The Visual Computer (2026) 42:95
https://doi.org/10.1007/s00371-025-04281-1

REVIEW

Survey of FOSS 3D/2D graphics software blender usage in science, academia, and industry

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Received: 15 July 2025 / Accepted: 27 September 2025

Abstract

Free and open-source software (FOSS) is a preferred tool for individuals and companies. The advantages of FOSS are minimal expenses, multi-platform and community support, transparent privacy policies, no vendor-related limitations, etc. Blender is a FOSS computer graphics 3D and 2D editor. It offers functions such as modeling, animating, video editing, simulations, image processing, scripting, rendering, etc. It is widely used as a free alternative to existing commercial products. This comprehensive survey examines Blender and its features and explores its usage in research, academic, and industrial projects, based on hundreds of collected and referenced sources. A comparison of Blender with alternative proprietary tools was conducted in terms of rendering performance, popularity, support, and feature set. According to this survey, Blender can be used as an efficient tool in film industry for visual effects composition, for dataset production for scientific experiments or deep learning methods, for educational purposes as a 3D geometrical problems demonstration tool, for the design of industrial models prepared, for example, for 3D printing, usage in augmented or virtual reality applications, etc. More specialized features are available as community-developed add-ons. The main reason why Blender is not used more often is that many professionals are used to other software.

Keywords Blender · 3D editing · FOSS · Animation · Multimedia processing

1 Introduction

Blender[1] is a free and open-source software (FOSS) written in C, C++, and Python [1]. It is maintained and developed under the GNU General Public License (GPL) by a non-profit organization, the Blender Foundation. It was founded by Ton Roosendaal, the original author of the first version of Blender [2]. The development is funded by users' donations, sponsorship by companies, and income from extra services such as Blender Studio. Most of the development is community-driven and is carried out by volunteers. Blender is a versatile computer graphics editor. Its main set of features focuses on the editing of 3D scenes, including their geometry, lighting, and materials. The built-in path-tracing rendering engine is capable of producing high-quality renders. However, Blender also contains tools for 2D animations, image processing, or video editing (see Fig. 1). Due to its multiple features, multi-platform support, and no cost, Blender is a popular tool for various tasks, including industrial, academic, or scientific assignments [3]. It is used to create assets for video games, produce 3D or 2D animated films, edit general videos, prepare models for 3D printing, design architectural or mechanical elements, etc. [4, 5].

This paper explores how Blender is used in different fields, how efficient it is in these fields, and how it compares with other existing products. In 2000, six years after its initial release, educational books about Blender already emerged [6] and graphic artists accepted Blender as a free and powerful alternative to commercial tools [7]. A year later, one of

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Published online: 26 December 2025

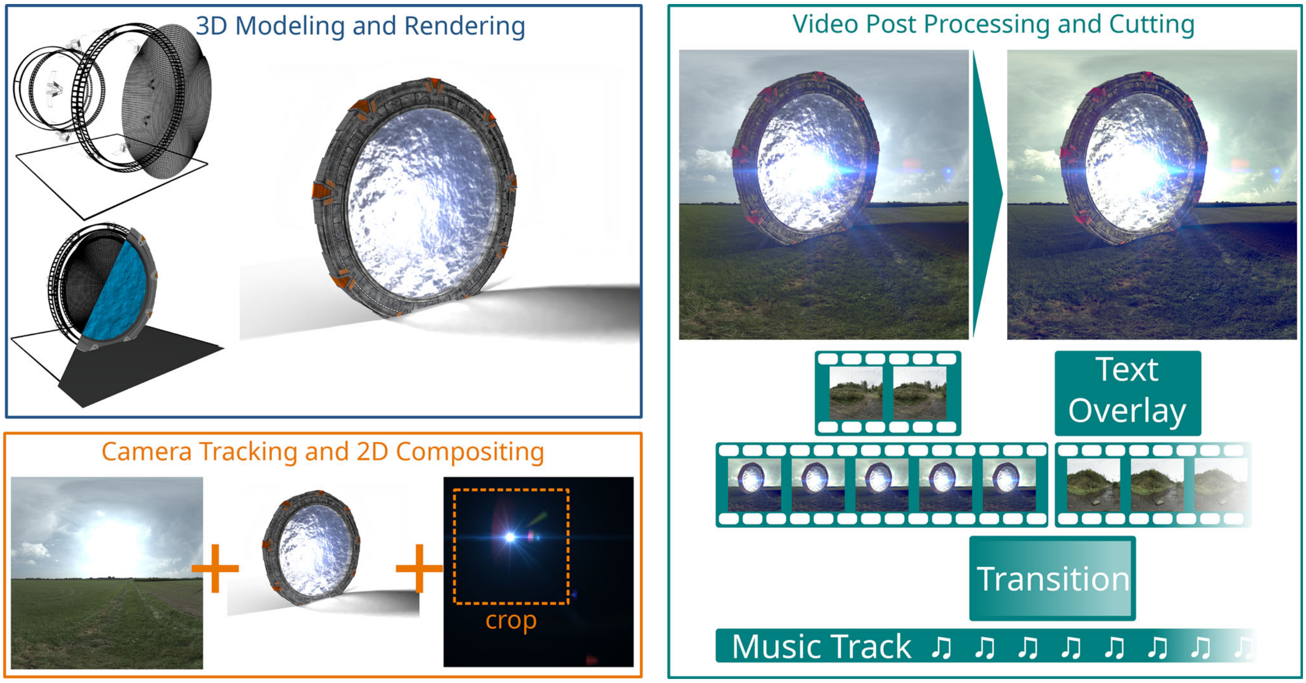


Fig. 1 Blender can be used not only for 3D modeling and rendering. It also supports 2D composition and video editing, so the whole film production is possible in one program. Stargate shown as a 3D model is an intellectual property of Metro-Goldwyn-Mayer Studios

the first scientific papers, on the topic of volumetric 3D display design, referenced Blender as a tool used in the research process [8]. This paper discusses the options that Blender offers with regard to various scientific problems and evaluates how suitable Blender is or what limitations have not yet been addressed by the developers. The significance of open-source software is growing. FOSS development is actively supported as a cheap alternative to proprietary programs, for example, by the NLnet Foundation [9], Free Software Foundation, or the Software Freedom Conservancy. Blender plays an important role in FOSS, and a comprehensive survey of its usage has not been published before this paper. The publications referenced in this survey were selected to cover different usage fields for generality, to be as recent as possible for relevance, and were also evaluated for their quality and possible impact.

2 Features of Blender

The description of the features is based on the currently developed Blender version 4.4. The terms defined in this paper correspond to the official Blender documentation.[2] Describing all features of Blender is beyond the scope of this paper. Therefore, only the most significant features are described.

Blender went through many major changes regarding its functionality and graphical user interface (GUI). Since version 2.8, developers have been seeking to maintain a consistent, user-friendly, and modern GUI [10]. The GUI is also highly customizable (see Fig. 2).

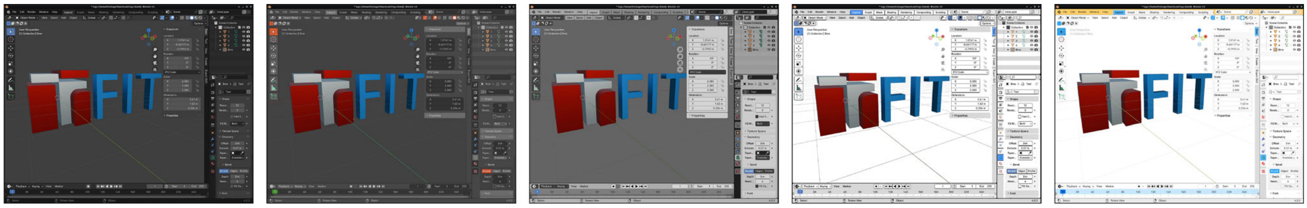
The application window consists of multiple *areas* which can be removed, added, and scaled. Each area contains an *editor* which is a specialized window that contains the editing tools for a specific type of data. The window layout that defines the size and positions of the areas and specifies the selected editors is called a *workspace*. Figure 3 shows the Blender windows with the mentioned elements.

2.1 3D modeling and rendering

The main set of features in Blender focuses on creation and editing of 3D meshes and their high-quality rendering. Blender contains three main geometry editing modes (see Fig. 4). *Object mode* is used for the general transformation of objects. *Edit mode* is used to change the positions and attributes of the vertices and polygons. *Sculpt mode* is used to modify the mesh geometry easier with more intuitive brush-like tools. Blender contains also *Vertex*, *Weight*, and *Texture* Paint modes to edit the mesh in relation to its visual attributes.

Tools for automatic processing of the meshed that ease certain operations can be used via *Modifiers* that can, for example, create arrays of the same models, deform the geometry based on textures, smoothen the geometry, triangulate

[2] Blender Documentation: docs.blender.org.



(a) Dark (b) Deep Grey (c) Light (d) Print Friendly (e) White

Fig. 2 Five of the official themes for Blender GUI are shown. The colors of the GUI elements can also be adjusted separately by the user

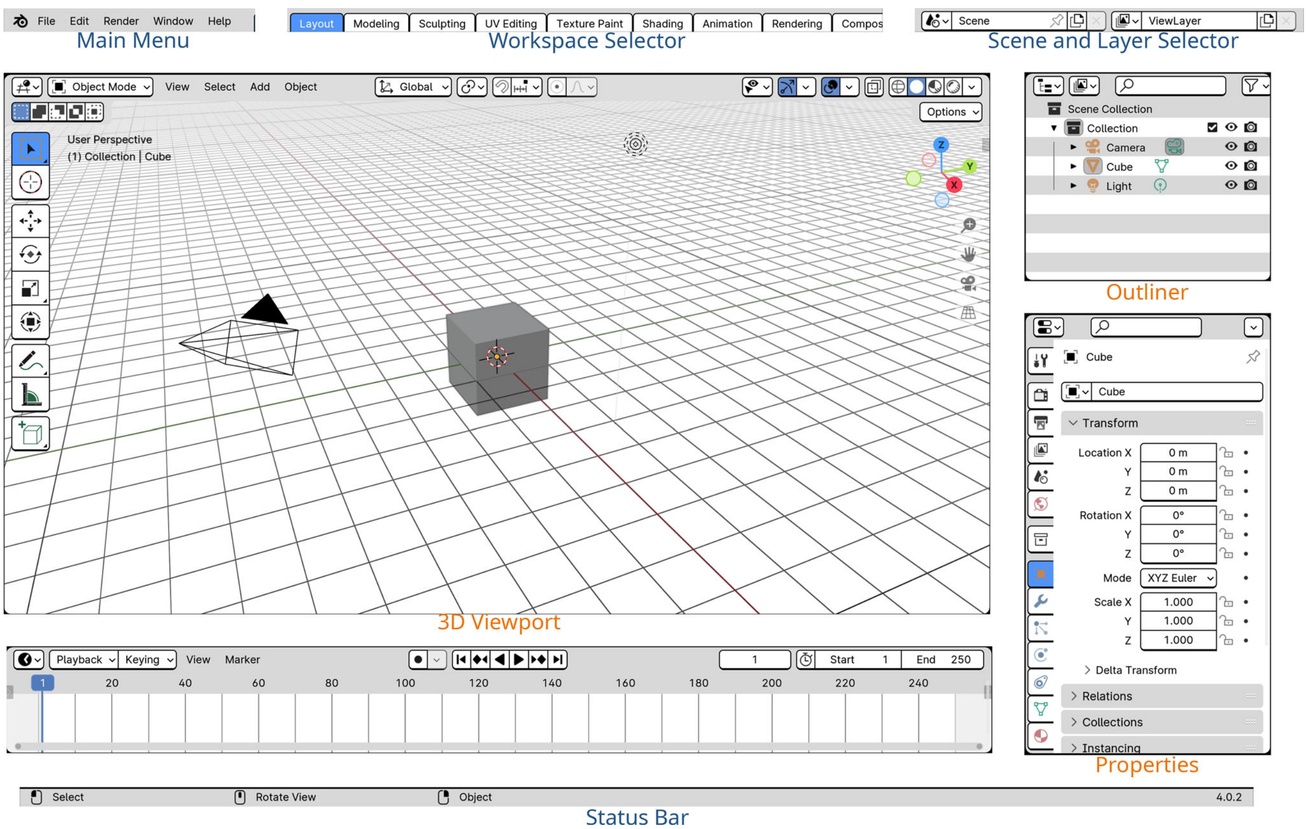
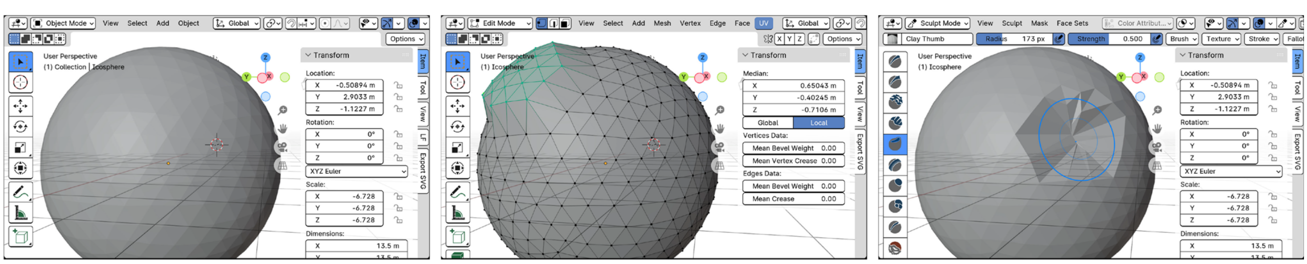


Fig. 3 Default Blender window with the static core GUI elements and adjustable areas with different editors is decomposed and described on the image



(a) Object (b) Edit (c) Sculpt

Fig. 4 The main mesh-editing modes are shown

the mesh, etc. *Constraints* can be used to create limits of the transformations performed on the objects. Vertices can be grouped in *Vertex Groups* so that certain operations are conducted only on them. *Shape Keys* can be used to create several variations and animations of the same geometry with different vertices positions. A more general tool is implemented in

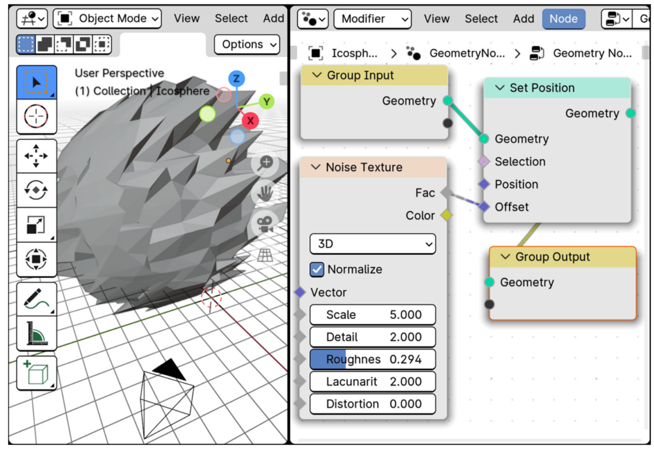


Fig. 5 *Geometry Nodes* can be used to displace the mesh geometry with a noise function

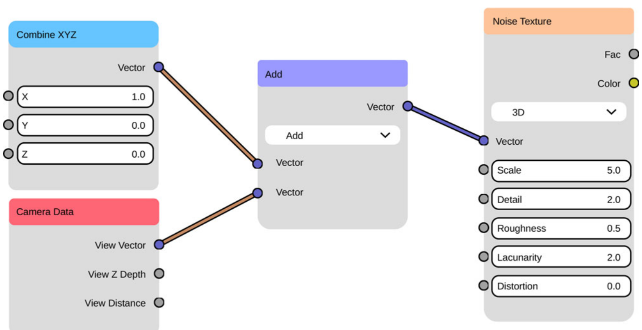


Fig. 6 *Node Editor* offers a visual programming interface. The example shows how camera view vector is shifted in X coordinate and used as a sampling coordinate for a noise function. The nodes can be described by term with 3D vectors: $\mathbf{noiseSample} = \mathbf{camera} + (\mathbf{1}, \mathbf{0}, \mathbf{0})$

Geometry Nodes. These nodes can be used to edit the geometry, especially to produce procedurally generated content (see Fig. 5). The *Node Editor* which is used in Blender several times is a form of visual programming (see Fig. 6). The nodes can be exported to SVG format with an add-on.[3]

Blender can be used to simulate rigid body dynamics for realistic animations. Similar simulations available in Blender are particles/hard, cloth, liquid, or fire/smoke used with the aid of the Mantaflow library [11]. These simulations were shown to be comparable to commercial products [12, 13]. A similar node system can be used to edit materials of the volumes or surfaces of objects (see Fig. 7).

The whole 3D scene can be rendered with a path-tracer rendering engine *Cycles* or with a faster but less realistic rasterization engine *EEVEE*. Both GPU or CPU can be used for the rendering with GPU's being significantly faster using NVIDIA OptiX, Cuda, or AMD HIP. According to Blender Open Data,[4] accessed at the end of 2024, 52% of the users use the CPU for rendering. Among GPU users, OptiX is the most widely used acceleration technology with 78% of the benchmarks. Using the ray-tracing cores seems to significantly speed up the rendering. NVIDIA GPUs also seem to reach the fastest rendering times. 82% of the benchmarks were conducted on Windows, 11% on Linux, and 7% on MacOS. Getting the median values of all benchmarks, GPU rendering is approximately 8× faster than CPU. Users can upload their own unified benchmark results to the Open Data platform.

An add-on[5] for SVG export can be used to store a view of the scene in vector image format. The 3D scene can also be exported to widely supported 3D model formats, such as OBJ, FBX, PLY, etc.

2.2 2D image processing

Another node system *Compositor* can be used to process 2D images and videos with various image operations and filters (see Fig. 8). This editor can be used to compose the rendered 3D animations with background 2D videos. Post-processing effects can be applied to the rendered results. Motion tracking can be used to properly position an artificial object in the input video. Blender also supports hand-drawn masks that can be used to affect only a specific part of the image.

2.3 2D animation

Blender also supports hand-drawn animations that can be mixed with 3D elements, leading to 2.5D animation [14]. The *Grease Pencil* tools act as a standard drawing brush, used in other drawing programs, but are in fact projected on a plane in a 3D space (see Fig. 9). Animation tools supporting *Onion Skinning* and brush settings are available for advanced animation use cases.

[3] GitHub-Blender Node Export: github.com/draberf/blender-node-export.

[4] Blender Open Data: opendata.blender.org.

[5] GitHub-Blender Scene To SVG 2.0: github.com/Craszh/BlenderModelToSVG.

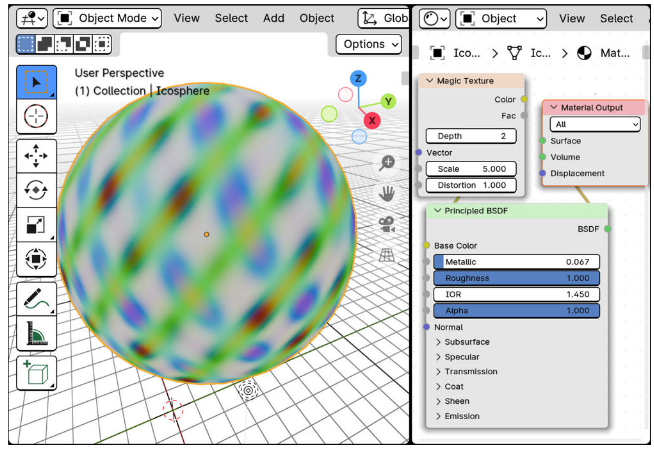


Fig. 7 Nodes in *Material Editor* can be used to apply a procedural texture on a 3D model

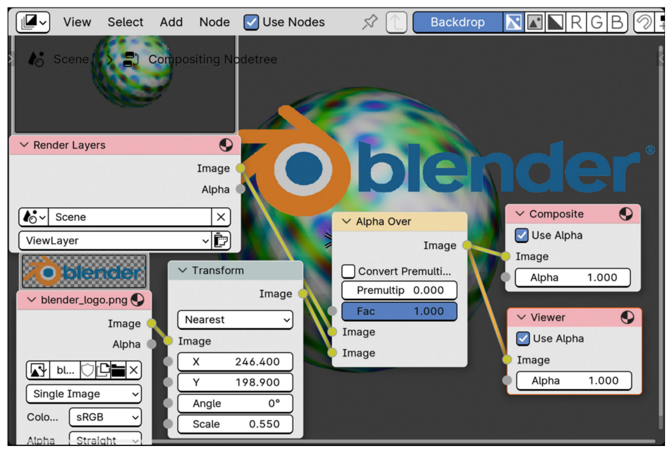


Fig. 8 *Compositor* can be used to mix an 2D image loaded from a file with the rendered 3D scene

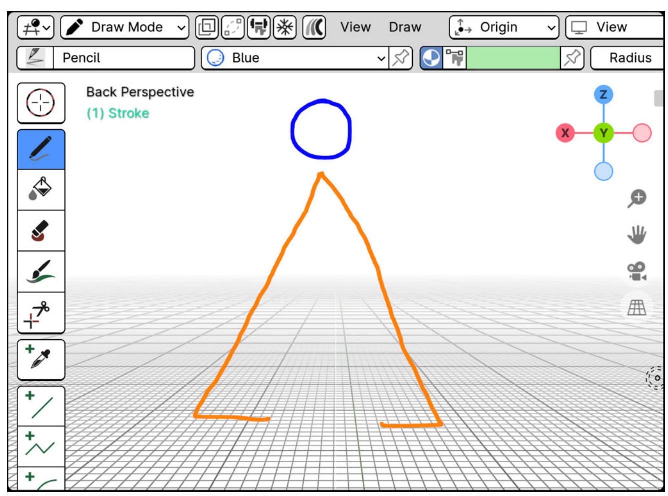


Fig. 9 *Grease Pencil* can be used to draw 2D still images or animations

2.4 Video editing

Blender contains a built-in *Sequencer* video editor (see Fig. 10). It supports basic cut and positioning of video strips, imports of various video and audio files, application of color grading filters, text layers, etc. In this way, Blender can be used to produce 3D/2D animations, combine them with real camera footage, add sounds, and export the whole film.

2.5 Scripting

One of the convenient features that can be used to automate the workflow in Blender is scripting [15]. Python programming language is used to create scripts that can access the Blender functions via the API. Blender contains a built-in scripts editor with syntax highlighting, console, and a set of code examples (see Fig. 11).

Fig. 10 *Sequencer* can be used to edit videos like in many other video-editing programs. The videos used are intellectual property of Munhwa Broadcasting Corporation

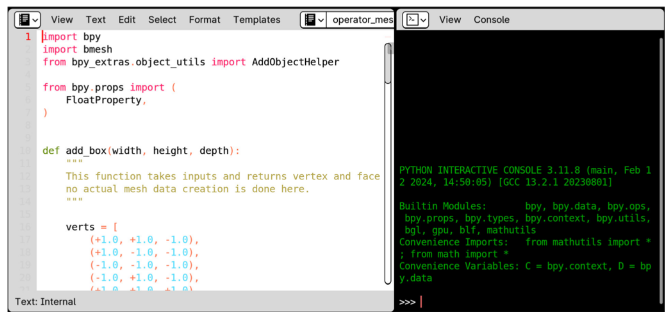


Fig. 11 Text Editor and Python Console can be used to create custom scripts that can access almost all features that Blender offers

2.6 Add-ons

Additional features can be obtained by installing *add-ons*. These add-ons are written in Python and use the Blender API. Blender offers an official set of add-ons but many more are developed by the community. They can be installed in the program simply by uploading the add-on archive in the *Preferences* window. As of March 2025, over 13,000 repositories with Blender add-ons and scripts are publicly available on GitHub and 3258 add-ons are available on Superhive Market website. Add-ons extend Blender with a lot of new features which open up a way of using Blender in many fields. One disadvantage of the community-developed add-ons is that some might not be maintained anymore, and they might not be working properly with new versions of Blender.

Thousands of add-ons and pre-made assets can be downloaded on websites, such as the official extensions site,[6] Superhive Market (former Blender Market),[7] Gumroad,[8] Blender Add-ons,[9] BlenderKit,[10] etc. The most downloaded add-ons on the official extensions site are LoopTools and Bool Tool for easier modeling process, Extra Mesh Objects, Extra Curve Objects, which add more pre-made objects, A.N.T.Landscape for procedural landscape generation, and 3D Print Toolbox to aid the model editing for 3D printing. The four largest categories on the extensions website are Import & Export category with 19.7% of the add-ons, 3D View with 15.4%, Object with 13.4%, and Mesh with 12.7%. Generally, on all websites providing these add-ons, users seem to most frequently download tools that aid them with the creation of 3D assets, be it procedural model generators or tools that make certain 3D edits quicker (see Fig. 12). The reported data were collected in March 2025.

2.7 2024 official survey

Blender developers conducted an official survey on the usage of Blender among its users with more than 7000 respondents. The purpose of the survey was to find out in which features are the users most interested and where should the future developed lead to. The published interpreted results[11] suggest that users value the freedom that Blender offers, since over 57% marked the free access to the creative tools with

[6] Blender Extensions: extensions.blender.org.

[7] Superhive Market (former Blender Market)): superhivemarket.com.

[8] Gumroad-Blender Assets: discover.gumroad.com/3d?query=blender.

[9] Blender Add-ons: blender-addons.org.

[10] BlenderKit: blenderkit.com.

[11] Blender Survey: survey.blender.org.

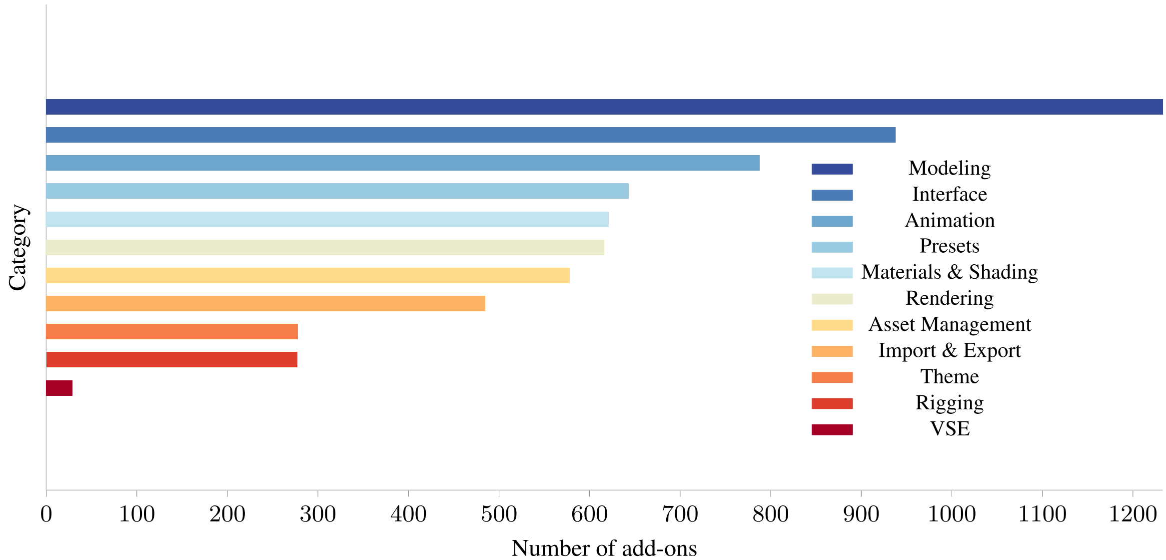


Fig. 12 The bars show the number of add-ons listed in each category of Superhive Market (former Blender Market). Some add-ons are listed in multiple categories

the highest score. About 28% of the respondents mentioned Autodesk 3ds Max as their first 3D editor but over 56% marked Blender, which is to be expected since the survey was released mainly among Blender users. The main motivation for using Blender is the free access with over 28%. Over 27% of the users claimed to use Blender for artistic purposes. Regarding the topic of this paper, over 15% use Blender as designers (regarded as industrial usage), over 7% as students and almost 4% as teachers (academic usage), and only over 2% as researchers (scientific usage). Almost 20% of the professionals use Blender for film and animations followed by about 14% graphic design and 13% game development.

The data collected in the survey were also openly published. Data were further analyzed, as part of this study, to discover insights into Blender usage with respect to the topics of this paper. Ten users suggested that Blender developers might actively participate in research grants and work together with universities. Nine users showed interest in add-ons for research purposes and scientific visualizations. Almost 200 users discussed issues and suggestions related to industry and comparison with other industrial software. Six respondents mentioned the usage of Blender related to history and heritage. Figure 13 shows detailed amounts of respondents regarding the topics covered in this paper. A surprising fact might be the high amount of respondents using Blender for architectural visualization.

3 Scientific usage

Blender has often been used in scientific research due to its free and open-source availability [16]. Except for its major usage in specific research tasks, Blender is frequently used to produce renders and 3D models of certain elements of the investigated objects [17–19] or to perform simple 3D/2D editing or analysis tasks [20–22]. The fact that Blender is often used in many different research fields indicates that its usage and free availability make it a top tool that is considered as the first software choice for the given task. While software, such as MeshLab, provides additional scientific tools for mesh analysis, Blender can be easily extended by add-ons or custom scripts, making it a useful tool for experiments.

3.1 Datasets

The ability of Blender to produce 3D model files, rendered images, or animations is often used in research to create various datasets [23]. The need to quickly produce different datasets is increasing with the increase in the popularity of machine learning algorithms. Blender is a suitable tool for this task due to its features that allow a high amount of automatization [24, 25].

Official Blender demo files[12] are open scenes that are often used in research as high-quality and easy-to-obtain 3D scenes (see Fig. 14). They are usually rendered from desired viewpoints and used as input and reference image data for testing of visual reconstruction methods. Scenes are used for testing of light field rendering [26, 27], antialiasing algorithms [28], hardware ray-tracing [29], preprocessing site-specific radio channels for virtual drive testing in [30], image denoising [31], etc. Synthetic animated scenes were used in the research of the 3D friendly scene identification method [32]. HDR

[12] Blender Demo Files: blender.org/download/demo-files.

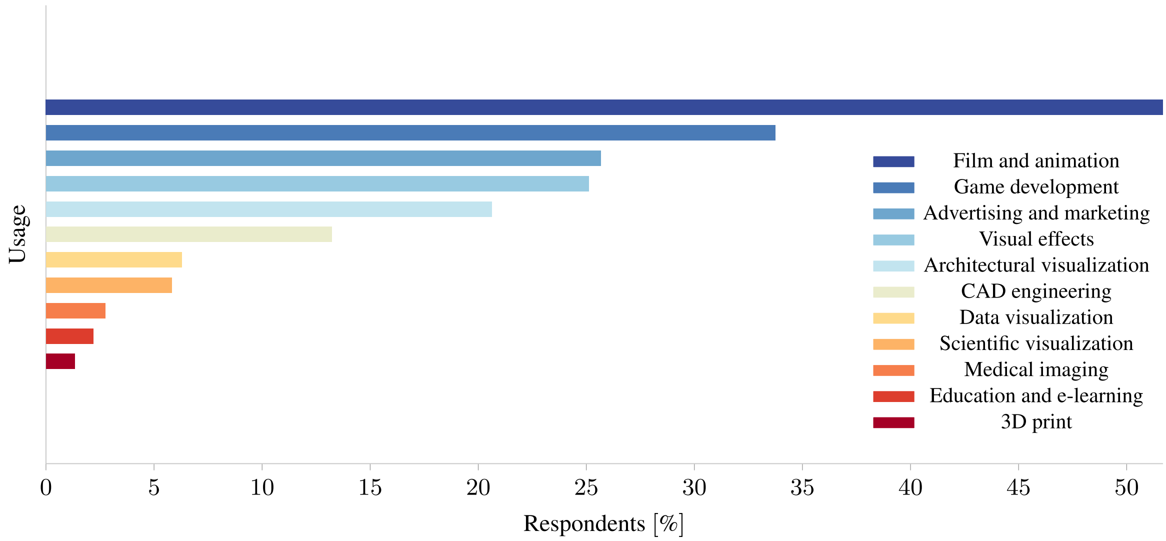


Fig. 13 The chart shows often mentioned fields of Blender's usage related to the topics of this paper. 0.66% of the respondents also mentioned general product visualization and 0.27% usage in automotive industry

(a) Barcelona Pavillion (eMirage CC-BY) (b) Classroom (Christophe Seux CC0) (c) BMW (Mike Pan CC0)

Fig. 14 Examples of often used scenes in various datasets from Blender demo files

light field dataset, using the demo scenes, was produced for the evaluation of multi-ISO sensor light field imaging [33].

A dataset used in the boulder segmentation method, which can be used in autonomous navigation algorithms, was generated in Blender using its Rock Generator add-on [34]. MotorFactory add-on is used to produce a dataset for the electric motor segmentation methods [35]. The authors designed this add-on to be used in an AgiProbot project for automatic detection, tracking, and disassembly of motors in vehicle manufacturing. Light field structured light dataset was generated in Blender to evaluate light field refocusing, depth map estimation, and biomedical image segmentation [36]. Similar multiview data were generated for the evaluation of distortion correction in the holographic stereogram printer [37]. Light field camera for lunar surface exploration was simulated using Blender Cycles path-tracer [38]. The refinement of the data set for the mental cutting test, which is used to measure human mental spatial skills, was proposed using Blender as the main tool [39, 40]. High-fidelity simulated wounds dataset Syn3DWound was rendered in Blender [41]. The entire methodology was proposed for the generation of synthetic datasets with Blender [42]. It is designed for mechanical structures under the influence of external forces. The finite element method simulates the deformation of system and the deformed mesh is rendered with Blender. The method of estimating the pose based on the view of an unknown circular object with the RGB-D camera was evaluated with a Blender-generated dataset [43]. Blender can be used to adjust existing datasets, for example, by adding 3D noise to the geometry, as in unsupervised outlier detection to enhance 3D point clouds [44].

A deep learning method was trained to predict the movement of the ship on a Blender-produced dataset with a realistic simulation of the ocean surface [45]. Neural radiance fields (NeRF) and 3D Gaussian Splatting were trained with data rendered in Blender and also simulated using its fluid simulation in the study on differentiable rendering for the visualization of laser-tissue ablation [46]. Datasets often used for training of many general NeRF synthesis frameworks were created in Blender [47], for example, Shiny Blender dataset containing challenging glossy materials [48]. The visual compass method that determines the direction of a camera based on input images was evaluated on a dataset produced in Blender [49]. Blender covers creation of other datasets, such as the shadow data set in agricultural settings for the photovoltaic field [50], aerial images of cars for vehicle detection purposes [51], Sim2Air, the synthetic aerial data set for the monitoring of unmanned aerial vehicles [52], virtual facial expression dataset [53], or parking dataset for autonomous driving methods [54]. VisionBlender [55] is a generator of synthetic endoscopic datasets with depth, disparity, normal, and segmentation maps output. Blender allows for realistic quality data that can be used to train or test methods for endoscopic robotic surgeries. Lensless depth camera dataset was also synthesized in Blender [56].

Not only 3D mesh-related datasets were produced in Blender. The built-in smoke simulation was used to create a dataset for deep smoke segmentation network and was shown to be efficient, as such datasets are not very common [57]. The study of early fire detection in the indoor environment used a similar approach [58]. A similar use case of the smoke simulation was in the training of multilevel feature learning attention-aware-based generative adversarial network for removing surgical smoke (MARS-GAN), which is designed to improve visibility during laparoscopic surgery [59]. A similar approach was used in endoscopic image classification [60]. Data for the development of live city fire tracking platforms were produced in Blender with the creation of the 3D city map and smoke and fire simulation [61]. Avatar Blender add-on and the cloth simulation were used to produce a dataset for PhysXNet, a framework for the simulation of human clothing [62]. Neural Haircut, reconstruction of hair geometry at the strand level from a monocular video used dataset generated by Blender and its hair simulator for the training process [63]. The Cycles path-tracer in Blender uses floating-point framebuffer. In combination with PixelManager repository,[13] the renders can be stored with many color profile transfer functions. This was used to create a dataset for the measurement of the color profile used and its effect on light field rendering [64].

3.2 Specific research tasks

Satellite visual and elevation data were used in a terrain relative navigation research by NASA [65]. Photometric observations were used to model the light curves of resident space objects in Blender with high accuracy [66]. The produced maps were used as a reference on a uncrewed suborbital spaceflight mission New Shepard in August 2021. Blender also proved to be a valid tool for simulation of landing and bouncing on the surface of an asteroid [67]. The pipeline for automatic realistic data generation for space flyby scenarios uses Blender to model nucleuses and dust clouds [68]. The geomorphometric modeling system for the topography of submarines in the Arctic ocean was developed using 3D terrain models generated in Blender [69].

Global navigation satellite systems are often problematic to use indoors due to the limited signal to the satellite. Indoor location-based services using visible light is a more reliable navigation system that transfers information using high-frequency changes in light sources. A simulator was implemented in Blender to evaluate this method [70]. Parallel intelligence to hydraulic engineering was applied using Blender to two case studies, dam analysis and high slope evaluation [71].

BLAINDER add-on for LiDAR and sonar simulations can be used to produce semantically annotated training point cloud data for machine learning algorithms [72]. Another sonar simulator was created as an add-on using recursive ray tracing to cover more types of scenes than existing tools [73]. BlenSor [74] simulates different types of range scanners, especially for obstacles detection and tracking. Blender was used to simulate multicamera investigative metrology systems and showed high accuracy and correspondence to real-world measurements [75]. The point cloud partition algorithms were extended with improved features and packed into a Blender add-on OpenXtract [76].

Blender's physics simulation is used to aid in text-to-video generation with the GPT-4 and Stable Diffusion XL models [77]. GPT4Motion is used to create a script for Blender. A simplified video based on this script is produced and used as an input reference to generate a full video in Stable Diffusion. An official Stable Diffusion add-on[14] by Stability AI is also publicly available. BlenderAlchemy is a tool that can be used for 3D editing of a Blender scene using a language model [78]. REVISION [79] and Pandora3D [80] use Blender for 3D rendering based on a text or image prompt. General benchmarking tool called BlenderGym was developed to evaluate the efficiency of vision language models [81].

The Cycles rendering engine path-tracer in Blender was used several times as a radar simulator [82, 83]. In addition to built-in renderers, Blender can be extended through add-ons by others [84], such as Mitsuba Renderer, which is often used in research [85]. BlenderPhotonics is an add-on for the simulation of photons in complex tissues [86]. Cycles engine was used in the aerial robotics simulator to estimate yields in indoor agriculture [87]. RenderGAN is a deep learning approach that aims to solve the issue of long rendering times of photorealistic scenes [88]. The rendered image from the real-time EEVEE renderer and a G-Buffer is used as input of the network. The network then quickly produces a novel render similar to the photorealistic results rendered in Cycles. Conversion of Gaussian splatting structures into meshes is

[13] github.com/Joegenco/PixelManager.

[14] GitHub-Stability Blender Add-On: github.com/Stability-AI/stability-blender-addon-public.

introduced in MeshSplats paper which uses Blender EEVEE renderer to render the results [89].

Blender was used to visualize molecular data from scientific databases [90]. It was also used to model Drosophila fly behavior based on a CT-scan and high-speed camera footage [91]. Zebrafish model was analyzed using Blender in the research regarding the effects of obesity on metabolic processes [92]. Visualization of molecular features and protein motion is implemented in BioBlender, which is based on plain Blender [93]. This project proved to be useful, and almost ten years later it was upgraded to reflect the new Blender features [94]. 3D model of a corn plant was created in Blender and used in the AR (augmented reality) application to identify plant diseases using neural networks [95]. Similarly, the results of the numerical simulation, focusing on astrophysical hydrodynamic experiments, were visualized [96]. FREELED (Flexible Image Transport System Real-time Explorer of Low Latency in Every Dimension) is an extension of Blender that visualizes multidimensional data on standard and stereoscopic devices, primarily focused on astronomical volumetric datasets [97]. The discrete element method, implemented in STAR-CCM+, and the rigid body simulation, implemented in Blender, solutions of particle-resolved computational fluid dynamic simulation were compared [98]. Blender is capable of a faster solution and even more accurate results in certain cases. The ability of Blender to render volumetric materials was exploited to render the results of large-scale computational fluid dynamics simulations in OpenVDB format [99].

Gene expression atlases and microscopic data were visualized during annelid *Platynereis dumerilii* research, and Blender was found to be easily able to perform this task even with other organisms [100]. *Chlamydomonas reinhardtii* cell membranes were similarly visualized and evaluated by experts [101]. NeuroMorph is a collection of tools, integrated in Blender, for segmentation of images captured by electron microscopy [102]. The dimensions of volumetric biological data are often reduced by a tissue cartography projection for further analysis and a Blender add-on for this task also exists [103].

Programs such as VMD, Chimera, or PyMOL for molecular dynamics visualizations are not capable of producing high-quality renders such as Blender. Pyrite add-on was developed that allows the import of this kind of data and leverages the Blender rendering capabilities [104]. Cella, a cell atlas visualization tool designed for plant development research, transforms single-cell transcriptomics data into 3D heat maps [105]. This tool uses Blender and its add-ons such as Cell Fracture, which uses the Voronoi diagram to subdivide a space. The cubic structures centered on the faces of the gold and platinum crystals were designed in Blender using scripting tools with precision according to scientific requirements [106]. Atomic and subatomic levels of particle transmission simulations can be performed in Geant4 software. Blender can be used to create scenes suitable for these simulations with easy import into the software [107]. Microscopy Nodes is an add-on for easy visualization of up to 5D microscopic data in TIFF or OME NGFF format [108].

The samples of extinct trigonotarbid arachnids were reconstructed and animated, and the result was used to conclude how these species lived and moved [109]. Retrodeforming fossil specimens and modeling of 3D muscles for palaeontologists in Blender were proposed [110]. The digital restoration of fossils based on computed tomographic images in paleontology used the characteristics of rigging and armature in Blender to reconstruct the motion of a dinosaur excavated in the Jurassic horizons of Niger [111]. Blender was used to visualize the Lark Quarry Dinosaur Trackways for presentation and research purposes. The combination of core functions and custom add-ons opens up new ways to investigate these sites [112]. The simulation of dinosaur behavior and biological attributes can be carried out using finite element analysis in the Fossils protocol on bone and muscle models [113]. The manual preparation of the data for computation is time-consuming and complex. BFEX (Blender Finite Element eXporter) is an add-on that automatizes this process and makes the usage of Fossils more user-friendly [114].

Human mental rotation ability can be improved using a 3D training application. A three-hour Blender training module was created and 42 participants underwent it [115]. Mental rotation ability improved by 26% according to the post-test and questionnaire after training. Similarly, two groups of participants were compared and the group using Blender for mental rotation training showed greater improvement over the group receiving formal classroom teaching [116]. This shows that Blender can play a major role in mental 3D skills and lead to better skills in, for example, engineering drawing.

A collision prediction tool, which ensures patient safety, was proposed for a TrueBeam system, a medical linear accelerator [117]. Blender was used as the main tool for the creation of the 3D model of the machine and the simulation environment with the estimation of the collision-free zones. Arduino-based sensors can be attached to the human body, and the motion is then reconstructed in Blender. This approach can be used for gait analysis of motion to reveal unnatural movements and predict possible injuries [118]. A 3D pacemaker model was created in Blender and virtually implanted in an adult mesh-type reference computational phantom to measure its dosimetric impact during breast cancer radiotherapy [119]. Visual noise mask for human point-light displays study uses Blender's 3D and 2D editing abilities to create visual stimuli of human poses [120].

Blender add-on was implemented to add support for bidirectional texture functions [121]. The Blender plugin was used to sync video and glTF animations to enhance the

VR (virtual reality) experience [122]. An alternative to the motion capture process was implemented in Blender using only keyframe images to produce a 3D pose animation [123]. NeRF was proposed to be used for film visual effects production, and Blender was used to align camera paths and composite NeRF renders with a 3D scene [124]. Blender was also used as an experimental environment for scientific comparison of different structure-from-motion pipelines [125].

The cerebral aneurysm with a clip that fixes the blood vessel was modeled in Blender to compare the cerebral blood flow of smokers and non-smokers using COMSOL Multiphysics [126]. The result showed that the different composition of the smoker's blood increases the risk of worsening the condition. Accurate organ models can be reconstructed from computerized tomography (CT) and magnetic resonance imaging (MRI) scans and processed by digital fracture to make them suitable for 3D bioprinting. Blender tools and official Cell Fracture add-on was used in the process [127].

4 Academic usage

Blender is often used as a tool that helps the teacher explain specific problems, not only with respect to 3D geometry [128]. Students, teachers, lectors, educational app developers, and therapists often use Blender as an easily accessible tool for minor 3D related tasks [129–132]. It has caught the attention of teachers since its early versions [133]. It is also used as reference software for 3D modeling courses [134, 135], or animation courses [136]. Blender was also used in an educational technology class for historical reconstruction [137]. It is also a highly accessible tool to produce 3D data for student projects, such as games or visualizations. The topic of transformations was explained using Blender 3D environment [138]. Biological [139] and medical [140] education can take advantage of 3D printing where Blender is often used, for example, to print organ models [141, 142]. Anatomical models can also be colored and annotated in Blender [143]. Animated videos explaining the topic of field effect transistors in the applied electronics techniques subject were created in Blender and were positively evaluated by experts and students as more efficient educational tools than standard materials and slides [144]. It is also a straightforward tool for quick edits of educational anatomy models, for example, for polygon reduction and model refinement [145]. Several Blender add-ons were produced as results of bachelor's and master's theses at the authors' institution.[15] Blender has also attracted the attention of researchers for the purpose of writing an academic paper, especially to produce professional-looking figures [146–148].

4.1 Educational applications

NASA uses Blender to create 3D assets and published its educational demo Experience Curiosity on a web-based open-source 3D rendering framework Blend4Web which uses Blender as its central modeling tool. Different types of astronomical data can be efficiently visualized in Blender [149]. The types of data tested were astronomical catalogs, N-body simulations, and asteroid models. AstroBlend is a library that processes astrophysical data and uses Blender to visualize the results [150].

Blender is often used in combination with Unity engine, for example, to create a virtual laboratory during the COVID-19 pandemic for remote education in an electronics practicum course [151], virtual handicraft tutoring applications [152], virtual polar expedition educational application [153], 3D modeling of lipids and proteins for AR application [154], AR mobile application for learning about solar system [155], mobile AR application for learning about traditional Indonesian houses [156] or PC assembly [157], VR training to assemble infrared computed tomography [158], and VR healthcare quality bootcamp [159]. A self-assessment platform using Blender was proposed for the corrosion engineering course [160]. The evaluation with the students showed that the proposal can be used efficiently in practice. The measurements showed that such a laboratory can be easily used in practice. Similarly, laboratory equipment was created for physics and chemistry experiments [161]. An experimental virtual web-based platform was also developed with the aid of Blender [162]. Gamification is an important element in educational applications, and Blender can be used for such purposes, for example, in medical education [163]. A 3D animated avatar was created in Blender and is used in an interactive educational application that evaluates the user's knowledge in various areas [164]. Blender was also used for the creation of the 3D model of a university campus which can be rendered on web for navigation purposes [165]. In combination with AI-driven ChatGPT for natural language processing, Google text-to-speech, Unreal and Unity for visualization, and Blender with Character Creator tool, a virtual teacher was developed for highly customized personal education [166].

It is possible to use Blender to create presentations and slides.[16] The Blender Community Add-ons can be used to produce 3D statistical charts[17] or convert Latex equations to editable 3D objects.[18]

[15] vut.cz/en/students/final-thesis?action_name=zform&formID=search_zav_praci&rok=&nazev=blender.

[16] Blender Market-Blender Slides: blendermarket.com/products/blenderslides.

[17] GitHub-Data Visualization Add-on for Blender: github.com/Griperis/BlenderDataVis.

[18] GitHub-Mathematical Equation Generator: github.com/kstrenkova/mathematical-equations.

BlendMol is an add-on for visualization of macromolecular structures [167]. Similar programs, such as VMD or PyMOL, do not offer advanced rendering options as Blender. Blender in its basic form, on the other hand, does not contain the necessary analysis tools that are included in this add-on. Electronic structure modeling in Gaussian16 software was connected with Blender in the Gaussian-2-Blender project to expand the options for 3D visualization of molecules and possible integration in virtual or AR [168]. A similar use case can be seen in the field of crystallography [169]. QMBlender add-on is capable of visualizing the dynamics of 3D quantum wave functions using particles [170].

The ability of Blender to produce 3D printable models and to visualize 3D scenes was exploited in the demonstration of *falling motion of a horizontally thrown ball*, and *tower of Hanoi problem* [171]. The authors concluded that the proposed approach helped their students better understand the topic. The 3D printing and Blender combination was also used in math education [172]. The teachers of the University of Applied Sciences in Zagreb used Blender as a free alternative to software, which might be inaccessible to students after finishing their studies, in the civil engineering course for construction tasks [173]. Physics learning animations on the atomic core topic were developed in Blender for a course in a senior high school and proved to be efficient [174]. Engineering course on Industry 4.0 used Blender as one of the educational tools for online assignments that received positive feedback [175]. Educational videos on topics of electric current and voltage are physics were created in Blender [176]. Blender also plays an important role in AR physics educational applications development [177]. Blender is a tool often used to create assets for educational trainers [178]. 3D models of various species for a wildlife encyclopedia were created in Blender [179] as well as models for educational holograms [180] and rigs in AR-based animal flashcards for children's education [181]. Photography and video were used in 3D photogrammetry to create accurate 3D models of harbor porpoises with the aid of Blender [182]. These were proved to be accurate when compared to real objects and are supposed to be used in scientific simulations or for educational purposes. The virtual rabbit anatomy simulator was implemented in Blender and CryEngine [183].

5 Industrial usage

Many top-production projects use Blender for visual effects and assets creation.[19] Blender is also sponsored[20] by big companies, such as AMD, META, Google, Epic Games, Adobe, Activision, etc. It is also one of the major tools for famous cinematography companies,[21] such as Ubisoft, Pixar, Netflix, etc. Companies such as Amazon, Microsoft, Tesla use Blender to create synthetic data for their applications or visualizations [184]. A delegation from the Blender developer team annually visits conferences, such as GDC (Game Developers Conference), SIGGRAPH (Special Interest Group on Computer Graphics and Interactive Techniques), or Annecy International Animation Film Festival where they meet potential partners and creators.

Blender is a convenient tool for industrial projects, for example, to visualize fusion data [185] or to create immersive artistic effects [186] and animated characters [187]. Photorealistic rendering is an important feature of Blender and is easy to achieve using, for example, BlenderProc2 add-on [188]. A study showed that, for example, the lighting models used in Blender are accurate for use in real-life reconstructions of shadows and possible connected analyses [189]. The relevance of Blender and its integration into industry is highlighted by recent research of special methods of text-to-3D-scene conversions designed for the Blender environment [190]. Existing state-of-the-art industrial products related to the 3D environment often provide software support for Blender. For example, Looking Glass Factory 3D display offers a Blender add-on to show the models in 3D, [22] Voxon volumetric displays were similarly connected to Blender,[23] 3D modeling platform Sketchfab has an add-on for direct Blender import/export,[24] Rokoko motion capture suits manufacturer supports Blender by an official add-on,[25] CC0 texture database ambientCG provides, material editor Adobe Substance 3D, vegetation modeling tool SpeedTree Cinema all provide official add-ons for Blender. The Cycles rendering engine was also adopted by Rhinoceros commercial 3D computer-aided design application as a figure posing and rendering editor Poser [191].

Many commercial render farms and related open-source frameworks support Blender [192–195]. The built-in rendering engine Cycles was successfully accelerated on Sunway supercomputers with a speedup of 128$times$ compared to the standard version [196]. This shows that the interest in Blender is significant even for large projects that require long rendering times.

[19] Blender User Stories: blender.org/user-stories.

[20] Blender Fund: fund.blender.org.

[21] Blender's Impact in Film: blender.org/news/blenders-impact-in-film.

[22] Looking Glass Factory Blender Add-On: lookingglassfactory.com/blender-add-on.

[23] Volumetric Display Add-on for Blender: voxon.co/volumetric-display-add-on-for-blender.

[24] GitHub-Sketchfab Blender Add-on: github.com/sketchfab/blender-plugin.

[25] GitHub-Rokoko Studio Live Plugin for Blender: github.com/Rokoko/rokoko-studio-live-blender.

5.1 Films

The role of Blender in the film industry is increasing as it provides all the necessary tools for film production [197]. Blender was used to create assets for major motion picture professional films, such as Spider-Man 2 (2004), Red Riding Hood (2011), Life of Pi (2012), Warcraft (2016), Lights Out (2016),[26] RRR (2022) [198], Everything Everywhere All at Once (2022),[27] Wonder Woman (2017),[28] Prospect (2018), Love, Death & Robots (2019), Spider-Man: Across the Spider-Verse (2023)[29] [199], etc. [5]. Annecy International Animation Film Festival, Annie Awards, Golden Globe Awards, and Oscar winner, in the category of the best animated feature film, Flow (2024) was fully animated in Blender.[30] Special effects in the TV show Red Dwarf X (2012) were also partially produced by Blender simulations. Barnstorm VFX studio uses Blender in their visual effects production and is behind the TV shows Man in the High Castle (2015–2019), Obi-Wan Kenobi (2022), or One Piece (2023). Goodbye Kansas Studios used Blender to create visual effects for the eighth season of the Walking Dead TV show or for the Mass Effect: The Andromeda Initiative cinematics. Blender was also used to create special effects in Friday or Another Day (2005) [200]. The movies Plumíferos (2010), Next-Gen (2018), and Maya and the Three (2021) by Netflix were entirely animated in Blender. It was also used in the production of Wolfwalkers (2020) where the early version of the hand drawing support in Blender was already useful. The animation tools in Blender are also used in Japanese anime films such as Evangelion: 3.0+1.0 (2021). The animation industry can make use of Blender instead of paid alternatives [201]. Blender developers also support open films[31] that have their assets publicly available and often use Blender for the entire production process. Such films are, for example, Elephants Dream (2005), Big Buck Bunny (2007), Cosmos Laundromat (2015) [202], etc. [203]. The uniqueness of these projects is demonstrated in the study in which Cosmos Laundromat was analyzed in a case study on the gift economy and the possible dangers hidden behind the concept of open online sharing [204]. Advertisements and commercials can also be produced in Blender [205].

A conducted study showed that human soft tissue dynamics can be efficiently simulated in Blender for human avatars that can be used in films or other applications [206]. 3D scenes in Chinese painting style are popular assets in films about Asian cultures. Blender can be used to create this type of scene easily according to the study conducted [207]. Professional video footage can be captured in various color profiles, such as logarithmic ones. Blender's 3D renderer, compositor, and video editor can use LUT (look-up-table) files and transform the image into various industrial color profiles with the integrated OpenColorIO library [208].

5.2 Games

Blender is a tool that supports many widely used formats and is easy to integrate into the game development process [209, 210], even with existing game engines such as Unity [211] or Unreal Engine [212, 213]. An official Blender Studios game project Dogwalk[32] demonstrates the seamless cooperation between Blender and Godot Engine. The role of FOSS in the gaming industry is significant, and Blender was identified as one of the most viable candidates for the use of FOSS in this field [214]. Embark Studios published a Blender add-on used for professional game development.[33] Similarly, Ubisoft released a Blender collaboration add-on.[34] TRACE studio, creating assets for video games such as Ghost of Tsushima, Call of Duty, or Baldur's Gate, cooperating with companies such as Blizzard, Activision, Sony, or Deep Silver, uses Blender for their AAA game resources. Arts Station platform[35] contains a lot of posts from game designers and their Blender-made artworks used for the final games. The artworks are 3D models and concept arts for games such as Cyberpunk, Star Wars: Jedi Survivor, Avatar: Frontiers of Pandora, Call of Duty: Modern Warfare III, etc. Wolfire Games studio used Blender for the character rigging and animation in the Overgrowth game. Bohemia Interactive, authors of Arma or Operation Flashpoint use Blender in cooperation with their engine Enfusion. Teams behind professional games Alan Wake 2 and Marathon also reported using Blender in the production.[36] Blender played an important role in the development of a popular e-sport game Rocket

[26] Interview with David Sandberg at OpenVisualFX: openvisualfx.com/2017/06/16/interview-with-david-f-sandberg.

[27] Everything Everywhere All at Once at BlenderNation: blendernation.com/2023/04/07/blender-used-in-award-winning-film-everything-everywhere-all-at-once/.

[28] Wonder Woman at ArtOfTheTitle: artofthetitle.com/title/wonder-woman.

[29] Spider-Verse at BlenderNation: blendernation.com/2023/06/11/blender-used-in-across-the-spiderverse/.

[30] Blender User Stories: blender.org/user-stories/making-flow-an-interview-with-director-gints-zilbalodis/.

[31] Blender Open Movies: studio.blender.org/films.

[32] Blender Studios-Dogwalk game: studio.blender.org/projects/project-dogwalk/.

[33] GitHub- Embark Blender Tools: github.com/EmbarkStudios/blender-tools.

[34] GitHub- Ubisoft Mixer-Blender Add-on: github.com/ubisoft/mixer.

[35] Blender at ArtsStation: artstation.com/ch/blender.

[36] Alan Wake 2 and Marathon at BlenderNation: blendernation.com/2023/06/21/blender-used-in-high-profile-games-alan-wake-2-and-marathon/.

League.[37] Blender can be used not only for the creation of the assets, but also for the analysis. For example, the LoDCalculator add-on can evaluate the geometric and radiometric fidelity of the given 3D model [215].

Blender versions prior to 2.8 contained a game engine. This engine was discontinued, but several fully playable games were created with it.[38] Henrik Svilling, the creative director of Istudios Visuals that produced many game trailers, highlighted the importance of Blender in their workflow.[39]

5.3 Industrial design

The variety of tools included in Blender makes it an appropriate software for architectural design [216, 217]. An add-on was created to simulate similar tools for architectural drawing, such as in Autodesk AutoCAD software [218]. Professional architects use Blender for visualization of their designs [219, 220]. Blender-Archipack[40] is an add-on that allows fast architectural visualizations. Blender can be used efficiently to visualize and design interiors, such as studios [221]. Building information modeling (BIM) focuses on digital representation of buildings or places and is useful in fields, such as facility management. Blender add-on BonsaiBIM implements openBIM standards and focuses on interoperability and an easy development process in BIM [222]. Blender can be used for side tasks in such industrial processes, for example, to automatically convert and split DAE files (Digital Asset Exchange) in the 4D BIM and robot task planning use case [223]. Blender can compete with professional tools for point cloud and mesh editing for urban planning, such as Rhinoceros 3D as it handles well complex geometrical editing using node programming [224]. However, it is lacking in the point cloud editing capabilities.

The seismic response of building structures was simulated in Blender where the shaking of the virtual surveillance camera can be easily scripted through the graph editor [225]. In the study of an emergency situation in a motorway tunnel, Blender was used to create the tunnel model [226]. While the rest of the simulation was done externally, it would be easier to use Blender solely with its current features for such a task nowadays. Blender was used as one of the tools for the design of a green corridor in Chinchero, Cusco [227]. VI-Suite is an add-on for contextual and performative buildings analysis in large geospatial datasets [228]. Although the visualization capabilities of Blender are ideal, the processing of geospatial data might be inaccurate. For example, unmanned aerial vehicle photogrammetry in Blender would require the development of specific add-ons due to precision problems [229]. Geographic data can be easily processed with the BlenderGIS add-on [230]. Patterns used in lithography can be produced with the aid of Blender [231].

Blender has been a good free option for the preparation of models for 3D printing [232]. One of the built-in official add-ons is a 3D Print Toolbox. This add-on automatically refines the model for the 3D printing use case and offers additional tools for 3D print model processing. Possible stringing defects in the printing can be detected using Blender-based simulation by comparing the rendered and real printed parts [233]. Blender serves as one of the tools for dental, biological, and implant elements [184, 234–236]. Dental tracking with 3D jaw animation reconstruction can be fully implemented using Blender's video tracker and 3D environment [237]. Prosthetic arms and other body parts are often modeled in Blender [238]. Facial surgery planning and evaluation can be improved with Blender due to its precise measurement and editing tools [239]. For learning and planning congenital cardiac surgery, Blender and 3D Slicer software can be used as core tools for the 3D printing pipeline [240]. A similar workflow with Blender was used in complex fistula-in-ano model production [241]. The low-cost usage of open source saves, according to the authors, a lot of money because specialized software is often expensive. The tools in Blender proved to be efficient for the creation of paper models used in art, decorations, building models, or sculpture [242]. Serious and life-threatening heart conditions can be related to the aortopulmonary window that was simulated in Blender for possible therapeutic use [243]. Blender was also integrated into the process of maxillofacial surgery in the process of orthognathic surgery virtual surgical planning [244].

Real-time emulation of production systems was implemented in Blender to simulate logistics operations [245]. Although the simulation was too simple to use in practice, the author claimed that additional adjustments would make the process more usable. Blender seems to be a good candidate for various tasks in robotics, especially in its current state, which contains missing features previously proposed [246]. For example, it was used to simulate the motion of an industrial robotic arm with a rigid body simulation that detects possible collisions with obstacles [247].

Blender can be used for computer-aided design (CAD). No crucial obstacles hinder Blender in this field. However, CAD software such as AutoCAD, Autodesk Inventor, SolidWorks, or Cadwork are industrial standards, and designers are rarely willing to change their tools. Migration to Blender from standard tools might be too time-consuming for users [248]. Blender can be used for precise modeling, offers most of the important CAD tools in its basic form, and advanced tools are available as add-ons, for example, advanced measurement

[37] Rocket League Artists Use Blender at CG Cookie: cgcookie.com/posts/how-rocket-league-artists-use-blender-for-game-production.

[38] Moby Games-Blender Engine Games: mobygames.com/group/14255/game-engine-blender.

[39] Blender Conference-Blender In high-end Game Trailer production: conference.blender.org/2019/presentations/549.

[40] Blender-Archipack: blender-archipack.org.

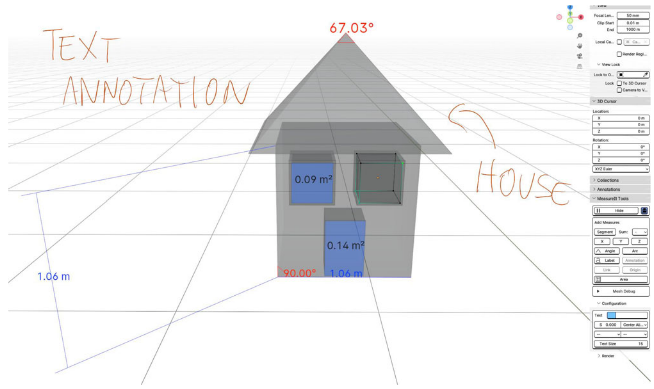


Fig. 15 The add-on MeasureIt can be used to measure distances, areas, angles, etc., and visualize the results. Handwritten annotations can be also added to the 3D scene without any add-ons

by official add-on MeasureIt (see Fig. 15). CAD industrial models were edited in Blender, adding a *flash* defect to them, for evaluation and training of the quality inspection method [249].

One obstacle can be that Blender focuses mostly on mesh editing, and parametric B-rep used in CAD software might be problematic to work with. Blender supports parametric curves or metaballs as well, but the workflow of CAD software might be more suitable for CAD tasks. Add-ons, such as Precision Drawing Tools, can be used to emulate CAD workflow, for example, for the creation of digital twins of industrial equipment [250]. In conjunction with other programs, the Blender add-on My Face Mask was used to design face masks for 3D printing during the COVID-19 pandemics [251]. Another kind of mask was produced and designed in Blender, for an 8-year-old patient with class III malocclusion who received a rapid palatal expander [252]. The mask was evaluated as fairly comfortable and efficient after 9 months of use. The 10-year-old patient who underwent microtia reconstruction received a mask designed in Blender according to facial scan made with the smartphone [253]. This showed that Blender can also be used for precise medical use.

5.4 Visualizations

BDICOM add-on can process data from computed tomography (CT) and magnetic resonance imaging (MRI) in DICOM format to produce medical 3D visualizations [254]. Synthetic CT scans can also be generated based on 3D geometry using DICOMator add-on [255]. The visualization of aircraft evacuation was successfully implemented in Blender and its Python API [256].

Blender is also an efficient tool for the reconstruction of historic buildings and cultural heritage visualization [257], such as Czech Starý Světlov castle [258], Rhine castles [259], Roman Villa of l'Albir [260], Roman sarcophagus [261], Finnish village Toivola [262], historic sites of Indonesian Bandung city [263], Roman cornice from Castulo archaeological site in Spain [264], Ashoka Pillar [265], simplification of the photogrammetry-reconstructed La Pastora dolmens [266], or modeling of Japanese Tsuruga-jo Castle [267] (see Fig. 16). Physically accurate lighting was implemented for visualization of cultural heritage, which requires special simulations, in Blender [268]. Blender was used as a visualization tool for structural collapse simulation with Bullet Physics [269]. Blender is used in archaeology to visualize reconstructions of various objects and sites, for example, in ReViBE protocol for visualizing lithic refits [270, 271]. Industrial, geodetic, and historical 3D scanning can be simulated in Blender [272], even in real time using TLSynth add-on [273].

An antemortem computed tomography scan of a person who was later killed was used to reconstruct the skull [274]. The dead body was severely crushed and reconstruction was necessary to prepare the body for investigation purposes. In this process, the free software 3D Slicer and Blender was used. The nasal prosthesis production workflow using Blender was proposed and was shown to reduce the necessary cost by 40% and the time by almost 90% [275]. Scoliosis treatment can be performed with spinal orthosis. Research showed that Blender can be used as a tool to model ultrasound-reinforced orthosis [276]. 3D modeling application with stereoscopic output, head tracking, and motion tracking input devices was implemented using Blender as the core editor [277]. Brain-computer interface MOTIV EPOC+ Neuroheadset was used to perform basic operations in Blender [278]. The study discovered that such an interface can be efficiently used for 3D editing after a training period which takes some time. This shows that non-traditional input/output devices can also be used in the Blender environment with certain adjustments.

6 Comparison with alternative products

Although similar 3D editors and animation tools exist, it is hard to find an alternative FOSS software that would contain as many features as Blender in the field of 3D/2D graphics editing.

(a) Distant view on the scene, rendered with EEVEE (b) Artistic view, rendered with Cycles and processed in Compositor

Fig. 16 Japanese Aizu Wakamatsu Castle, also called Tsuruga-jo, was reconstructed in Blender and the model is used in this figure [267]. A tree was generated procedurally using the official Blender built-in add-on Sapling Tree Gen

6.1 Popularity

Blender is mostly popular in the indie development and with amateurs. Based on the exploration of jobs offers at website ShowbizJobs[41] conducted in March 2024, Blender skills are wanted in offers from companies such as Netflix, Ubisoft, Psyonix, Electronic Arts, etc. Blender skills are also required in job offers by Nvidia, Disney, Blizzard Entertainment, Amazon, etc., placed on the official websites. Corridor Digital studio, famous for their pop-culture visual effects videos on YouTube with hundreds of millions of views, often uses Blender as seen in their behind-the-scenes videos. Blender Conference is an annual event featuring famous artists, CEOs, designers, and technical leaders from the whole world. Workshops on advanced Blender features are held among amateurs and experts [279–281].

The most popular candidates for the comparison that offer similar functionality are:

- Autodesk 3ds Max—professional 3D editor,
- Autodesk Maya—professional 3D animation tool,
- Adobe After Effects—mainly 2D compositor with limited 3D options,
- Cinema 4D—easy to use 3D animation tool,
- SketchUp—easy to use 3D modeling and designing tool,
- ZBrush—digital sculpting 3D and 2D tool.

None of the mentioned tools supports such a variety of features as Blender (see Table 1). The features were evaluated by manually exploring the software and by analyzing information from official websites and forums. However, certain features might be more advanced in specific programs.

The popularity of each of the mentioned tools can be estimated by the amount of search queries on the Internet. Google Trends service was used to analyze how much each of the tools is searched for on Google search engine worldwide. To exclude similar keyword searches that do not relate to the given software, additional keywords were added. The names of the tools were searched in combination with the following keywords: *3D*, *tutorial*, *software*, *editor*. The results were averaged. The data in Google Trends (GT) are normalized to show a percentage of interest in the given topic. Figure 17 shows that Blender is the most searched tool in recent years.

Another statistical analysis was conducted on the YouTube video-streaming platform. The number of tutorials for the mentioned tools was counted each year as shown in Fig. 18. The total number is shown in Fig. 19. YouTube Data API v3 was used to retrieve the data. The results show that Blender is covered by official and community tutorials significantly more than other 3D editors. Adobe After Effects shows the highest number of tutorials because of its popularity in 2D video composition and visual effects. The chart shows how the recent development of additional features for 2D compositing in Blender makes it surpass Adobe After Effects in the end. Note the peak in the charts around the year 2019 where the COVID-19 pandemic occurred. Lockdowns around the world caused an increase in video-streaming bandwidth and online education [282].

Google Trends were also used to estimate the popularity of Blender in the less known features. Additional tools in the other fields that Blender also covers were compared. A comparison of Blender with existing video editors was conducted. The name of the tool was searched with *video editor* keyword to specify the context. The results are presented in Fig. 20. The video editor in Blender is not as rich as in the dedicated video editing programs. However, given that the Blender video editor is just a simple tool, the results presented show that it plays a big role in video-editing field and its popularity outperforms other existing programs.

[41] ShowbizJobs: showbizjobs.com.

Table 1 Information about the support of features in Blender and alternative software

Feature	Blender	3ds Max	Maya	After effects	Cinema 4D	Sketchup	ZBrush
Path tracing	+++	+++	+++	–	+++	–	+
Rasterization	+++	+++	+++	–	+	–	++
3D mesh edits	+++	+++	+++	+	+++	++	++
Video editing	++	–	–	++	–	–	–
2D composition	++	+	++	+++	–	–	–
Hand drawing	++	+	++	+	–	–	++
Scripting	+++	++	+++	++	+++	+++	++
Motion tracking	+++	++	+	+++	+++	–	–
Platform	+++	–	++	+	++	+	+
Price	+++	–	–	+	+	++	+

The "–" denotes zero support, and "+", "++", "+++" range from partial to full and best support. Only the built-in features in the basic version of each program are counted. Only Blender is free; the price ratings correspond to the expenses per month

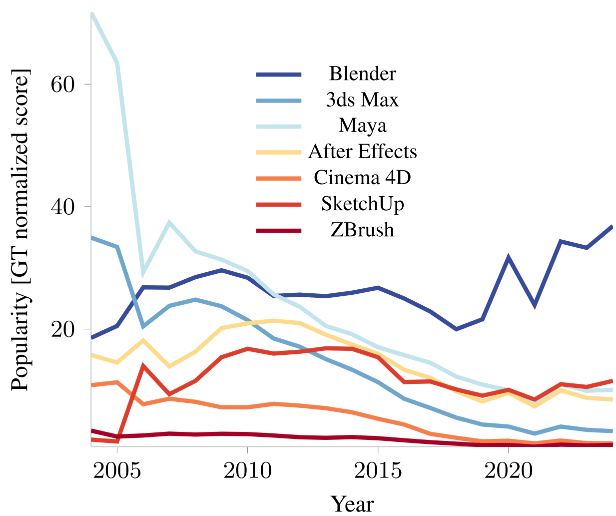


Fig. 17 The chart shows how often was the specific tool searched for on Google in years 2004–2024

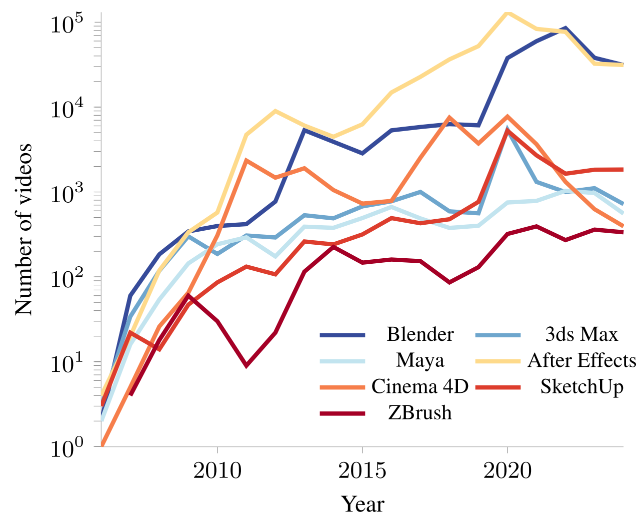


Fig. 18 The chart shows the number of new tutorials for the specific tool on video-streaming platform YouTube in years 2005–2024. Note that the difference might be higher than that perceived due to the logarithmic scale of the vertical axis

A similar comparison was conducted to find out how popular Blender is in the field of visual effects. The keyword added to the tool names was the commonly used abbreviation *VFX*. The results are presented in Fig. 21. It seems like game engines are starting to gain popularity in the field of visual effects because they recently got video-editing support. However, the significance of Blender in this field rises as well and has kept its high position for a long time. Fire and explosions are widely desired VFX. Blender was compared to EmberGen, showing that the wide range of settings in Blender might provide users with more refined control over the visual quality of the result, while EmberGen provides faster simulation, more convenient for real-time usage [283].

The comparison of Blender with existing 2D animation and drawing tools is presented in Fig. 22. The keyword added to the tool names was *2D animation*. Surprisingly, Blender 2D animation features have been searched for a long time much more than more feature-rich tools specifically designed for 2D animating. Although 2D animation was possible in Blender since the early versions, it received a feature boost in 2019 with a dedicated workspace and enhanced workflow. The graph shows a significant increase in interest since 2019, reflecting this update.

Viewed in 2025, major 3D model distribution websites, CGTrader and TurboSquid, host models in various formats. The formats were filtered, and the results are presented in Table 2. It seems that general formats like obj are much more used than software-specific ones, which is to be expected due to their universal design. 3ds Max is the most widely used software-bound format with Blender covering about half of that but outperforming other software formats. Blender project format is capable of containing a vast amount of infor-

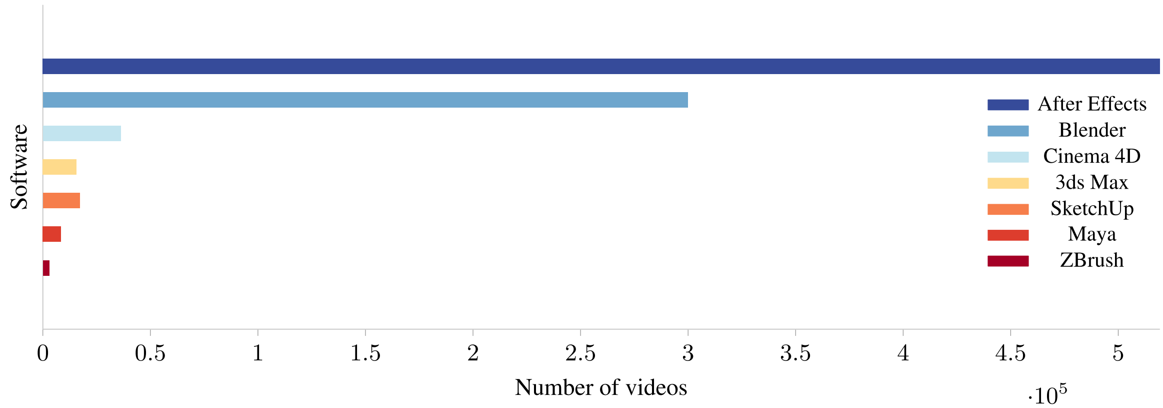


Fig. 19 The chart shows the total number of tutorials on YouTube for the given tool from year 2006 to 2024

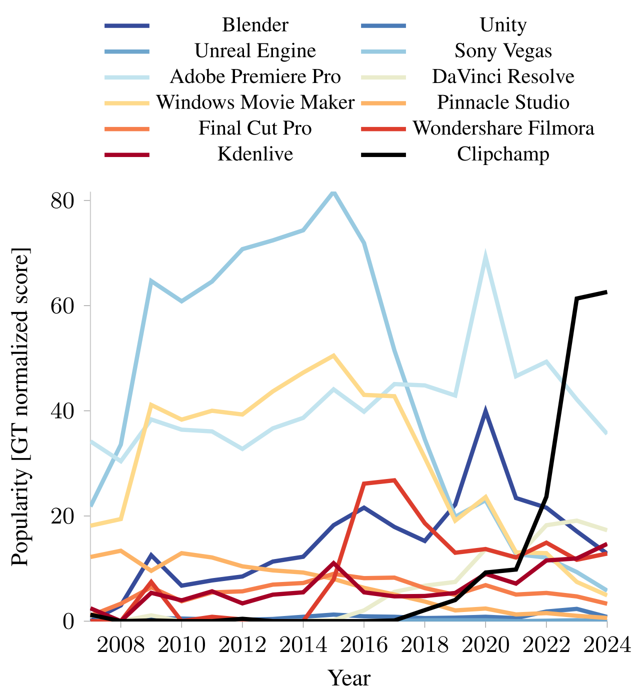


Fig. 20 The chart shows how often was the specific tool searched for in the context of video editors on Google in years 2007–2024

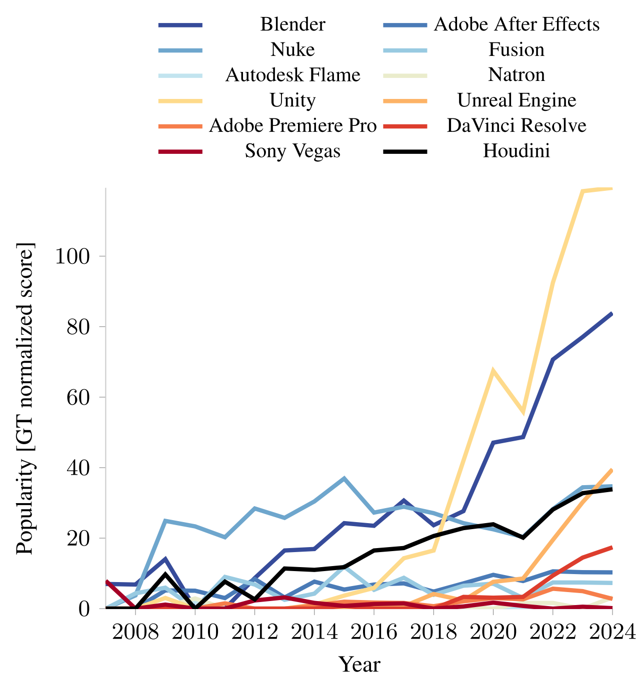


Fig. 21 The chart shows how often the specific tool was searched in the context of visual effects editors on Google in the years 2007–2024

mation regarding all scene settings and is often considered a good way to distribute these data [284].

6.2 Rendering engines

Blender includes a physically based path-tracing renderer Cycles and a rasterization renderer EEVEE. Additional rendering tools can be installed in Blender through add-ons. The most well-known third-party renderers are:

- Arnold—Monte Carlo ray-tracing renderer by Autodesk, used in 3ds Max and Maya,
- BEER—open-source real-time non-photoreal renderer for illustration style rendering,
- Corona—renderer created for architectural visualization,
- E-Cycles—commercial photorealistic Blender render engine,
- LuxCore—free physically based and unbiased renderer,
- Mitsuba—research-oriented open-source retargetable rendering system,
- Octane—commercial unbiased path-tracer,
- Radeon ProRenderer—physically based renderer by AMD,
- Redshift—GPU-accelerated biased renderer by Maxon used in Cinema 4D,

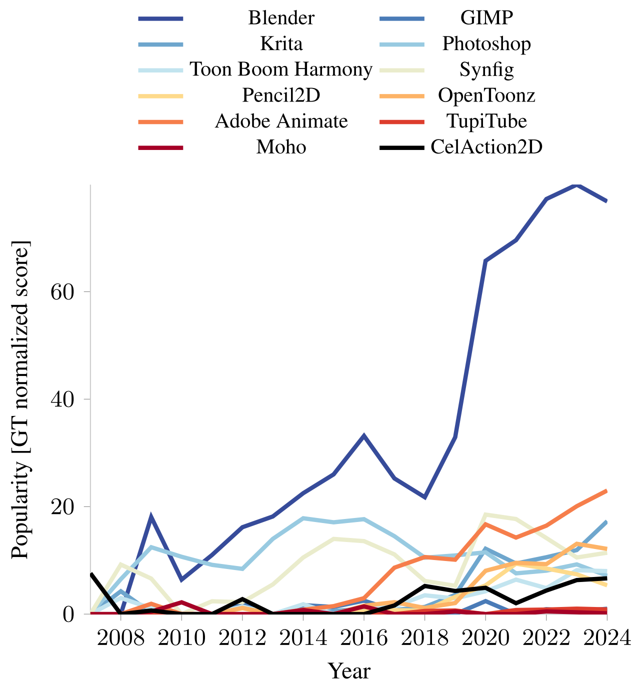


Fig. 22 The chart shows how often was the specific tool searched for in the context of drawn 2D animation on Google in years 2007–2024

Table 2 The widely used 3D model formats connected to a specific software were compared in terms of the number of the models distributed in these formats on two major model-sharing platforms

		Count on the website	
Software	Format	CGTrader	TurboSquid
Blender	Blend	424 750	300 631
3ds Max	Max	702 352	882 896
Cinema4D	c4d	128 031	283 824
Maya	ma, mb	151 044	253 307
Wavefront	Obj	1 442 478	994 885

A general obj format was also added as a reference

- V-Ray—commercial renderer that supports path tracing, photon mapping, irradiance maps and directly computed global illumination.

The available renderers have already been compared by the Blender Guru YouTube channel,[42] in 2021, on a machine equipped with a Gigabyte Vision 3090 GPU and Intel 7820x CPU. The general results measuring the speed of the rendering while reaching the same quality are shown in Fig. 23.

Another comparison evaluated the performance of Cycles, EEVEE, and LuxCore [84]. The authors concluded that LuxCore might be more efficient for scenes with complex lighting conditions due to its support of bidirectional path tracing. For standard scenes, both Cycles and LuxCore can be equally useful. Rendering with Cycles was faster than LuxCore.

The available and compatible engines with Blender 4.x in 2024 were selected and used to measure their performance during the research of this paper. The scene used in the evaluation is a Cornell Box with diffuse, slightly reflective, and glass materials. Note that this is not an in-depth benchmark and comparison of the engines. Such a comparison would require advanced adjustment and tuning of each engine and rendering on a large number of scenes with various materials, which is out of the scope of this paper. The goal of this experiment is to compare the engine with mostly default settings or slight changes that an ordinary user would do to achieve a good quality result. Each renderer produces slightly different results despite having the same scene settings. The scene materials were edited so that the results look as visually similar as possible. Figure 24 is an example of different glass simulations and caustics in different renderers. The caustics in Cycles do not seem to be able to simulate complex caustics from reflected light, as the caustic on the ground is only white. Cycles renderer is capable of producing realistic renders, but other renderers might be needed when extreme realism is required. Some renderers, such as Arnold, RedShift, or LuxCore, do not use default Cycles materials, and new materials of the given type need to be added. V-Ray does not seem to be supported in the current version of Blender. Octane even requires special Blender edition and Mitsuba processing by external program.

An exact comparison of the result between the renderers is not possible. Therefore, each renderer was used to produce a high-quality reference with an extremely large number of samples so that any increase in the sample count would not significantly lower the amount of noise. The rendering of the references took between one and three hours. Then the renderer was used to produce an almost visually lossless render with approximately 40 dB PSNR and 0.91 SSIM to the reference. In this way, it is possible to estimate how fast a particular renderer can produce visually acceptable result according to its own capabilities and converge to the ideal image. Denoising was turned off in each renderer. The resolution of the renderings was 4K (3840×2160) and raw 32-bit floating-point EXR files were stored and compared with FFmpeg PSNR and SSIM filters. The machine was equipped with $2\times$ Xeon 2.4GHz (8/16) and $2\times$ NVIDIA RTX 2080Ti. This reflects the standard usage when the user has a dedicated GPU and does not use an integrated one for rendering. CPU and GPU times should be evaluated separately, as GPU is expected to be always faster.

Figure 25 shows the results of the rendering performance comparison. The built-in Cycles engine can produce high-quality renders quickly in the GPU-accelerated version. Redshift seems to be highly optimized on GPU and wins the

[42] Blender Guru-Render Engine Speed Comparison: youtu.be/myg-VbapLno.

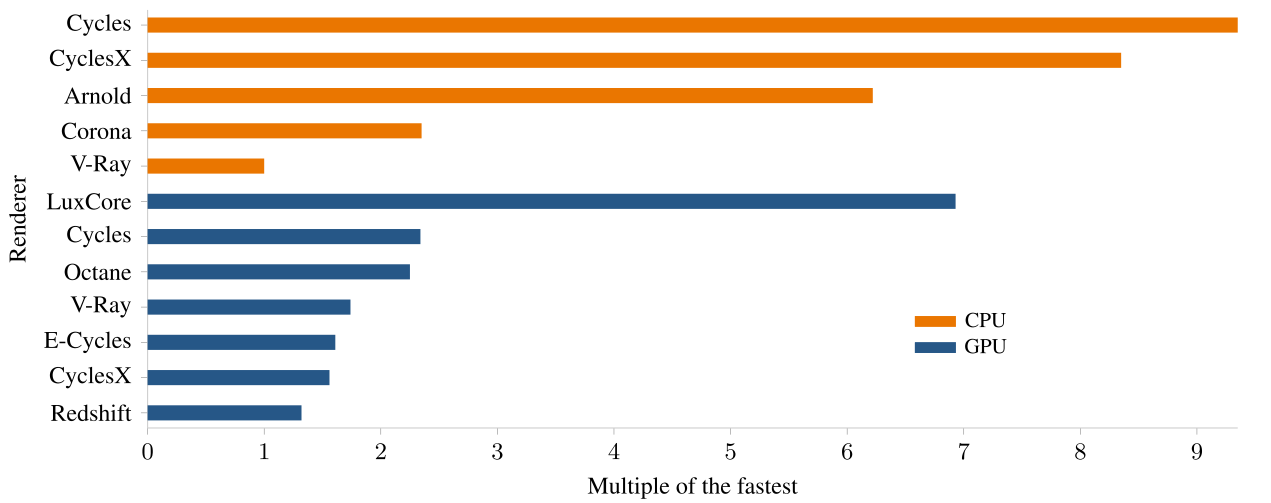


Fig. 23 The chart shows the results of Blender Guru comparison of existing render engines in 2021. Cycles-X was an experimental version of Cycles that was later merged into Cycles

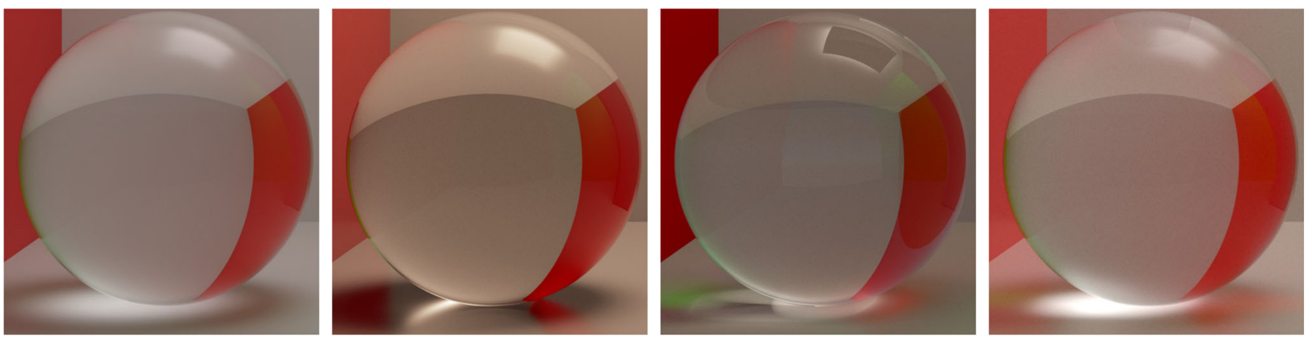


Fig. 24 Different renderers solve caustics in different ways. The difference is visible despite the effort to create consistent materials

comparison. Arnold is also very efficient when compared to the CPU renderers. Note that each renderer can handle different effects optimally. For example, advanced lighting effects like caustics are better simulated in LuxCore or Redshift than in Cycles. However, all the compared renderers can reasonably simulate the basic effects. Blender also contains the EEVEE rasterization and Workbench preview renderer. These renderers can be used for specific tasks where photorealism is not necessary (see Fig. 26). EEVEE is an optimal choice for fast renderings without complex lighting conditions and materials [285].

6.3 Denoisers

To speed up the rendering process and use a smaller number of samples, denoisers are included in Blender. OptiX, OpenImage, and Super Image Denoiser add-ons were compared in Cycles. The same reference file was used as in the previous experiments. OptiX offers is a highly GPU-accelerated denoising which is several times faster than the rest. All denoisers take just a few seconds to process the result, which is an irrelevant time compared to the whole rendering. The quality of the denoising in relation to the reference is shown in Fig. 27. The external add-on shows slightly better results, and the differences are most significant with small number of samples. However, in general, all denoisers seem to be very useful.

6.4 Usability

The software quality of 3ds Max and Blender was compared in accordance with ISO 9126. The study with 30 participants showed that Blender outperforms 3ds Max in terms of features and ease of use [286]. However, 3ds Max offers more efficient and faster rendering, which is in accordance with the experiment carried out above (see Fig. 25). Blender and SketchUp were compared on the same scene design and rendering, with the conclusion that rendering speed and visual quality in Blender is superior [287]. Blender and AutoCAD were compared among students with the task of applying

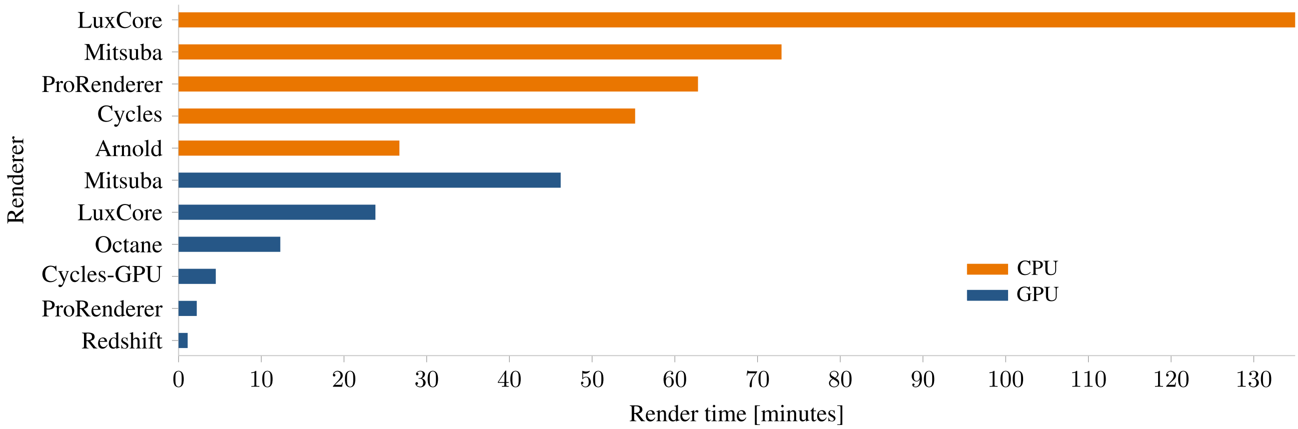
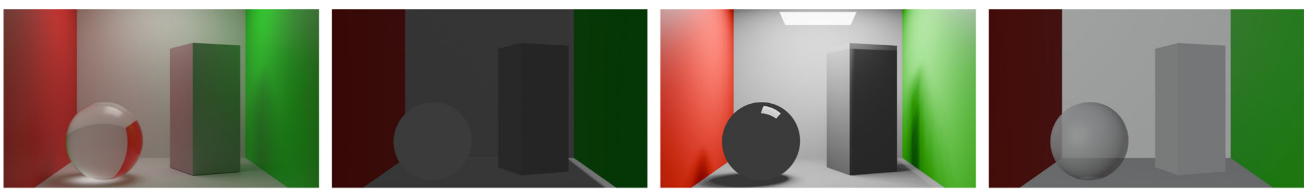


Fig. 25 Each engine was used to produce the reference image with a large number samples to achieve noise-free look. The settings of each renderer were adjusted to reach similar quality of approximately 40 dB PSNR and 0.91 SSIM relatively to the reference. GPU version of Mitsuba could not reach this quality level due to the sample count limit, so the result was compared in HD (1280×720) and the time was multiplied by 9 to match the number of pixels



(a) Cycles (b) EEVEE (c) EEVEE (rotated light) (d) Workbench

Fig. 26 The same scene was rendered with three built-in Blender renderers. The area light at the top is rotated toward the ceiling to test how the renderer solves the reflections of the rays so the scene is lit indirectly. EEVEE version with the light rotated toward the scene is also shown

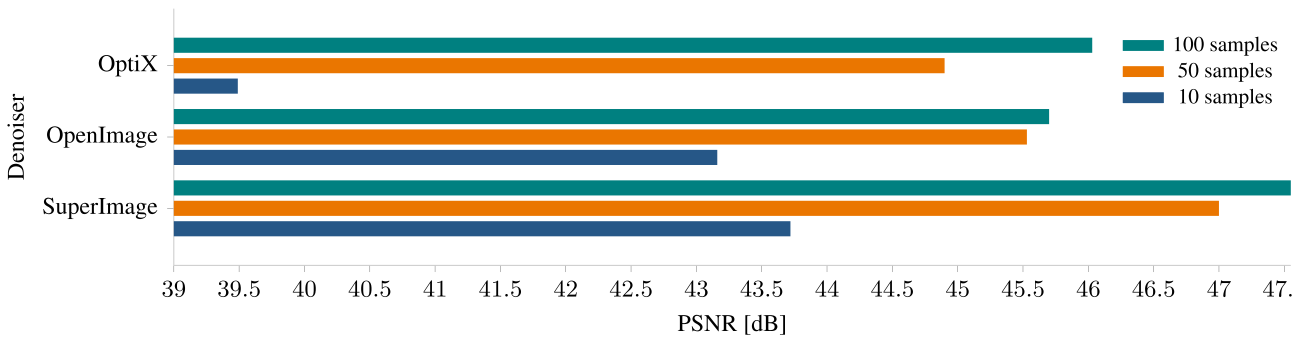


Fig. 27 The chart shows the visual quality of the denoised image, rendered with the given samples count, and compared to the reference

modifications to 3D cubes and cylinders and producing a 3D bottle model [288]. Blender was identified as the preferred tool by the majority of participants.

Blender was selected as the 3D editing tool in the study on creating 3D geometric models using live depth images. The authors *prefer to use the tool named Blender for assisting the user to cut these parts. Its cutting function is very easy to understand even for novices* [289]. Some authors combine the editors. For example, during the development of virtual driving simulation game, they used Blender for the environment modeling, rigging, and motion tracking, and Maya to model more detailed elements such as buildings or traffic lights [290]. A comparison of ray-tracing programs concluded that Blender offers a lot of unique features and has a large community support but is not the number one tool in large studios due to slower rendering than other tools [191].

Andrew Price conducted a survey in 2024 on the usage of 3D software and presented its results on Poliigon website.[43] 6 251 respondents participated and 64% reported being Blender users with 3ds Max, Houdini, Maya, Cinema 4D, Unreal Engine, and Unity having 4-7%. The main indus-

[43] Poliigon-State of 3D 2024: poliigon.com/articles/state-of-3d-2024.

trial usage of Blender was claimed to be in animation and 3D printing. Houdini had the highest number of users in the VFX field and 3ds Max in architectural and technical visualization. Unity shows a large number of users focused on educational purposes. Users also marked modeling as Blender's strongest feature, and simulations as the weakest. Blender users reported the highest satisfaction with the software, while 3ds Max users the lowest.

For example,[44] Hiroyasu Kobayashi and Daisuke Onitsuka, from the Japanese animation studio Khara, and Takumi Shigyo from Project Studio Q, mentioned that big projects are hard to handle with software, such as 3ds Max. The reason is that cooperation with other companies and artists requires software that is easily and inexpensively accessible to everyone. Also, according to them, Blender has obtained all the professional tools necessary and is easy to learn. Graphic designer Amy Lofts wrote an article[45] on AALofts Design website comparing Blender and 3ds Max. The conclusion of the article is that Blender offers a lot of features and is convenient for most of the users, while 3ds Max is still a top software in industry and highly regarded by professionals. According to the article, 3ds Max might be easier to use and provide better rendering options. 3D animator Nathan Duck wrote an article[46] on School Of Motion website comparing Blender and Cinema 4D concluding that motion Cinema 4D makes many tasks related to motion graphics much easier and faster to achieve than Blender. 2D and 3D artist Parsa Aminian wrote an article[47] on Pixune Studios website comparing Blender and Maya. The learning curve of Blender might be steep and Maya's rigging, animation, and NURBS features might be superior to Blender. However, the supportive large community and versatility of Blender is a big advantage. All authors agree that Blender offers comparable features to the other products and that the huge difference in costs, where Blender is completely free, while other software costs tens or hundreds of dollars per month, is a crucial reason that Blender might be the best choice for many users. Designer and Architect Saili Sawantt wrote an article[48] on Futurly website comparing Blender with Houdini. Houdini apparently provides more tools for procedural generation of 3D objects but might be harder to learn than Blender. Houdini is also used more in industry, for example, in Marvel studios.

7 Conclusion

This paper explored fields where Blender software is commonly used. Blender is free open-source software. It offers features that are equal to, and sometimes even better than, those of existing proprietary programs. Its large community also helps users solve common problems and get the necessary support. Many researchers reported that they used Blender in their works, especially for its wide extensibility with Python and the free availability, which makes the final solutions less expensive.

In science, Blender is often used to generate various 2D or 3D datasets for the evaluation of novel methods and the training of deep learning techniques. It also serves as an easily accessible tool for editing experimental 3D models. The simulation and rendering engines in Blender can be used for various scientific simulations, and the Python API can be used to prepare automatized experimental settings. Many scientific software can be used to model various phenomena, but their rendering capabilities are usually not perfect. Blender can be used to properly visualize such data. Numerical imprecision and the lack of built-in 3D data analysis tools might hinder the scientific work, and special add-ons are necessary for some tasks.

Blender is often used in various courses in high schools and universities. It can be used especially for explanations of difficult geometric issues such as 3D transformations. Various digital 3D assets for virtual laboratories or educational applications are often modeled in Blender. Several add-ons exist to visualize special kinds of data, such as charts, physical phenomena, microscopic structures, etc. The user interface might be difficult to learn and not intuitive for many people, which could reduce its usability in education.

Many visual effects in the film industry were produced in Blender, as well as many 3D assets for well-known video games. Due to its variety of features, many large companies worldwide have sponsored Blender. Blender support is also available for many state-of-the-art technological solutions, such as 3D displays or motion capture suits. The modeling precision in Blender is high enough to make it usable in the design of various medical implants, industrial components, or objects prepared for 3D printing. Many classic programs dominate the CAD industry, but Blender seems to be capable of many CAD operations as well. However, the lack of specialized tools and data representations used in CAD can be problematic. Blender was used in many projects related to digital reconstruction of historical sites and monuments. Professional software is usually well promoted and supported in

[44] BlenderUser Stories-Japanese anime studio Khara moving to Blender: blender.org/user-stories/japanese-anime-studio-khara-moving-to-blender.

[45] AALofts Design-Should I Learn 3ds Max or Blender?: aaloftsdesign.com/should-i-learn-3ds-max-or-blender.

[46] School Of Motion-When choosing your 3D program, should you go with Blender or Cinema 4D?: schoolofmotion.com/blog/blender-vs-cinema-4d.

[47] Pixune Studios—Comparison of Maya and Blender, Which One Is the Best for You?: pixune.com/blog/maya-vs-blender/.

[48] Futurly-Blender vs Houdini: Ruling the Digital Future: futurly.com/blog/blender-vs-houdini-ruling-the-digital-future.

industry and Blender might be viewed as an additional tool in the process, despite its professional features.

Although Blender is versatile and offers many features, proprietary programs that focus on specific domains might be a better choice in certain cases. Developers would need to focus on the following aspects to make Blender a fair competitor in these cases. For example, the rendering engines in other 3D editors might produce better visual results and support more complex lighting simulations. CAD editors often use parametric B-rep shapes. Blender partially supports this format in the form of metaballs, but works primarily with polygonal meshes. Blender excels in mesh editing, but lacks advanced tools for point cloud manipulation. Blender can be used for 2D video editing and visual effects composition, but standalone video editors and compositing programs offer more features. Similarly, 2D drawing and image editing are present in Blender but not as rich as in special animation, drawing, or image processing software. The information gathered in this survey led to a future work plan of conducting a case study regarding the usage of FOSS like Blender as a teaching and experimental tool in higher education.

Acknowledgements NGI0 Entrust is made possible with financial support from the European Commission's Next Generation Internet programme, under the aegis of DG Communications Networks, Content and Technology. This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069594. The authors would like to thank the reviewers for their valuable feedback and the editors for their assistance.

Author Contributions T. Chlubna contributed to conceptualization, formal analysis, investigation, methodology, visualization, and writing—original draft. M. Vlnas performed formal analysis, validation, visualization, and writing—original draft. T. Milet contributed to conceptualization, investigation, and methodology. P. Zemčík contributed to funding acquisition, methodology, project administration, and supervision.

Funding Open access publishing supported by the institutions participating in the CzechELib Transformative Agreement.

Data Availability No datasets were generated or analyzed during the current study https://github.com/ichlubna/blenderSurvey.

Declarations

Conflicting interests All authors declare that they have no conflicts of interest.

Competing interests The authors declare no competing interests.

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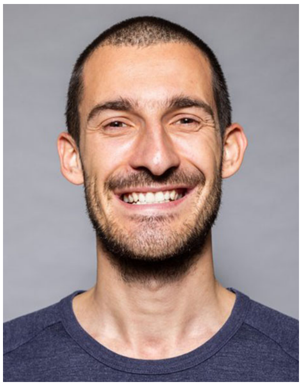

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