Evaluation of point cloud data acquisition techniques for Scan-to-BIM workflows in Healthcare

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1 MOTIVATION

Securing care for people is a major challenge in our aging society. Across Europe, millions of people rely on care services (ADI 2013). This demand collides with a health system that is overburdened by shortage of skilled workers in both, the nursing specialty and nursing assistant sector (European Commission 2020). In long terms, this situation forecasts an inability to secure the need for care and thus the risk of insufficient services arises. As a consequence, the immigration of skilled workers from emerging countries can be identified, which will result in another service shortages in the respective countries (Wittenborg und Ziller 2013). In order to solve this structural issue, alternative concepts are needed that relieve health system by both, assigning more responsibilities to relatives and using more modern information and communication technology (ICT) to simplify interconnection between professionals and patients (e-health). Thus, the concept Aging in Place[1] (Wiles et al. 2012) proves beneficial. It addresses the personnel bottleneck in health system and fulfils people's in need of care desire for an independent and self-determined life in their familiar environment (Stula 2012; Harrefors et al. 2009). However, not every person in need of care, hereinafter patients, is physically or mentally able to be treated at home. In addition, the housing situation plays a crucial role especially in scope of risk prevention and adaption to increasing or complementary disabilities in old age. At present, both aspects are evaluated under medical-technical requirements periodically, whereby in particular the latter is time-consuming and may not be feasible for an already overburdened health system staff. Due to this, the demand to automate housing evaluation with respect to patient constitution arises as well as to provide it in a patient-friendly way as assisted living (AL) system (Avila und Sampogna 2011) in order to achieve discharge in health system and to support caring relatives or affected persons as unknowledgeable main users of the AL system.
We propose to tackle this issue with an AL system based on decision support (DS) technology, that assist people in decision-making process by collecting relevant information, evaluating it in context and providing explainable conclusions (Papathanasiou et al. 2016). To achieve this, our approach, which is described in another paper by the first author, utilize multiple components such as Building Information Modeling (BIM), Artificial Intelligence (AI) and semantics technology. In order to evaluate the suitability of the as-built living environment, up-to-date information is needed as well as criteria, which can be checked. According to state of the art, geometric information and semantic attributes for 3D object representation can be obtained from dense point clouds acquired by scanning or imaging techniques. Nowadays, the

[1] Ability to live in one's own home regardless of age or disability.

market offers a wide range of sensors based on different technologies and characterized by various specifications, which will be evaluated from different points of view in this paper. Our research presents a balanced cross-section of available professional sensors on the one hand and consumer products on the other. In addition, it is based on standards defining living space requirements in a universal way.
As a proof of concept (PoC) we present a case study in this paper considering a wheel-chaired human within a simulated living environment, incorporating requirements described in DIN 18040-2 for barrier-free living and unrestricted wheelchair usage. The methodology and the design of our project environment is described in section 2. Then, a brief description of the selected data acquisition technologies is provided. The evaluation of the technologies is presented in section 4 and examined two aspects: (a) technical quality criteria, which are deduced from 3D point cloud data and thus become relevant to the final evaluation based on a modeled BIM and (b) features such as usage requirements and usability, which plays a key role for the main users mentioned above. Both dedicated criteria fill a matrix used for the final sensor evaluation. The sensor comparison illustrates, that imaging techniques are laborious and therefore less suitable, whereas even low-cost scanning solutions are user-friendly and produce trustworthy results. This study investigated the potential of different 3D data acquisition technologies. The current state of the art allows even unknowledgeable users to capture objects entirely in 3D and thus confirms an important component in our DS approach to relieve caregivers and maintain the autonomy and safety of Aging in Place patients.

2 METHODOLOGY

The objective of the study described here is to investigate the available market of 3D data acquisition technologies and to identify sensors that can be applied by unknowledgeable users to produce a qualified point cloud for BIM modeling. From a total of 11 sensors, including two terrestrial laser scanners (TLS), two mobile mapping systems (MMS), two time-of-flight (TOF) cameras, three traditional digital cameras and two pattern projection-based sensors, each from different price categories (professional market segment to consumer product range), five technologies are presented and compared in section 3 of this paper. A project environment was prepared to provide a realistic PoC while ensuring an unchanging measurement scene. As illustrated in section 2.2, the project environment shows a living and dining room structured by constitute elements (e.g. walls, floor, pillar), functional furniture components (e.g. chairs, shelves, tables) and decorative items (e.g. carpet, curtain, plant). Requirements for barrier-free living and unrestricted wheelchair usage are defined in DIN 18040-2. Evaluation criteria such as point and distance accuracy or measurement noise are extracted from these requirements in a way described in section 2.3. First, the challenge associated with the requirements for barrier-free living will be explained.

2.1 Standardized requirements for barrier-free living

According to German law, the technical term barrier-free describes a condition of everyday objects, ICT systems and other design areas of life as well as built facilities, if they can be used and accessed by humans with disabilities without particular difficulty or support from third parties (BMJV 2020). Following this definition, living environments are divided into different areas, which in turn are subject to geometric and object-related requirements. As part of an additional research, these requirements were formulated as rules to evaluate the living space as a BIM model and determine suitability or unsuitability for Aging in Place of a wheel-chaired. Considering that the as-built BIM is modeled by using 3D point cloud data, the geometric requirements also play a major role for the selection of data acquisition technologies to obtain these. DIN 18040-2 distinguishes between structural facilities such as living environments that are (a) barrier-free usable or (b) barrier-free and unrestricted usable with a wheelchair. Our PoC addresses the latter case with respect to a standard wheelchair of 0.70 m × 1.20 m. Thus, barrier-free living and unrestricted wheelchair usage of the living environment is given, if the rooms are threshold-free and have sufficient movement space, doors have a width modified to wheelchair use, windows have an adapted operating height and objects of use such as tables are accessible through an enhanced height. In the described PoC sanitary rooms or outdoor places are not included. Based on these requirements, technical evaluation criteria can be extracted. As described in Table 1, the requirements according to DIN 18040-2 were translated into point accuracy, distance accuracy and measurement noise. In addition, the point density for modeling purposes plays an important role and thus needs to be considered as well.

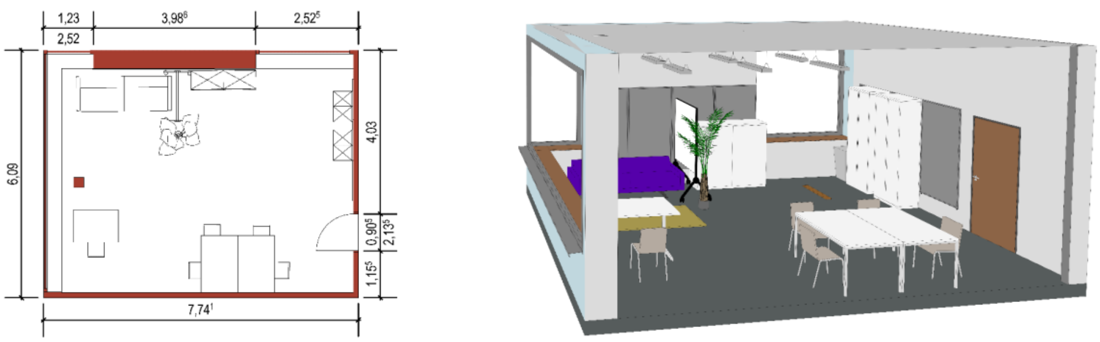
Table 1 – Translation schema of the proposed criteria according to DIN 18040-2 for geodetic-technical sensor evaluation.

Selection of requirements according to DIN 18040-2	**Requirements meaning in living space and applied measurement principle**	**Proposed criteria for evaluation**
At least one movement area of ≥ 1.50 m × 1.50 m must be provided.	The area is calculated as the difference of the room's area to the total sum of the area occupied by several objects.	3D point accuracy
Doors must have a width of ≥ 0.90 m and a height of ≥ 2.05 m. Objects of use (e.g. tables) must have a height of ≥ 0.80 m and must be accessible in a depth of ≥ 0.55 m.	The geometric properties of access and control elements are determined with respect to bordering horizontal and vertical room elements such as the floor, a wall or a worktop.	range accuracy
Accessibility is given if entrances can be passed safely. Thresholds are not permitted or must not be higher than 0.02 m. Access areas must not be inclined more than 3 %.	Area-related properties with marginal size can not be measured directly but are determined by amounts of points.	measurement noise
Objects of use must be designed in such a way that they can also be used while sitting. This is achieved by e.g. an access height of ≥ 0.55 m.	Detailed object-related requirements need a complete BIM model, which is obtained from dense point clouds.	point density

The technical evaluation criteria from the table above were extended by the cost of the data acquisition system, the user-friendliness of the sensor and the reliability to produce a 3D point cloud. The latter aspects are focused on the intended main users. Major objective of the evaluation is to identify a cost-effective, reliable, intuitive and precise sensor for Aging in Place challenges in e-health.
Our initial intention to base the requirements for barrier-free living on international standards failed due to the lack of such policies from the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) either. Therefore, the German DIN policy was adapted and serves as the foundation for this study. In future, the ISO/FDIS 21542 and the EN 17210:2021 will describe general minimum requirements and recommendations for barrier-free living and unrestricted use of built facilities. Currently the work on this documents is still in progress.

2.2 Project environment design

As described before, an approx. 40 sqm room was transformed into a living environment by adding domestic furnishing elements, which are also addressed by DIN 18040-2. Figure 1 illustrates the final room design, which is bounded by two interior and two mainly glazed exterior walls. The room is organized in two areas: the living area, characterized by a sofa corner with carpet and a decorative plant as well as a shelf wall and the working and dining area, which is defined by chairs and tables. Both areas are separated from each other by an open movement zone in the middle of the room. The windows have external and internal curtains, which are not subject of this study due to missing requirements and therefore are not taken into account.



(a) (b)

Figure 1 – Design of the project environment: floor plan with metric units (a) and modeled as-built BIM (b).

Beyond the described furnishing elements, verification areas were tagged inside the room in order to contribute to the evaluation of the criteria from Table 1. These involved 2D paper targets on the room walls, the ceiling and the floor (not included in the BIM model) on the one hand and an additional 3D verification object on the floor on the other (c.f. Figure 1b, room zone righthandside). The following section describes the use of the verification areas for sensor evaluation purpose.

2.3 Proposed analysis workflow

The proposed workflow for evaluating 3D data acquisition technology as part of the AL system for Aging in Place is split into geodetic-technical criteria and usage criteria.

2.3.1 Geodetic-technical data acquisition criteria

The resulting 3D point clouds were compared with each other to evaluate the respective sensors. To permit a comparison, the point clouds were aligned into a unique system, which is usually defined by the most precise technology. The alignment to the point cloud of the Trimble X7 was performed using cloud-based matching according to the Iterative Closest Point (ICP) algorithm originally proposed by Besl und McKay 1992. In order to keep the inner point cloud geometry, the scale factor was constantly set to $m = 1$. After the point cloud alignment, the 3D point accuracy, averaged over 14 b/w standard paper targets in chessboard optics, was determined to its local references. The inner accuracy of the point cloud is described by the range accuracy, which was calculated by taking the difference between three variously oriented target ranges in the room space. The measurement noise also influences the point cloud quality. It is caused by various factors, some of them are interdependent either. For this reason, seven 0.40 m × 0.40 m verification areas of different surfaces (e.g. concrete, wood, glass, low-texture wall paint, felt, stainless steel) were analyzed to cover different environmental properties and target-dependent influences such as roughness, color and reflectance. These areas had already been included by the 3D verification object fixed to the floor. The point density was also determined within these verification areas.

2.3.2 User-friendliness and reliability of data acquisition principle

In accordance to the framed main users of the proposed approach for evaluating the living environments for Aging in Place, the sensors must not only provide dense and precise point clouds but also be as easy as possible to use. The level of technical knowledge of a user must therefore not have significant impact on the quality of the collected point cloud data. This requires an intuitive usability of the data acquisition technology and a visual guidance during measurement process for tagging already acquired areas. Furthermore, dependencies while data processing, e.g. through additional software, play a role.

Table 2 – Translation schema of the proposed criteria according to the demands of unknowledgeable users.

Derived demands from unknowledgeable main users	Proposed criteria for evaluation
compact sensor and evaluation hardware	
rapid and intuitive project setup	
no or just simple sensor calibration	usability of measurement
simple measurement configuration options	
visual guidance during measurement process	

Derived demands from unknowledgeable main users	Proposed criteria for evaluation
automatic data processing	simplicity of point cloud processing
short processing times	
no or just little additional software required	
immediate data export capability	
robust and error-prone measurement process	reliability of data acquisition technology
stable processing routines	
fluent result visualization	
free support services	

Table 2 shows the evaluation criteria of usability of measurement, simplicity of 3D point cloud processing and reliability of the data acquisition technology with respect to the demands of the unknowledgeable users. All of the data acquisition technologies, which are categorized and presented in the following section, in sum offer the capability to provide the resulting 3D point cloud by open data interfaces for further treatments.

3 DATA ACQUISITION TECHNOLOGIES

For the acquisition of 3D point clouds, a distinction was made between two basic methods: (a) active scanning and (b) passive photogrammetry. The active scanning solutions considered in our study included Trimble X7, Leica BLK2GO and two ToF cameras, the Intel RealSense L515 and the Apple iPad Pro with Light Detection and Ranging (LiDAR) technology. The Nikon D3200 SLR camera is the sole passive sensor, which uses structure from motion (SfM) approach to generate 3D point clouds. In the following sections, the sensors are presented, first the established professional scanning technologies and then the low-cost consumer systems that have been less tested for BIM domain. The results of the sensors are consistently colored 3D point clouds, which are sampled to 5 mm point spacing for data reduction and comparability purposes. Due to empirical analysis within this study, the point density after sampling process is sufficient for modeling as-built BIM in a level of development (LoD) 300 for an AL use case in e-health.

3.1 Professional scanning sensors

The professional scanning solutions tested are based on the principle of active range measurement with pulsed light of laser class 1. LiDAR technology has been evolved in recent years. Two different developments of this technology are presented below.

The Trimble X7 uses a 1,550 nm pulsed laser to serve a maximum measurement range up to 80 m in a 360° × 282° field of view (FOV). The scanning speed is 500 kHz. At 10 m the stand-alone TLS system achieves a 3D point accuracy of 2.4 mm. Three integrated coaxial HDR cameras allow immediate colorization of the registered point cloud. With a tablet the scanning process, the point cloud registration and data management is controlled. The 5.8 kg compact system is lightweight and easy to use due to the mobile tablet application with a user-friendly interface. The project environment was scanned in high quality using six overlapping viewpoints and took approx. 30 minutes. The Trimble X7 represented the highest quality system and most precise sensor. This is why it served as the reference scan for analyzing all other 3D point clouds.

The Leica BLK2Go is a portable imaging laser scanner that uses a dual-axis LiDAR module, a multi-camera system and an inertial measurement unit (IMU) to provide simultaneous localization and 3D mapping (SLAM). This setup allows measurements to be taken at a distance of up to 25 m within a FOV of 360° × 270°. The mobile scanner's weight is 650 g at a height of 0.30 m and reaches a scanning speed of maximum 420 kHz. The 3D point accuracy is specified with 20 mm, regardless of the range. For control and visualization of the scanning process a mobile iOS device is required. Compared to the static Trimble X7, the project room was scanned dynamically in loop trajectories starting from an initialization point, which, however, is not allowed to use for final closure calculation to increase accuracy. About 5 minutes were needed to scan the entire room. To output the resulting point cloud into a manufacturer-independent format, additional software from the manufacturer is required. So, the BLK2GO is not a stand-alone solution. At the same time, it lacks various quality modes.

3.2 Low-cost consumer sensors

The second category concerns consumer products from a lower price range. Two of three cameras classified here also rely on LiDAR technology to obtain depth information for 3D point cloud generation. This ratio underlines the importance of this technology in the field of 3D environment scanning.

The Intel RealSense L515 is a portable scanning system designed for indoor use composed by a RGB camera with LiDAR module and IMU and thus reaches frame rate of 30 fps. The imaging modules generate data for RGBD channels up to a distance of 9 m. The RGB frame with rolling shutter creates FHD images in a FOV of 70° × 43°, while the depth image from LiDAR module is characterized by a slightly lower resolution of 1,020 px × 768 px but a larger FOV of 70° × 55°. The L515 LiDAR camera's size is 61 mm × 26 mm and thus represents the smallest sensor. However, the system is not designed to register 3D point cloud data directly. Regarding this, an additional physical device is needed, which can be connected via USB-C interface. For the study, a notebook with the proprietary software Dot3D Pro[2] was used. The project environment was scanned by systematic trajectories with closure calculation while yawing and tilting the camera. It took about 20 minutes for the 3D point cloud to be available for further treatment.

The Apple iPad Pro of the 2020 generation is composed by similar components. FHD images from two RGB cameras are connected and can be extended with depth information measured by the LiDAR module at a maximum distance of 5 m at 30 fps. In combination with the 3-axis

[2] www.dotproduct3d.com

gyroscope sensor, the iPad becomes a hand-held stand-alone scanning solution that is suitable for both, indoor and outdoor use. No more technical specifications are given by the manufacturer. The tablet itself does not provide a standard application for 3D data processing, hence an additional solution is needed here as well. A free application named 3D Scanner App[3] was used as one example of available software. It creates a photo-realistic triangular irregular network (TIN) during scanning, which can then be exported as a registered 3D point cloud. In addition, the application offers different measurement modes for scan resolution, measurement distance and confidence level. A high resolution at maximum measurement distance with a medium confidence level was chosen for room scanning. The time taken for scanning and processing was approx. 15 minutes.

The Nikon D3200 is a SLR camera with CMOS sensor, a standard lens of 18 mm – 55 mm focal length and an image resolution of 6,016 px × 4,000 px at 3.9 µm pixel size. As sole sensor the Nikon D3200 have no active measurement unit, thereby using the technical approach of SfM to generate point clouds from 2D multi image bundles. First, the image data was captured in 18 mm wide-angle setting and radial measurement principle in order to cover as large as possible image area with approx. 70 % overlap while keeping the amount of data small. Moreover, the automatic focus mode was activated to investigate the influence of an instable focal length on the 3D point cloud quality for unknowledgeable users. The processing of point cloud data by image bundle adjustment was realized in Agisoft Metashape, because freely available solutions did not produce treatable data. In total, about 4.5 hours were needed for capturing and processing the data.

4 DISCUSSION AND STUDY RESULTS

For BIM modeling of living environments for suitability evaluation purpose with respect to Aging in Place, five sensors were investigated that differ in terms of data acquisition technique, costs and targeted market. As shown in Figure 2, each sensor provided a colored point cloud, which served as comparative data for evaluation. The findings (c.f. Table 3) are related to the described use case and do not rate the quality and usability of the sensors in general.

(Trimble X7) (Leica BLK2GO) (RealSense L515) (Apple iPad Pro) (Nikon D3200)

Figure 2 – Resulting 3D point clouds of the investigated data acquisition technologies.

As the plots in Figure 2 show, the 3D point cloud quality vary in part significantly. The Trimble X7 as the sensor with the most precise scanning module, provided the best results concerning a very dense, radiometrical high-resolution and uniform point cloud pattern across all areas of the project environment. The scan shadows, produced by the TLS did not result in big occlusions due to sufficient overlapping viewpoints. On the contrary, the Leica BLK2GO

[3] www.3dscannerapp.com

as the second professional scanning solution (c.f. section 3.1) created a less dense point cloud that is also dominated by smearing effects due to the dual-axis LiDAR. In particular, this effects are critical if the orientation of the smears due to the movement direction is equal to a key edge as this is therefore no longer recognizable in the data set (c.f. Figure 3, Leica BLK2GO). Despite this, the hand-held scanner convinced with its simple guided handling and flexible applicability for indoor scanning, which discredited the Trimble X7 due to necessary additional equipment of a geodetic total station (e.g. tripod). Overall, the cost-benefit ratio of both systems argued against a suitability for our application.

Table 3 – Comparison of investigated point cloud data acquisition technologies.
*1 variance comparison as 3D euclidean distance according to reference targets,
*2 variance comparison to reference lengths, *3 before point cloud subsampling

Evaluation criteria	Trimble X7	Leica BLK2GO	RealSense L515	Apple iPad Pro	Nikon D3200
3D point accuracy*1	reference	3 mm	8 mm	35 mm	11 mm
range accuracy*2	reference	4 mm	13 mm	41 mm	46 mm
measurement noise	2 mm	4 mm	4 mm	4 mm	10 mm
point density*3	very high	moderate	moderate	high	high
usability	moderate	good	good	very good	bad
simplicity	very good	bad	good	good	bad
reliability	robust	instable	stable	instable	stable
cost sensor	very high	very high	low	low	low
cost addt'l. software	included	moderate	moderate	free	high

A point cloud generated by photogrammetric approach, such as that based on Nikon D3200 data, has huge advantages in terms of density and equal point distribution pattern, assuming that there is sufficient surface texturing for identifying corresponding points. The existing monochrome white and thus texture-poor wall or furniture surfaces inside the project environment caused a noisy and artefactual point cloud data with distorted geometries (c.f. Figure 3, Nikon D3200). For this reason, it was impossible to model the real object geometry in these areas. Besides, the less intuitive measurement, time-consuming and specialized data processing did not fit the requirements of unknowledgeable users.


(Leica BLK2GO)


(Nikon D3200)

Figure 3 – Detailed top view of the rejected point clouds due to data loss by smearing effects on Leica BLK2GO and object deformation on Nikon D3200.

As a result, the two left ToF cameras proved to be the most suitable sensors for the tested application. The RealSense L515 combined with a portable control unit, such as a notebook (c.f. section 3.2), created a radiometric well resolved, mainly regular dense and comparatively precise point cloud. The scanning process is illustrated by a colored mesh, which is placed over already measured areas as a visual feedback allows even unknowledgeable users to familiarize very quickly with that system. The stability and reliability of the low-cost solution remained stable during the test period. A deficit of this solution was the fragmented point cloud on areas with less surface texture, as can be seen in Figure 4, subplot RealSense L515. However, the occlusions proved to be significantly smaller and more local-related than those from the Nikon D3200. A similar dense and radiometrical resolved point cloud result was produced from the Apple iPad Pro (c.f. Figure 4). Compared to the RealSense L515, the data occlusion was even more sparse and smaller. For the visual feedback an identical methodology was used as described above. The geometric accuracy of the point cloud was poorer but still sufficient precise for the BIM modeling requirements (c.f. section 3). For the Apple iPad Pro, a challenge was encountered while scanning large objects in a high resolution. As a consequence of this the application usually crashed by processing larger amount of data (approx. ≥ 500 MB).

(RealSense L515)

(Apple iPad Pro)

Figure 4 – Detailed side view of the best-evaluated point clouds.

To conclude, both ToF cameras have shown a high user-friendliness, a good cost-benefit ratio and a sufficient point cloud data quality, which fitted the requirements for the application purpose presented in this paper. Despite this, the RealSense L515 and the Apple iPad Pro have different deficits such as data occlusion or trouble while processing large amount of data. Due to the fact that both devices have just recently come out, we consider these deficits to be minor issues and assume that they will be fixed in close future.

5 CONCLUSIONS AND OUTLOOK

This paper presents an evaluation of currently available data acquisition technologies to obtain 3D point cloud data of 3D object representations such as living environments. The objective of this study was to use this point cloud to determine the suitability for people in need of care on the foundation of a BIM model, taken into account standardized requirements for barrier-free living and unrestricted wheelchair usage. From a total of 11 tested data acquisition sensors, five were presented here and rated according to evaluation criteria. An important conclusion is that low-cost technology clearly outperforms professional scanning hardware. In addition to the good cost-benefit ratio, this finding also based on a high user-friendliness with a simple and intuitive usability, which is an important aspect in terms of unknowledgeable main users, rapid data acquisition and automatic data processing. The presented evaluation also considered the accuracy and quality of the resulting colorized point cloud in accordance with the requirements for the inspected use case. Due to the lack of available international standards, the requirements were deduced from the DIN 18040-2. After release of the policies ISO/FDIS 21542 and EN 17210:2021, which are currently in progress, the approach must be verified or supplemented if necessary.

The valuable insights from this study allow to incorporate the data acquisition part of our DS approach with low-cost scanning technology. In future projects the BIM modeling process based on the acquired point cloud will be considered in order to perform this in an automatic way. For this, intelligent software approaches and AI methods will be required to segment and classify a point cloud in staggered sequence at first and then to recognize the various BIM model elements such as building components or furnishing items (Plaß 2020). This approach also empowers the understanding of point cloud data beyond the application of Aging in Place in e-health. Thus, the collision-free use of robots in confident spaces, e.g. in production can be supported by this methodology.

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