Integrated approach for older adult friendly home staircase architectural design

Abstract

The older adult population requires special consideration in terms of interior architectural design. This paper presents a methodology which aims to investigate the risk of falling associated with the architectural design of staircase elements, in order to suggest best practices to create elderly-friendly design that enhances safety for older adults. The proposed methodology uses the concept of evidence-based assessment to evaluate staircase elements such as handrail and step design. This paper also presents a scenario-based rating system that assesses the degree of the risk of falling for different types of architectural staircase design. The proposed rating system was incorporated into a mathematical model and a Design Assessment Tree (DAT) that calculate the degree of risk associated with architectural staircase design to facilitate a building information modeling (BIM) approach. A hypothetical case study is presented to illustrate the effectiveness of the proposed methodology and highlights the essential features of the proposed model.

Keywords

- Staircase design;
- Older adult;
- Risk of falling;
- Home design;
- Building information modeling

1. Introduction

As the so-called “baby boomer” generation approaches retirement, the current paradigm is shifting toward elderly-friendly design. In order to create elderly-friendly design, a cohesive set of information needs to be uploaded to each design object, such as the staircase design assessment developed in this study, to create more efficient building information modeling (BIM) serving this purpose. Inter-disciplinary collaboration must be achieved between gerontological and architectural research as the first step toward creating elderly-friendly design that enhances safety for older adults. Developing this inter-disciplinary collaboration will define the gap between the space users' requirements—in this case older adults—and the architectural specifications that satisfy those requirements. This inter-disciplinary collaboration requires reliable methods to integrate, share, and restore information. The framework for this collaboration can be supported through computer-aid design (CAD) packages to encourage data exchange of 2D and 3D drawing. BIM can be implemented in this transformation, where strong, reliable information for each home design object—such as staircase—is the key that support and facilitate this building information system.

Considering the staircase as a home design object that can be assessed to enhance safety for older adults, the processes of ascending and descending staircases have been reported as difficult daily activities for older adults [1]. Statistically, one out of four older adults is expected to fall when climbing staircases in the home environment [2]. Falling for older adults might lead to injuries [2] and [3]. In addition to experiencing physical harm, older adults might experience loss of confidence or develop a fear of falling, which will impact their performance while ascending or descending staircases [2], [4], [5] and [6]. There is a wide variation of staircase configurations such as spiral staircases, straight staircases with landing, and U-shaped staircases. Each staircase configuration has been associated with different handrailing, lighting, and step dimensions (riser and tread). The concept of modifying staircase configuration plays an important role in maintaining safety for older adults. Previous studies have investigated the cause of falling during staircase ascent/descent for older adults [1], [2], [6], [7], [8] and [9]. Other studies have recommended staircase modifications for handrail, lighting, and step design to reduce the risk of falling [4], [10], [11], [12], [13], [14], [15] and [16].

This paper presents an evidence-based integrated framework that combines all aspects related to staircase architectural design in order to provide an assessment to support elderly-friendly design. Previous evidence-based studies are collected to build detailed specifications for each design feature of the staircase. Hierarchical lists of evidence-based scenarios are then provided as an outcome of the integration of gerontological and architectural researches on staircases. A new developed rating system has been created to assess the developed hierarchical lists, the primary purpose of which is to provide a numerical evaluation that reflects the hierarchical lists to support the BIM model for the staircase design elements, creating elderly-friendly design. To further enhance the inter-disciplinary collaboration of gerontology and architecture and facilitate BIM integration, the first step in this assessment involves assigning a rating number to each associated staircase design element and feature (represented through 2D and 3D specifications), which represents the safety factor, the extent to which the given element or feature reduces the risk of falling for older adults. This assessment can also be presented through such CAD packages as ArchiCAD and Revit, so the assessment can be introduced as a loaded information algorithm/module for the 3D objects of the building, such as staircases, in order to create elderly-friendly design.

2. Evidence-based research for staircase design

Templer's [17] and [18] is among the foremost research that provide detailed analyses for the behavioral and movement patterns on staircases, as well as a historical study of various staircase types. Haslam and Stubbs [19] added to this an examination of the causes of falls that considers a combination of design specification factors and behavioral factors of an individual ascending or descending a staircase. In addition, Lee and Chou [4] and Zietz et al. [20] provided an ergonomics approach involving an analytical study of older adult movement during staircase ascent/descent to detect gait instability. Problems associated with staircase design, such as irregularity in gait pattern, were addressed as stimulating factors that increase the possibility of falls [10], [17] and [19]. However, the concept of linking these problems with a specific type of staircase geometry was not introduced. For example, both inconsistent dimensions of the first three steps of the staircase [13] and [20] and a mixed step combination such as the winder [10], [17] and [19] are found to increase the risk of falling for older adults. However, linking these causes of falls with the staircase configuration of “composite staircases” has not been proposed in previous research studies.

By introducing proper handrail designs that are conducive to grasping and provide stability for cases of lost balance, the risk of falling can be reduced [14], [15] and [21]. Maki et al. [14], [15] and [22] developed an experimental study that addressed the influence of handrail height, cross-section, size and surface texture on grasping force by testing the ability to push or pull on handrails while standing braced in an upright posture. In addition, older adults as a subgroup have also been studied to highlight the role of the handrail in maintaining stability while ascending or descending staircases [11] and [21]. Hill et al. [21] interviewed 157 participants, aged 65 to 96, reporting that over 70% of the participants used the handrail to maintain stability while ascending and descending staircases. Based on their findings, Hill et al. [21] proposed the handrail as an essential tool for older adults not only to reduce the risk of falling by providing a graspable object, but also because it serves as a tool to sustain one's stability while ascending or descending staircases [21]. Staircase lighting is an important factor that provides visual information to assess older adult movement when ascending or descending staircases [23]. Previous studies have provided evidence that poor lighting is associated with higher risk of falling for older adults [4], [17] and [24]. It has also been shown that lighting throughout the staircase helps older adults to gather the balance control information needed to plan foot placement for safe navigation [4] and [24]. Furthermore, a study by Zietz et al. (2011) showed that the amount of lighting affects individual behavior, as the individual tends to reduce the speed of walking in the case of inadequate lighting [4]. Templer [17] provided some recommendations regarding adequate lighting for both older adults and younger people. The Illuminating Engineering Society of North America [23] has made a practical lighting recommendation that focuses on older adults with respect to the valid assumption that the amount of lighting is typically insufficient for older adults.

3. Proposed objective and methodology

The objective of this research is to establish an evidence-based integrated assessment framework to evaluate staircase design in order to reduce the risk of falling for older adults. The proposed assessment is built based on a developed hierarchical outcome list extracted from previous evidence-based studies related to staircase design. The proposed assessment brings together scattered information related to staircase design, refining the existing evidence-based research and integrating these studies into one new assessment approach that effectively represents the staircase object. Furthermore, the developed assessment forms a numerical representation of the data extracted from the evidence-based studies to facilitate BIM for elderly-friendly design.

The research methodology is divided into three stages: (1) the staircase is divided into four design elements (staircase geometrical design; handrail design; lighting; and step design) that represent its architectural design. These elements are then each divided into a number of features that provide more detailed specifications. For example, the handrail design element, if exists, is divided into five features: handrail height; handrail cross-section; handrail surface texture; handrail extension; and minimum handrail-wall clearance. Each feature has different scenarios that represent the architectural design alternatives for that feature. For example, handrail height feature (Hh) has four scenarios: 1) 910-mm ≤ Hh ≤ 970-mm; 2) Hh < 910-mm; 3) Hh ≥ 1000-mm; and 4) 970-mm < Hh < 1000-mm. The outcome of this stage is the establishment of hierarchical list representation of different scenarios based on previous evidence-based studies. (2) Based on the developed evidenced-based hierarchical list, an assessment is developed through mathematical modeling equations to represent the risk reduction associated with each scenario, in which a rating factor is calculated for each scenario to represent how much it affects the risk of falling for older adults. (3) A design assessment tree (DAT) has been developed to provide a complete vision of different staircase design scenarios, as well as an automated extraction of the assessment calculations, as each branch in the DAT provides the exact assessment numbers calculated mathematically through the assessment equations. The DAT is considered as a comprehensive design chart by which for architects to directly evaluate any proposed staircase design, and to visualize the optimal design scenario compared to other scenarios in each branch. The proposed methodology is presented to assess proposed staircase layouts, which are obtained from 2D- and 3D-CAD models. This model can represent a draft design or an existing design for potential modification, and the detailed staircase specification information is extracted from that model. A practical case study of staircase design is presented from the perspective of reducing the risk of falling for older adults. This case study demonstrates the proposed methodology by applying the assessment equations and the developed DAT.

3.1. Proposed rating system

The developed rating system represents the degree by which the risk of falling for older adults is reduced. A rating factor (R) is assigned to different alternatives (scenarios). This rating factor is calculated based on an evidence-based comparison with alternative scenarios. To set the comparison, a scale of numbers between 0.00 and 1.00 has been adopted to indicate how much each scenario may reduce the risk of falling for older adults. The rating factor 1.00 represents optimal risk reduction; the scaled numbers from 0.00 to 1.00 represents the scaled reduction of the risk of falling for older adults, as illustrated in Table 1. The rating factor 0.0 means that the feature does not exist. For example, if the handrail does not exist, the rating factor of the “handrail existing” feature will be 0.00.

Table 1.

Explanations of rating factors.

Rating factor	Explanation
1.00	The risk of falling for older adults is optimally reduced by the selected scenario (optimal design feature)

Rating factor	Explanation
0.75	The risk of falling for older adults is strongly reduced by the selected scenario (strong design feature)
0.50	The risk of falling for older adults is moderately reduced by the selected scenario (moderate design feature)
0.25	The risk of falling for older adults is increased by the selected scenario (weak design feature)
0.00	The design features does not exist (highest risk of falling)

4. Staircase elements and features analysis and rating

In this study, the staircase is divided into four design elements: staircase geometrical design; handrail design; lighting; and step design. Handrail, lighting and step specifications are provided in the building code as subdivisions of the staircase design specifications. In addition, staircase geometric design is considered to be a design element that presents the formation of the staircase as an independent design object, which can only be tracked by the geometrical design of the staircase. The staircase geometrical design element is divided into the staircase configuration and the number of steps per flight, represented as two subdivision features. The other three elements—handrail design, lighting, and step design—are also divided into a number of features that define the architectural design, as illustrated in Fig. 1. For instance, the step design has four features: going depth; riser height; nosing; and step finishing material.

Fig. 1.

Full-size image (69 K)

Staircase elements and features flow chart.

Each design element in the staircase is divided into a number of features, and each feature in turn is divided into a number of scenarios that are hierarchically arranged according to the extent to which each scenario reduces the risk of falling for older adult. A rating factor is assigned to each scenario to represent the risk reduction, where the rating factor (R) is calculated based on the evidenced-based hierarchical outcome list for each staircase design feature. The scenario that optimally reduces the risk of falling takes a rating factor (R) equal to 1.00. Assuming a constant rating factor interval between the hierarchized scenarios, Solver has been used to generate rating factors that represent this scaled hierarchy, approximated to the nearest two-digit decimal number. This method generates scaled factors to represent the hierarchical list of scenarios that is the outcome of the evidence-based studies.

4.1. Element 1: staircase geometrical design

From the perspective of investigating the risk of falling for older adults, staircase configuration [10], [13], [17], [19] and [20]; and length of each flight [12], [13] and [17] of the staircase are two important factors. Therefore, staircase geometrical design, as an element, can be divided into two main features that specify its architectural design: 1) staircase configuration which represents variation in staircase shapes (straight, circular or composite); and 2) number of steps per flight.

4.1.1. Feature 1: staircase configuration (Gg)

This paper covers a wide range of staircase configurations including: (1) U-shaped staircases; (2) Quarter-turn staircases; (3) Straight staircases with landing; (4) Straight staircases without landing; (5) Helical staircases; (6) Spiral staircases; and (7) Composite staircases, illustrated in Fig. 2, arranged from highest to lowest risk reduction in terms of falling for older adults. The optimal staircase design has been found to be the U-shaped staircase design [17] and [25], which has an associated rating factor of 1.00. The composite staircase is defined as a mixed staircase configuration in one staircase connecting two floors. The worst staircase configuration is the composite staircase, as it causes an irregular gait pattern which increases the risk of falling for older adults [10], [17], [19] and [26].

Fig. 2.

Full-size image (59 K)

Staircase geometrical design: staircase configuration: (a) straight flight staircases with landing; (b) straight flight staircases without landing; (c) quarter-turn staircases; (e) U-shaped staircases; (f) spiral staircases; (g) helical staircases; and (h) composite staircases: (h1) example illustrates inconsistency of step dimensions throughout the staircase; (h2) example illustrates mixing straight and circular flights; and (h3) Example illustrates winder staircase.

The composite staircase has an associated rating factor of 0.14. The remaining staircase configurations have a range of rating factors according to how much each staircase configuration reduces the risk of falling for older adults. The staircase configuration can be listed hierarchically from highest to lowest risk reduction as follows [27]: (1) U-shaped stairs with an associated rating factor of 1.00, as this represents the optimal case scenario; (2) quarter-turn stairs, with an associated rating factor of 0.85; (3) straight stairs with landing, with an associated rating factor of 0.71; (4) straight stairs without landing, with an associated rating factor of 0.57; (5) helical stairs, with an associated rating factor of 0.43; (6) spiral stairs, with an associated rating factor of 0.29; and (7) composite stairs, with an associated rating factor of 0.14.

4.1.2. Feature 2: number of steps per flight (Gs)

Long flights (over 12 steps) or short flights (less than 6 steps) have been found to increase the risk of falling [12], [13] and [17]. There are four scenarios for the “number of steps per flight” feature (Gs): (1) $10 \le Gs \le 12$, which is the optimal case and has an associated rating factor of 1.00; (2) $7 \le Gs \le 9$, with an associated rating factor of 0.67; (3) $Gs \le 6$; and (4) $Gs \ge 13$, which has the worst-case scenario, with an associated rating factor of 0.33 indicating that they highly increase the risk of falling for older adults.

4.2. Element 2: handrail design

The handrail is an essential tool that assists older adults' movement while ascending and descending staircases [21]. Handrail design consists of six features: handrail existence, handrail height, handrail cross-section, handrail surface texture, handrail extension, and minimum handrail-wall clearance. These six features are chosen to represent the handrail design specifications that have been found to reduce the risk of falling for older adults. To express importance of each scenario compared to others, a suitable rating factor is assigned to each of the scenarios according to the potential reduction in the risk of falling for older adults.

4.2.1. Feature 1: handrail existence (He)

Evidence suggests that as a person ages, the need for a handrail increases [11]. Safety in ascending and descending a staircase is further enhanced when a handrail exists on both sides of the staircase [11] and [21]. The scenarios for “handrail existence” (He) are: (1) to have one handrail on each side of the staircase, which is the optimal design scenario with a rating factor of 1.00; (2) to have one handrail on one side of the staircase, which has an associated rating factor of 0.67 as a moderate case; and (3) to have no handrail on either side of the staircase, with a rating factor of 0.00 as the feature does not exist.

4.2.2. Feature 2: handrail height (Hh)

Handrail height is the vertical line from the top of the rail to the outside edge of the staircase, as illustrated in Fig. 3(a). There are four scenarios for the “handrail height” feature (Hh) [15] and [17]: (1) 910-mm ≤ Hh ≤ 970-mm, which is considered the optimal handrail height, as it is the most preferred height by older adult users [15], and has an associated rating factor of 1.00; (2) Hh < 910-mm; and (3) Hh ≥ 1000-mm, both of these cases are considered worst-case scenarios, with a rating factor of 0.33; and (4) 970-mm < Hh < 1000-mm, which is neither the optimal nor the worst case, with an associated rating factor of 0.67 as an over-moderate design.

Full-size image (23 K)

Fig. 3.

Handrail design specifications: (a) staircase section and (b) handrail cross-section detail. Hh: handrail height; Hex: handrail extension; and Hw: handrail-wall clearance.

4.2.3. Feature 3: handrail cross-section (Hc)

By facilitating handrail graspability, the risk of falling could be reduced [14]. Accordingly, to facilitate graspability of the handrail a suitable handrail cross-section should be selected [14]. The “handrail cross-section” feature (Hc) is considered to be a function of the handrail shape and the handrail cross-section dimension [14] and [19]. The optimal scenario, based on the ability to grasp the handrail, is to have a circular handrail cross-section with a circumferences between 100-mm (32-mm diameter) and 160-mm (51-mm diameter), or to have an oval handrail cross-section with dimension of 50-mm in height and 37-mm in width [14]. These two scenarios have an associated rating factor of 1.00 representing the optimal case of the handrail cross-section. Other handrail cross-sections had lower levels of comfort than those of circular and oval cross-sections, and participants had some difficulty manipulating their hand grasp on them [14]. Therefore, other handrail cross-sections have an associated rating factor of 0.50.

4.2.4. Feature 4: handrail surface texture

In order to facilitate handrail graspability, the surface texture needs to be not too smooth or not too rough [14] and [17]. This case is considered as the optimal scenario of the “handrail surface texture” feature, and is thus rated as 1.00. The second scenario is to have too smooth handrail surface texture or too rough handrail surface texture. In that case the associated rating factor is 0.50, as it increases the risk of falling [14] and [17].

4.2.5. Feature 5: handrail extension (Hex)

Handrail extension at the top and bottom of staircases, as illustrated in Fig. 3(b), has been found to be important in assessing older adult movement when ascending or descending the staircases [11]. There are four scenarios for the dimension of the “handrail extension” feature (Hex) [11]: (1) 320-mm ≤ handrail extension on at least one handrail ≤ 480-mm, which is found to be the optimal scenario and is therefore assigned a rating of 1.00; (2) handrail extension on at least one handrail > 480-mm, which is lower than the optimal case scenario with an associated rating factor of 0.75; (3) no handrail extension, which is associated with a rating factor of 0.50 as it moderately increases the risk of falling for older adults; and (4) handrail extension on at least one handrail < 320-mm, which is the worst-case scenario, as it has been found that a short handrail extension increases the risk of falling more than does no handrail extension [11]; thus, the associated rating factor is 0.25.

4.2.6. Feature 6: minimum handrail-wall clearance (Hw)

The purpose of investigating the minimum handrail-wall clearance, illustrated in Fig. 3(b), is to provide a sufficient space to grasp the handrail in case of a falling emergency. There are four scenarios for the “min handrail-wall clearance” feature (Hw) [17] and [28]: (1) a smooth wall surface and Hw ≥ 57-mm; and (2) a rough wall surface and Hw ≥ 75-mm, both of these cases are the optimal cases which have a rating factor of 1.00; (3) a smooth wall surface and Hw < 57-mm; and (4) a rough wall surface and Hw < 75-mm, these two cases are the worst scenarios as they increase the risk of having finger injuries while moving the hand on the handrail and increase the risk of falling when ascending or descending the staircase [11], and thus have a rating factor of 0.50, indicating a lower than moderate design.

4.3. Element 3: lighting

Poor vision is associated with an increased risk of falling for older adults on staircases, as older adults often require an increased lighting level [23] and [24]. The lighting element is divided into three features that specify: (1) illumination level; (2) consistency of lighting; and (3) light switch types and locations.

4.3.1. Feature 1: illumination level (Li)

Lighting for older adults has been recommended by Illuminating Engineering Society of North America- IESNA to be a minimum of 300-lux throughout the entire staircase [23]. The “Illumination level” feature (Li) is divided into two scenarios: (1) Li ≥ 300-lux, which is the optimal scenario and has an associated rating factor of 1.00; and (2) Li ≤ 300-lux, which is the worst scenario and has an associated rating factor of 0.50.

4.3.2. Feature 2: consistency of lighting (Lc)

Providing consistent lighting throughout the entire staircase is a very important factor that contributes to reducing the risk of falling for older adults [17] and [23]. Providing inconsistent lighting may cause shaded areas on staircases which could cause confusion and might result in falls [17] and [23]. Two scenarios are provided for the “consistency of lighting” feature (Lc): (1) consistent staircase lighting, which is the optimal scenario and has an associated rating factor of 1.00; and (2) inconsistent staircase lighting, which is the worst scenario and has an associated rating factor of 0.50.

4.3.3. Feature 3: light switch types and locations (Ls)

In order to reduce the risk of falling, light switches need to be placed away from the staircase path and should be two-way [17] and [19]. Four scenarios are provided for the “light switches” feature (Ls). The first scenario is light switch away from staircase path and two-way light switch, which is the optimal case and has an associated rating factor of 1.00. The second and third scenarios are: (1) light switch through staircase path and two-way light switch, and (2) light switch away from staircase path and one-way light switch, both cases have an associated rating of 0.67. The last scenario is light switch through staircase path and one-way light switch, which is the worst case, with an associated rating factor of 0.33.

4.4. Element 4: step design

The step design element considers step design specifications, which are: going depth; riser height; nosing shape and dimensions; and step finishing material (see Fig. 4). In this paper, the selected step design specification is based on the most preferred step dimensions provided in previous evidence-based studies for different age groups, including older adults [[16] and [18]].

Fig. 4.

Full-size image (23 K)

Step design specifications. Sr: riser height; Sg: going (tread w/o nosing) depth; and T: tread.

4.4.1. Feature 1: going depth (Sg)

The going depth represents the depth of the tread without nosing, as illustrated in Fig. 4. For the “going depth dimension” feature (Sg), there are three scenarios [16] and [17]: (1) 280-mm ≤ Sg ≤ 330-mm, which is the optimal scenario and has an associated rating factor of 1.00; (2) Sg < 280-mm; and (3) Sg > 330-mm. The latter two scenarios are the worst-case and have an associated rating factor of 0.50.

4.4.2. Feature 2: riser height (Sr)

Three scenarios are provided for the “riser height dimension” (Sr) feature [16] and [17]: (1) 152-mm ≤ Sr ≤ 190-mm, which is the optimal scenario and has an associated rating factor of 1.00; (2) Sr < 152-mm; and (3) Sr > 190-mm. The latter two scenarios are the worst-case and have an associated rating factor of 0.50.

4.4.3. Feature 3: nosing (Sn)

Safer staircase design can be achieved by optimizing the staircase nosing [17] and [29]. The optimal scenario for the “nosing” feature (Sn) is to be rounded with nosing depth between 15-mm and 25-mm [17] and [29]. The worst-case scenario is non-rounded with nosing depth outside of the range of the optimal scenario. The worst case has an associated rating factor of 0.25 as it is highly associated with increasing the risk of falling for older adults [29].

4.4.4. Feature 4: step finishing material (Sf)

Finishing step material represents the texture, pattern and color of the finishing material of each staircase step. The optimal case scenario for the “finishing step material” feature (Sf) is to have cohesive finishing material with uniform slip-resistance for the staircase steps [17] and [29], which has an associated rating factor of 1.00. The worst-case scenario is to have non-cohesive finishing material and non-uniform slip-resistance for staircase steps. In this case, the associated rating factor is assigned to be 0.33. The intermediate case scenario is to have finishing material that provide un-evened throughout the staircases and provide uniform slip-resistance or to have finishing material provide evened throughout the staircases and provide non-uniform slip-resistance, which have an associated rating factor of 0.67.

5. Assessment calculations

One scenario is selected to represent the proposed staircase design. Based on the rating factor (R) that is assigned to each scenario for each feature, an average rating factor $\bar{R}$ is calculated for each element, representing the selected scenario of each feature. This average rating factor represents the extent to which the proposed features for each element reduce the risk of falling for older adults. The average rating factor must satisfy Eq. (1).

equation(1)

$$\bar{R}_Y = \sum R_X / n$$

Turn MathJax on

where:

$\bar{R}_Y$

average rating factor $\bar{R}$ for element Y;

R(X)

rating factor (R) for feature X;

Y

index for element symbol;

X

index for feature symbol; and

n

the total number of features for element Y (n = 2 for staircase geometrical design (G), n = 6 for handrail design element (H), n = 3 for lighting element (L), and n = 4 for the step design element (S)).

A rating number (N) is generated to represent and rank the importance of each of the four elements. The summation of the four rating numbers is 100. This paper proposes an equal rating number (N) for the four staircase elements (25 each). The purpose of assuming such an equal rating number is not to make any element more important than the others, since there is no evidence in the literature to support such a measure. The corrected rating number $N_c(Y)$, is calculated by multiplying the rating number by the average rating factor of each element, which represents how much each element, relative to the other elements, reduces the risk of falling for older adults. The corrected rating number $N_c(Y)$ for each of the four elements must satisfy Eq. (2).

equation(2)

$$N_c(Y) = \bar{R}(Y)\,N(Y)$$

Turn MathJax on

where:

$N_c(Y)$

corrected rating number for element Y;

$\bar{R}(Y)$

average rating factor $\bar{R}$ for element Y;

N(Y)

rating number (N) for design element Y;

Y

index for element symbol.

The summation of the four corrected rating numbers represents how much the proposed staircase design reduces the risk of falling for older adults. Thus, in the perfect hypothetical case, the staircase rating must equal 100. The total rating for staircase design is calculated satisfying Eq. (3).

equation(3)

$$N_{total} = \sum N_c(X)$$

Turn MathJax on

where:

N_{total}

total rating number of the proposed staircase architectural design;

$N_c(X)$

corrected rating number for staircase element (X).

A scale is developed to categorize the total rating of the staircase from the perspective of reducing the risk of falling for older adults. A total rating from (100 to 90) represents the optimal staircase design; (90 to 65) represents strong staircase design; (65 to 40) represents moderate staircase design; (40 to 15) represents a weak staircase design; and (15 to 0) represents the staircase design associated with the highest risk of falling.

5.1. Design assessment tree (DAT)

The Design Assessment Tree (DAT) is a decision tree that has only decision nodes. DAT works as a manual for architects to represent a complete vision for staircase assessment for any proposed design, and represents an automated process to directly extract the assessment values for any staircase design scenario. In addition, DAT allows the architect to visualize the optimal design scenario compared to other scenarios in each branch. Each individual branch in the DAT carries the rating factor (R) of each scenario, and the same assessment results can be obtained from the DAT. There are two columns at the end of each DAT branch, as illustrated in Fig. 5: the first column lists the average rating factor for each design scenario, calculated satisfying Eq. (1); the second column displays the corrected rating number $N_C(Y)$ for each design scenario, calculated satisfying Eq. (2). DAT is developed for each element independently.

Full-size image (36 K)

6. Case example

To illustrate the effectiveness of the proposed staircase assessment, the case example of straight staircase without landing is presented, as shown in Fig. 6. The proposed staircase is represented by 2D- and 3D-CAD models that specify each feature of the staircase design. The proposed staircase design specifications are as follows: (1) staircase geometrical design specifications: the staircase is straight without landing, and consists of 16 steps per flight. (2) Handrail design specifications: the handrail height is 900-mm, and it exists on one side of the staircase. The handrail cross-section shape is rectangular with smoothed edges. (3) Lighting specifications: the illumination level = 250-lux and the lighting throughout the staircase is consistent. The light switch is away from the staircase path and is a two-way light switch. (4) Step design specifications: the going depth is 269-mm, the riser height is 174-mm, with a 40-mm nosing and an even finish material throughout the staircase. Table 2, Table 3, Table 4 and Table 5 illustrate the actual scenarios for each feature based on the proposed staircase design, and provide the associated rating factors.

Fig. 5.

Part of the DAT for lighting switche feature illustrat the associa $\overline{R}$ and N_c for each scenari

Fig. 6.

Perspective and plan view: straight staircases without landing.

Full-size image (20 K)

Table 2.

Features of staircase geometrical design.

Feature no	Feature's name	Proposed scenario	Rating factor (R)
Feature 1	Staircase configuration (Gg)	Straight staircases without landing	0.57
Feature 2	Step no/flight (Gs)	(Gs = 16 steps) ≥ 13	0.33

Table 3.

Features of handrail design.

Feature no	Feature's name	Proposed scenario	Rating factor (R)
Feature 1	Handrail existence (He)	One handrail	0.67
Feature 2	Handrail height (Hh)	(Hh = 900) ≤ 910-mm	0.33

Feature no	Feature's name	Proposed scenario	Rating factor (R)
Feature 3	Handrail cross-section (Hc)	Other handrail shapes and dimensions	0.5
Feature 4	Handrail surface texture (Ht)	Comfortable handrail surface texture (not too smooth or not too rough)	1
Feature 5	Handrail extension (Hex)	No handrail extension	0.5
Feature 6	Minimum handrail-wall clearance (Hw)	Smooth wall surface and handrail-wall clearance ≥ 57-mm	1

Table 4.

Features of lighting.

Feature no	Feature's name	Proposed scenario	Rating factor (R)
Feature 1	Illumination level (Li)	(Li = 250-lux) ≤ 300-lux	0.5
Feature 2	Consistence lighting amount (Lc)	Lighting throughout staircases is consistent	1
Feature 3	Light switches (Ls)	Light switch away from staircases path and two-way light switch	1

Table 5.

Features of step design.

Feature no	Feature's name	Proposed scenario	Rating factor (R)
Feature 1	Going depth (Sg)	(Sg = 269-mm) ≤ 280-mm	0.5
Feature 2	Riser height (Sr)	152 ≤ (Sr = 174-mm) ≤ 190-mm	1
Feature 3	Nosing (Sn)	(Nosing dimension = 40-mm) ≥ 25-mm and not rounded	0.25
Feature 4	Step finishing material (Sf)	Finish material provide evened throughout the stairs and provide uniform slip-resistance	1

The average rating factor $\bar{R}$ for the staircase geometrical design element (G), handrail design (H), lighting (L) and step design (S) is calculated satisfying Eq. (1), as follows:

View the MathML source

R¯G=0.57+0.3/2=0.45R¯H=0.67+0.33+0.50+1+0.50+1/6=0.66R¯L=0.50+1+1/3=0.83R¯S=0.5+1+0.25+1/4=0.69.

Turn MathJax on

The corrected rating number for the staircase geometric design element (G) handrail design (H), lighting (L), and step design (S) is calculated satisfying Eq. (2), as follows:

View the MathML source

$$N_{cG}=\bar{R}_G N_G=0.45\times25=11.25 \quad N_{cH}=\bar{R}_H N_H=0.66\times25=16.50 \quad N_{cL}=\bar{R}_L N_L=0.83\times25=20.75 \quad N_{cS}=\bar{R}_S N_S=0.69\times25=17.25.$$

Turn MathJax on

The total rating for the proposed straight staircase without landing is obtained satisfying Eq. (3). The total rating for the proposed staircase design (65.75) indicates that the proposed straight staircase without landing has a moderate staircase design.

$$N_{total}=11.25+16.50+20.75+17.25=65.75.$$

Turn MathJax on

The same results can be obtained by selecting DAT branches that express the proposed scenarios. The total rating of the staircase can be optimized by selecting better scenarios for different design features from the developed DAT. For example, as illustrated in Fig. 7, the number of steps per flight can be optimized by selecting the optimal scenario, with an associated rating factor of 1.00, which is to have between 10 and 12 steps per flight. Also, the effect of choosing a certain scenario on the average rating factor $\bar{R}$ can be tracked. Therefore, the architect might decide to add a landing in the middle of the staircase to satisfy the optimal number of steps per flight; in that case, the average rating factor will be optimized from 0.45 to 0.8. This process can be applied to different features of the four elements to optimize the whole staircase design. The advantage of using DAT for optimization is that rating factor for the different scenarios of each feature are visually easier to extract and compare.

Full-size image (46 K)

Fig. 7.

Scenarios for number of steps per flight and its associated rating factors.

7. Conclusion

In this paper, a new integrated assessment has been proposed for staircase architectural design to reduce the risk of falling for older adults. The assessment has considered all the features of staircase design that could be improved through different scenarios. An evidence-based analysis of the staircase elements—staircase geometrical design, handrail design, lighting, and step design—has been used to divide the staircase object into a number of features. Additionally, based on the previous evidence-based studies, a hierarchical list has been proposed for the different scenarios corresponding to each of the design features. Mathematical modeling equations have been developed in order to reflect the hierarchy of the developed lists of scenarios. These developed equations have been incorporated in an assessment to evaluate the risk of falling associated with different scenarios of each staircase design feature. A DAT has been built to collect all possible current design alternative scenarios for staircase and automate the assessment process. Each branch in the developed DAT represents a different design alternative scenario for the presented staircase feature. Additionally, the mathematical model has been incorporated into the DAT to provide a direct value that assesses each design scenario alternative in each branch. A case study has been generated to demonstrate the application of the developed assessment to evaluate staircase design. The proposed integrated staircase rating system enables architects to assess the proposed staircase design and facilitate the BIM integration, with the aim of reducing the risk of falling for older adults.

One of the significant benefits of BIM is to create an integrated digital model for various building objects. This goal needs to be supported by several inter-disciplinary layers of information. The proposed assessment of staircase design objects to reduce the risk of falling for older adults is introduced numerically so it can be used as part of a BIM model. The assessment combines a selection of previous evidenced-based assessments in order to build an integrated set of building specifications for the staircase object which are categorized under elements and feature specifications. Based on the proposed assessment, the rating factors attached to each design element can be introduced in CAD software, such as Revit, as loaded information algorithm/module for different 3D objects of the home building for the purpose of BIM for elderly-friendly design. This research will facilitate the upgrading of any existing or drafted design to elderly-friendly design through conscious participation in the BIM model.

This research can be considered as a potential algorithm for CAD and BIM implementation for elderly-friendly design, focusing on reducing the risk of falling for older adults. Incorporating BIM technology (front loading the 3D model with information relevant to assessment of design for older adults) is a step toward automation. The provided assessment not only attaches information to each categorized element and feature, but also provides a combined assessment in the form of staircase object design, which can be implemented in the BIM model to reduce the risk of falling for older adults. The proposed methodology can be significantly expanded to provide an assessment by which to build standardized elderly-friendly criteria for various building types, such as assisted living facilities and hospitals. Moreover, by choosing the optimal staircase scenario associated with the lowest risk of falling, a modular staircase can be provided to be implemented widely in modular housing for older adults.

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