at handle level in many adjacent points Hi ($P_{initial}$ *to* P_{final}), (see Fig. 3). The person should reach successively by his/her hand these points. At each point we compute the values of the joint variables θ_i that describe the configuration $f(\theta_i)$ of the upper body and θ_0 values that describe wheelchair configurations/displacements in the mobility space, by minimizing the error function between the hand and the target point (Cter1). The Cter2 used to compute the number of the reachable points.

Finally, we evaluate the value of the Cter2 with that of the Hn (number of hand path point), if we confirm that Cter2 value is the same as Hn so the handling element is accessible else it will be not. This condition is fixed to guarantee entirely the accessibility of handling element, but we can in some cases, change the value of Hn in the two last lines of the algorithm by a threshold. The decision in this case is done according to the number and the positions of the not accessible points, because of the hand path points are very closer (in order of a few centimeters). If an inaccessible point lies between two others accessible points, we can consider that is accessible, consequently the element is accessible.

In the case of opening and closing an involving door, the path to be executed corresponds to a semicircle. To open door, person must grasp the handle, turn the door around its pivot and move the wheelchair. The action carried out on the door requires, first, continuous contact between the hand of the person and the door handle (inverse kinematics). Secondly, it requires feasible wheelchair configurations and finally feasible wheelchair displacements. Such operation is divided into three sub-operations, and the algorithm functionality is divided in three principal operations:

- *Inverse kinematic of articulated structure.*
- *Wheelchair configurations.*
- *Wheelchair configuration displacement.*

Step 1: Inverse Kinematics

The first step determines the configuration of the upper part of the person body. The methodology principle detailed in paper proposed by Otmani and Moussaoui [26] virtual reality or game in particular, are very interested in these algorithms. We propose in this paper a comparison between several algorithms of incremental type. The considered application concerns the accessibility evaluation of an environment used by a handicapped person (an apartment, a house, an institution…), is to optimize the error between the hand and the point to reach (the path between $P_{initial}$ *and* P_{final}) changing incrementally the values of the joint variables. The computation of the inverse kinematic of the articulated structure is realized, not in

Tab. 1. Estimation/generation of wheelchair-user configurations

Inputs	Algorithm	Outputs
– Joint limits constraints of the articulated structure. – Constraints related to the habitat geometry. – Wheelchair dimensions and non-holonomic constraints. – Characteristics of the handling element. – Wheelchair dynamic mobility space . – Hand path points $P_{initial}$ to P_{final}. – Acceptable error between hand and target point equal to 1 unite.	Estimation/generation of wheelchair-user configurations.	Upper body configurations. Wheelchair configurations.

Note. θ^L, θ^U lower and upper joint limits variables θi, respectively. C wheelchair mobility space. $P_{initial}$ and P_{final} represent the initial and final target hand points.

relation to a point but with respect to a surface that corresponds to the mobility space including the target point ($P_{initial}$ ...P_i ...P_{final}). The inverse kinematics allows us to compute the configuration of the articulated structure and the position as well as the orientation of the hand with respect to the universal landmark.

Step 2: Wheelchair Configurations

When we determine the position of the hand by computing inverse kinematics, we get all joint variables values. They allow us to determine the position of the wheelchair by the direct kinematics assuming that the error between the hand and the target point equal to zero. This method has the advantage of ensuring obstacle avoidance without using path-planning techniques.

Step 3: Wheelchair Configuration Displacements

The second advantage of this method is that it allows us to have the right configurations displacements without using the path-planning techniques. Because we are not interested in the shape of the trajectory or its optimization, it is sufficient that the translations are feasible in the mobility space. To have feasible displacements of the wheelchair, the constraint of obstacle avoidance and that of a non-holonomy must be respected.

The first constraint was already verified by the computation of mobility space and by step 2. The following property ensures that the displacements of a wheelchair is still feasible and respect the constraints of a non-holonomy:

- Property: In [27], Laumond proved that if two configurations belong to the same domain connected then there exist feasible paths that connect them and respect the joint limit constraints.

According to this property, the translations of the wheelchair are feasible if the wheelchair configurations belong to the same connected mobility space. Our approach aims to determine wheelchair clearance space required, which ensures the conviviality of the handling element. The verification of the wheelchair displacement feasibility is successively realized between each two feasible configurations of the wheelchair computed by steps 1 and 2 for the following two reasons:

- The initial and final configurations of the wheelchair are not predefined at the start of computation. That is why the path-planning in this case is not feasible.
- The process of the accessibility evaluation of handling elements aims to check at each position and orientation of the handling element, if there are feasible wheelchair-user configurations.

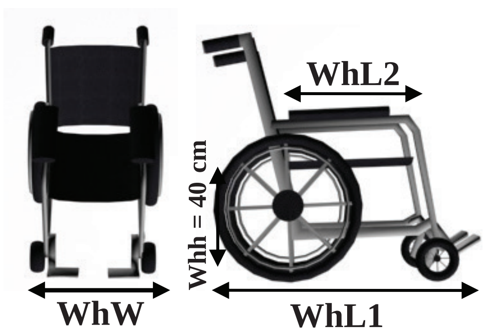

Fig. 4. Wheelchair Dimensions

In this particular example, wheelchair having the following dimension values: wheelchair width value (WhW) = 60 centimeters (cm), wheelchair length on the ground value (WhL1) = 60 centimeters (cm) and wheelchair length on seat level value (WhL2) = 60 centimeters (cm). We use this example to illustrate different steps of a wheelchair minimum clearance space computation during the process of the opening/crossing/closing of a pull/push revolving door, and the suitable handle-door height interval values according to person capacities (see Table 3).

6. Results and Discussion

6.1. Revolving Door to Push: Results and Discussion

The corridor width relative to the push revolving door width value must have sufficient dimensions, to ensure an ample wheelchair user clearance space. In fact, the wheelchair maneuver space in front of doors not only depends on the wheelchair geometric, but also to the volume form occupied by the person arm, while contacting the handle door. The advantage of our approach is that it considers person upper body in the accessibility evaluation. Depending of the needs

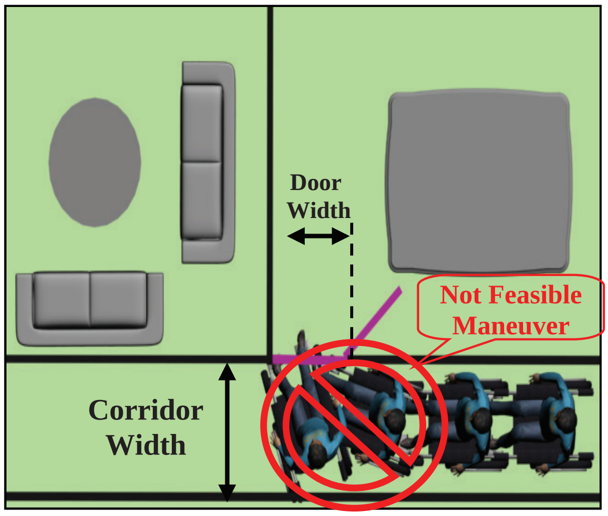

Fig. 5. Example of a not crossed revolving door to push

of the experience, it is possible to exploit certain parts of the upper body structure without others.

Figure 5 presents an example of a not-crossed revolving door to push, with inconvenient dimensions.

6.1.1. Minimum Corridor Width

To ensure appropriate and reasonable modification to the habitat for a wheelchair user in this case, we need to determine the minimum required corridor/door width values. In the initial stage we fix a door width at the value 88 cm superior to WhW which ensuring a direct cross. Then we gradually reduce the corridor width from 190 cm value (which is superior to the wheelchair diagonal value 180 cm, ensuring a direct cross), to 60 cm (value sufficiently

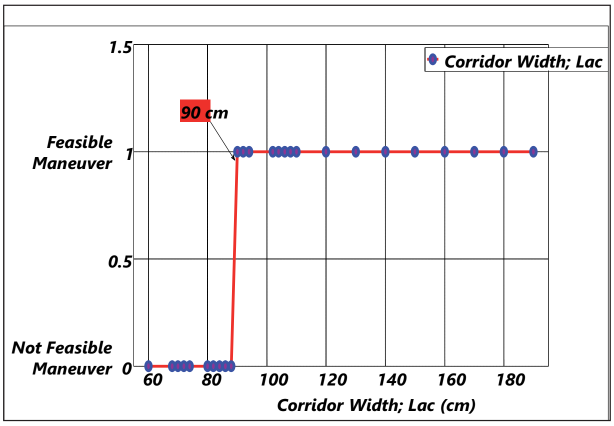

Fig. 6a. Feasibility to cross a revolving door to push in relation to the corridor width

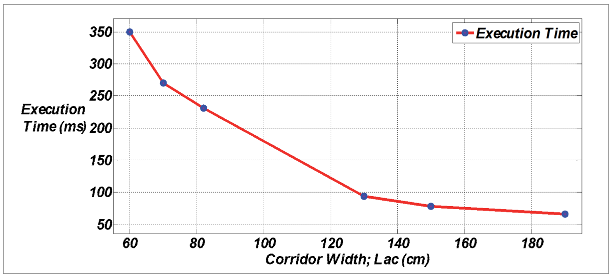

Fig. 6b. Execution time

inferior to wheelchair diagonal, 180 cm), by checking at each corridor width value the possibility of a crossing the door or not. The results of the simulations are presented in the Fig. 6.

The curve shown in Fig. 6a can be shared in two parts. The first one, when the corridor width values belong to the interval [190 cm, 90 cm], is the interval of values when the wheelchair maneuver to cross the door is possible. The second one, [90 cm, 60 cm] contains the values of corridor width when wheelchair maneuver is not possible. We observe that to cross a push revolving door having a width equal 88 cm, by a wheelchair having such dimensions (WhW= 60 cm, WhL1 = 90 cm and WhL2 = 60 cm), the corridor width value must be superior or equal to 90 cm. The variations of the corridor width values to an eventual modification may implicate a displacement of the wall entirely, which is difficult to realize in practice, because it would be convenient to increase the doorway or just the right parts of the door.

The execution time is a method for evaluating algorithm performances in real time application. Figure 6b shows the execution time of the crossing revolving door to push process for several values of the corridor width. We note that the runtime decrease while increasing corridor width and it is increasing when the corridor width values approach to the wheelchair width. When the wheelchair maneuver exists, we note that the algorithms take an average of 0.33 milliseconds (ms) to compute the appropriate wheelchair-user configuration if it exists. When the wheelchair maneuver does not exist the algorithms take an average of 87.50 ms to confirm that wheelchair-user configuration is not realizable.

6.1.2. Minimum Revolving Door to Push Width (Corridor Width Value Fixed at 90 Centimeter)

In this step, we determine the minimum width value of the door guaranteeing wheelchair maneuver, with corridor width value equal to 90 cm. We have to make the same computation as the previous step. Figure 7a presents door width values used. We note that the range of values [70 cm, 87 cm] contain no feasible maneuver of the wheelchair. Because of the area is not sufficient to turn the wheelchair from its horizontal position to the perpendicular position.

When door width value is equal to or greater than 88 cm, the wheelchair maneuver is realizable. So, we notice that the minimum sum of the door width + corridor width, required to cross a door in this case, with such wheelchair dimensions is 178 cm. This value is computed with respect to the wheelchair design and specific person upper body capabilities (see Table 3), our simulation tool allows changing easily these constraints according to the person and the experience needs.

6.2. Revolving Door to Pull: Results and Discussion

To cross a pull revolving door with wheelchair, the rectangle corresponds to the corridor width/length must be sufficiently wide. In the previous case, we are interested to compute the minimum sum of door and corridor widths. In this second case, we determine the minimum width/length of the corridor which guaranteeing wheelchair maneuver with a fixed door width value. According to the simulation carried out using different corridor width/length values presented in Fig. 9a, we notice that we require a corridor of a minimum length equal to 194 cm and a minimum width 164 cm, to cross a pull revolving door, irrespective of the arrival direction of the wheelchair.

6.3. Minimum and Maximum Handle Height of Revolving Door to Push/Pull

The door handle grip position must be installed in such a way as will be easy to handle. In order to easy use it, we have to consider several aspects, among them its position in relating to internal angle of the wall or any other obstacle, and the kind of handle used (generally the handle grip that can handle by “drop it the hand”) which are the most appropriates. We have computed the interval of the handle grip height values from the ground which are the best suited to handling door. According to the data shown in the Fig. 11, we note that the height handle values directly affect the clearance space dimensions of the door.

Figure 11 presents the simulation results of an opening pull/push revolving door with different handle grip heights and in different clearance space dimensions (corridor width/length). We will notice that the interval of handle height [40 cm, 100 cm] contains the appropriate handle height values, because it is the only one which its values allow the wheelchair user to cross pull/push a door in the minimum clearance space (164 cm to 194 cm) computed previously in section 6.2. Therefore, we can consider it as the most appropriate interval to opening/closing a revolving door to pull/push, with such person joint limits (see Table 3) and wheelchair constraints (see Fig. 4).

Crossing pull/push revolving door by a wheelchair user has been tested with various handle heights and within various clearance space dimensions. Heights values between [40 cm to 100 cm] are the only ones in which the person can cross such a door easily when the wheelchair clearance space is minimum (164 cm to 194 cm).

Figure 12 presents useful simulation times to opening revolving door with different handle heights and in different wheelchair clearance space dimensions. Handle heights values between [40 cm, 100 cm], are the most suitable to the wheelchair dimensions in this case. The period necessary to opening a revolving door to pull/push when wheelchair clearance space dimension is (164 cm to 194 cm) is an average of 200 ms. It is noted that this period of simulation is decreased (an average of 80 ms) when the clearance space dimension at door is sufficiently wide (184 cm to 248 cm), and it is increased gradually (an average of 400 ms) when the clearance space is decreased.

In the two others intervals [10 cm, 20 cm] and [140 cm, 138 cm], we need to an average of 400 ms to evaluate each height handle. However, the period simulation in the three intervals does not exceed 400 ms.

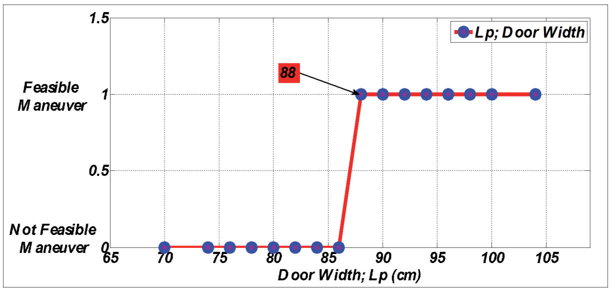

Fig. 7a. Feasibility to cross a door with a push in relation to the door width

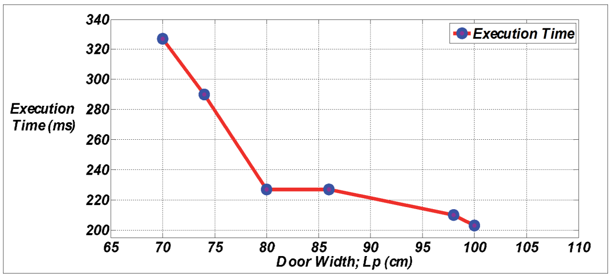

Fig. 7b. Execution time

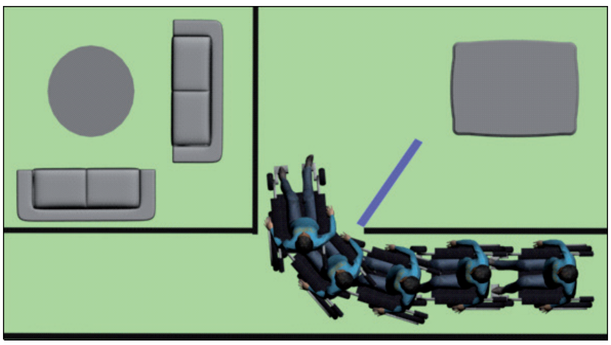

Fig. 8. Crossed revolving door to push

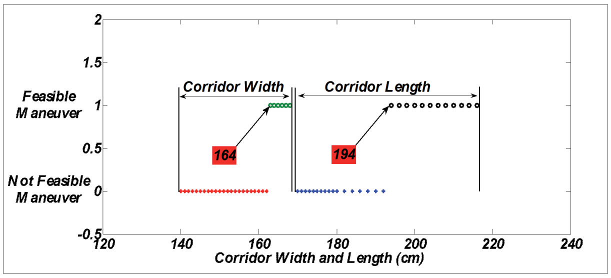

Fig. 9a. Revolving door to pull: required clearance space dimensions

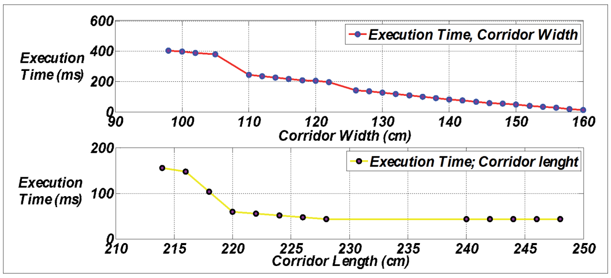

Fig. 9b. Execution time

7. Comparative with Alternative and Supplementary Approaches

Figures 13 and 14 present four main configurations of wheelchair-user to opening a pull/push revolving door. Here, we can see clearly the clearance space dimensions that could be respected in home design according to the position of the wheelchair-user configurations (as we detailed in sections 6.1, 6.2 and 6.3).

Compared to the results adopted by the governments of some countries like United state [3] and France [2], legal requirements prescription presented by these approaches ignored individual abilities/preferences details. For example, the prescriptive ADAAG can inform the design of the wheelchair by manufactures, but it cannot represent their specific situation.

In our approach, the detailed behavior model and simulation can readily accommodate the behavior details of different wheelchair designs, and designers can also use this method to analyze the performance of different wheelchairs within different building designs while considering the disabilities and preferences of different users.

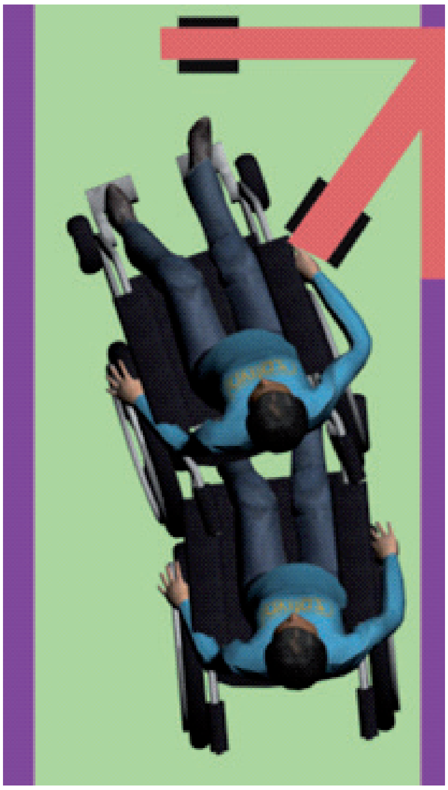

Fig. 10. Revolving door to pull: required clearance space dimensions

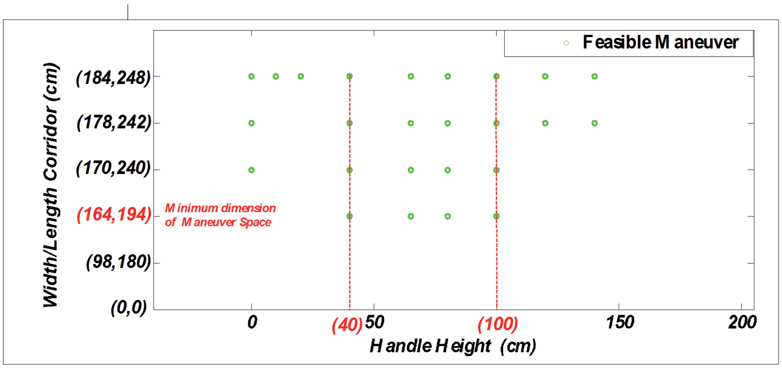

Fig. 11. Wheelchair clearance space of revolving door to push/pull in relation to handle height

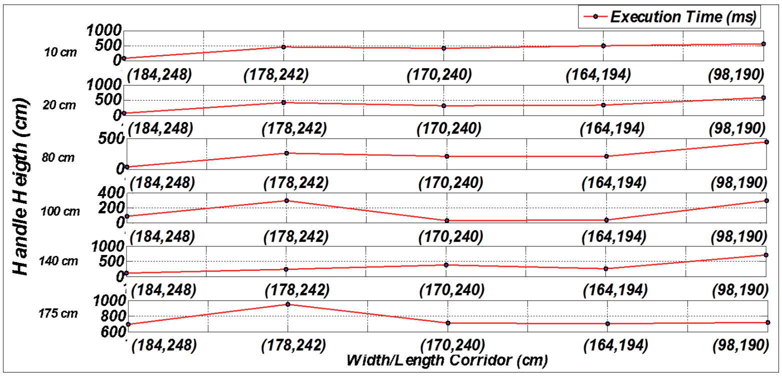

Fig. 12. Execution time

Our approach allows us to accurate computing the useful handle height values and a wheelchair clearance space, with respect to the constraints of a person body and a wheelchair design used, which allows customizing the accessibility assessment. Unlike real environments, it makes accessibility assessment safe, without risks with less expensive. It also allows manipulating freely person and wheelchair specifications imposed in simulation. The simulation tool that we have developed enabled us to simulate 3D feasible movements of wheelchair-user couple, which allow us to evaluate the interior pieces of habitat, by computing the required clearance space at the pull/push revolving door as well as the appropriate heights of the corresponding handle. Our developed simulation tool based on virtual reality in which we can control easily the interaction between the person with disabilities and his/her environment. Its structure makes easy to consider the detailed abilities and preferences of any wheelchair user, handling elements dimensions and the habitat interior design. The wheelchair mobility space is computed in way that it can be changed according to the wheelchair orientations and handling elements variations (paragraph 5.1). Unlike to the precedent approaches that aim to determine the adequate mobility space width linked between different pieces in the habitat, in our cases we aim to determine the clearance space dimensions around handling element (doors, windows,... etc.). We created feasible movements of a person upper body. The following Table 2 presents the positive and negative points provided by our proposed approach against the approaches adopted in some countries for handling elements accessibility assessment.

The following table (Table 4) gives the benefits provided by the approach proposed here, compared to the approaches used in France and the USA, in accessibility assessment for a wheelchair user.

8. Conclusion and Future Works

In this paper, we proposed a new numerical approach to analyze the accessibility of a handling elements indoor habitat for person on wheelchair. Accessibility assessment prescriptions adopted in many are manually approaches, based on norms or recommendations. The manual measurements can be ambiguous, and unduly restrictive in practice. In order to compensate the measurements error of these approaches we used computer data-based tool implemented on Visual Studio, to simulate feasible behavior of wheelchair user at handling elements. Here, we have discussed our results using an example of revolving-door which is considered as an essential element of access and required an important clearance space with specific dimension. To guarantee the correct handling of this element by wheelchair user, we determine for both door type push and pull, the corridor length/width minimum values in the case of an involving door to pull and minimum door/corridor width values in the case of an involving door to push. We also determined the handle door height values and its influence on wheelchair clearance space size.

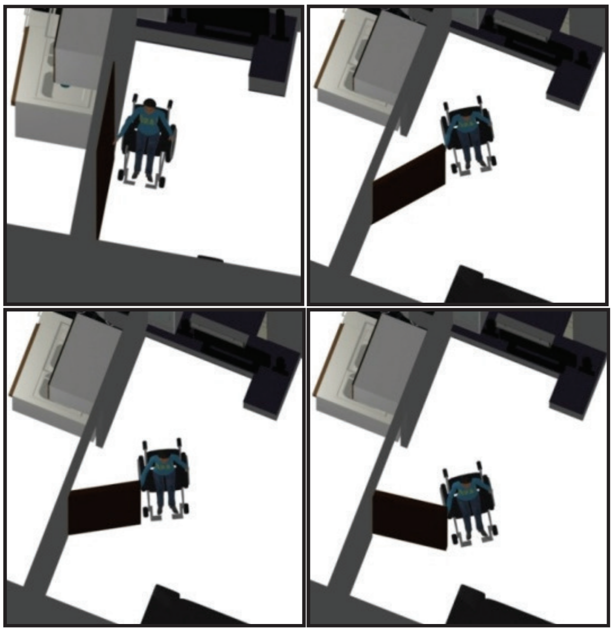

Fig. 13. Mains configurations to opening revolving door to pull

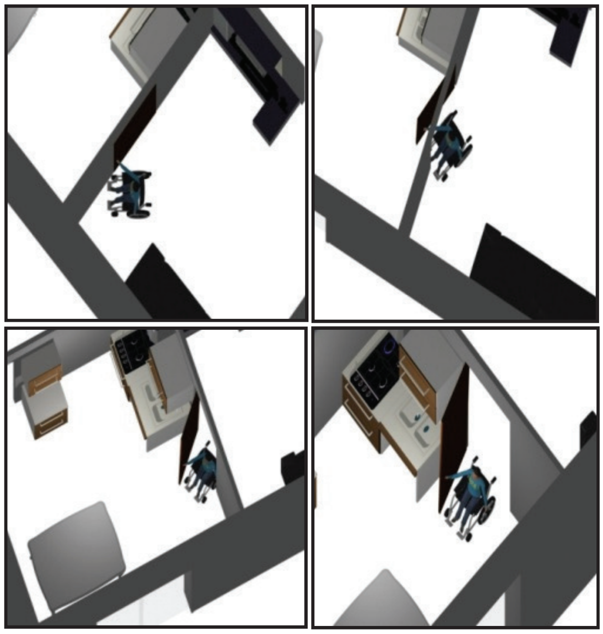

Fig. 14. Mains configurations to opening revolving door to push

Tab. 2. Handling element assessment positive and negatives points provided by our proposed approach against the approaches adopted in some countries

Wheelchair maneuvering clearances dimension	Wheelchair maneuvering clearances position	Interpretation
– Corridor width + door width (doorways) must be superior or equal to 2 meter [20].	– The maneuvering clearances length extends from the hinge of the door, integrating the door and the handle.	– The wheelchair maneuvering clearance dimension is very specific and it is computed without considering person's deficiencies, beside the wheelchair approach direction didn't taken into account.
– Swinging door to push: wheelchair clearances equal to: 1.7 m × 1.2 m [20].	– The maneuvering clearances length extends from the hinge of the door, integrating the door and the handle.	
– Swinging door to pull: wheelchair clearances equal to: 2.2 m×1.2 m [20].	– The maneuvering clearances length extends from the hinge of the door, integrating the door and the handle.	
– Swinging door to push: for front side approach the wheelchair maneuvering clearances equal to: doorways × 1.22 m for hinged approach must be equal to: (doorways+0.56 m) × 1.07 m and for latch approach must be equal to: (doorways+0.61 m) × 1.07 m [3].	– The maneuvering clearances length extends from the hinge of the door, integrating the door and the handle. For the hinged approach the maneuvering clearances length extends from the latch of the door, integrating the door and the handle.	– The relation between maneuvering clearance dimension and wheelchair used is not defined clearly. The values defined are very specific and person's deficiencies didn't considered.
– Swinging door to pull: for front side approach the wheelchair maneuvering clearances equal to: (doorways+0.46 m) × 1.52 m. for hinged approach must be equal to: (doorways+0.91 m) ×1.52 m and for latch approach must be equal to: (doorways+0.61 m) × 1.22 m [3].		
– Forward reach: the handle height shall be 1.22 m maximum where the minimum is 0.51 m [3]. – Handle door height must be to 0.4 m to 1.3 m [20]. – side reach: the handle height shall be 1.22 m maximum and the 0.38 minimum [3].	– The maneuvering clearances length extends from the hinge of the door, integrating the door and the handle.	– Generally, the reachability area is defined according to the person's capabilities at upper body articulated structure level, so these values must be specifics for one person, and they are not converting specific needs for the others.

Our approach has advantages over traditional approaches for assessing acceptability of designs, which is adopted until today by countries for assessing wheelchair accessibility. These methods can be complex and difficult to implement as a computer application. Our new numerical tool models a feasible wheelchair user behavior that is related to handling elements design inside individual or public apartments and to the wheelchair user requirements. In another hand, handling elements accessibility analysis is done by considering the volume occupied by person body which determined by the person capabilities. Because we negligee handling element weights, the dynamics constraints used in ergonomic field to predict actually a person upper body movement are ignored, so just the joints limits constraints are used to decide the results. In the case we believe that if the articulated structure posture respects the joint limit constraints (see Table 3), so it is feasible physically by the person.

Although, the analysis of the accessibility with only joint limit constraints of the person stores it in one aspect, a more general analysis could store both the geometric (joint limit) and dynamic aspect of the user for more potential and reusable analysis. One of the lines that we will work on in the future is to introduce the dynamic constraints in the assessment accessibility process such as muscular energy rate, external loads, torque limits to predict real human movements in the simulation.

Tab.3. Person upper body joint limits

Joint number	Joint rotation limits	
	Minimum	Maximum
0	-180	+180
1	0	0
2	-9	+15
3	-9	+9
4	-9	+9
5	-9	+9
6	-9	+9
7	-9	+9
8	-9	+9
9	-9	+9
10	-9	+9
11	-9	+9
12	0	+15
13	-15	+15
14	0	+30
15	-89	+89
16	0	+120
17	-60	+60
18	0	+120
19	-30	+30
20	-90	+90
21	-19	+19

Note. Upper body segments have following lengths in centimeter (cm) (see Fig. 1): L1=10 cm, L2=20 cm, L3=10 cm, L4=5 cm, L5=0.1 m, L6=10 cm, L7=30 cm, L8=30 cm

Appendix

Here, we present Tables that containing clearance space dimensions at the both kind of revolving door to push/pull with different wheelchair dimensions.

Tab.4. Useful corridor and revolving door to push width for different wheelchair dimensions

Wheelchair dimension in centimeter (cm)	Minimum corridor width values in centimeter (cm)		Minimum door width values in centimeter (cm)	
	Min1	Min2	Min1	Min2
WhL1=100, WhW=70, WhL2=50	104	94	90	100
WhL1=110, WhW=80, WhL2=60	115	105	100	110
WhL1=120, WhW=90, WhL2=70	127	116	110	120
WhL1=130, WhW =100, WhL2=80	138	127	120	130
WhL1=140, WhW=110, WhL2=90	148	138	130	140

Tab.5. Minimum wheelchair clearance space dimensions at revolving door to pull according to wheelchair dimensions

Wheelchair dimension in centimeter (cm)	Minimum corridor width values in centimeter (cm)	Minimum corridor length values in centimeter (cm)
WhL1=100, WhW =70, WhL2=0.5	174	204
WhL1=110, WhW =80, WhL2=60	184	214
WhL1=120, WhW =90, WhL2=70	195	225
WhL1=130, WhW=100, WhL2=80	206	233

Tab.6. Achievable height handles of revolving door to pull according to different wheelchair dimension

Wheelchair dimension in centimeter (cm)	Height handle intervals [Minimum, Maximum] in centimeter (cm)
WhL1=100, WhW =70, WhL2=50	[40 , 162]
WhL1=130, WhW =100, WhL2=90	[40 , 155]
WhL1=150, WhW =130, WhL2=110	[40 , 143]
WhL1=160, WhW =150, WhL2=110	[40 , 134]

Tab.7. Achievable height handles of revolving door to pull according to different wheelchair dimensions

Wheelchair dimension in centimeter (cm)	Height handle intervals [Minimum, Maximum] in centimeter (cm)
WhL1=100, WhW =70, WhL2=50	[40 , 162]
WhL1=100, WhW =100, WhL2=90	[40 , 153]
WhL1=100, WhW =130, WhL2=110	[40 , 143]
WhL1=100, WhW =150, WhL2=110	[40 , 133]

Note. WhL1 is fixed at 100 centimeter (cm)

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