

Article

Optimising Amber Processing Using 3D Scanning: New Perspectives in Cultural Heritage

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Abstract: This article aims to present the practical and functional application of advanced 3D scanning technologies in the process of designing products made of amber. The processing of amber is complex and expensive because mass or serial production is not possible. Moreover, processing is challenging because each product is treated as unique and requires individual handling. The optimisation process is illustrated using the example of amber blocks that were scanned to obtain virtual 3D models. The scope of this work includes the characterisation of three-dimensional jewellery design processes, along with a description of a wide range of methods and functions used in computer-aided jewellery design. The use of computer-aided design software for developing virtual models of decorative products used in goldsmithing is described in this paper. The obtained sets of models underwent engineering analysis using Boolean algebra and data science calculations. In this way, a design methodology was developed regarding the selection of input material as the unprocessed stone for jewellery modelling. The developed method allows for the minimisation of material waste, which is associated with reducing costs in the processing of amber. This article also describes the differences between previous traditional methods and the authors' proprietary method. The proposed methodology can be implemented in jewellery workshops specialising in the processing of materials.

Keywords: amber; 3D scanning; stone processing; computer-aided design; intangible cultural heritage



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1. Introduction

Gemstones and decorative minerals have been used in jewellery, adornments and decorations for centuries, and they hold economic value as well as a significant cultural value. Since ancient times, the processing of stone has been held in high esteem in the hierarchy of craftsmanship, and its underlying knowledge has been shrouded in mystery. Skills such as metalworking have always commanded admiration and respect for this profession [1] and can even be considered as intangible cultural heritage [2]. Therefore, it is crucial to possess knowledge of the properties of the materials being processed, as well as the tools and technologies used in the materials' transformation process.

Materials used in the production of jewellery should possess certain properties such as high hardness, transparency, captivating colour and lustre [3]. This applies to both minerals such as corundum (ruby, sapphire), beryl (emerald, bixbite), nesosilicates (garnet, zircon) as well as organic materials such as amber, jet, or pearl. These features determine the choice of processing methods. In view of the unique properties of each specific piece, the processing of gemstones is complex and expensive due to the absence of mass or serial production methods.

One common challenge in gemstone processing is the susceptibility to mistakes. Typically, each processed stone has an irregular, unique shape, dimensional measurements, and an internal structure. Processing errors are irreversible and often cannot be rectified or

repaired [4]. Their characteristics and geometric properties are achieved through various processes, including cleaving, cutting, grinding and polishing [5,6].

The implementation of new technologies that increase efficiency in the manufacturing process and offer products that meet the expectations of a wide range of customers is necessary. The adoption of new technologies in gemstone processing, such as 3D scanning, is also driven by consumers who expect unique and personalised products. Jewellery serves as an example of such products, where the most valued items are unique and not mass-produced [7]. Meeting such demands requires significant effort and financial costs. The labour-intensive process involves designing and constructing models for the creation of moulds and patterns, and making revisions to the design is often impractical. However, with the advancement of computer-aided design and scanning devices, a breakthrough has occurred, enabling the use of tools that were once only within the realm of designers' dreams. Three-dimensional scanning technology allows for the acquisition of virtual models that reflect the shapes of gemstones, allowing work with models in virtual space [8,9]. The use of virtual gemstone and jewellery models reduces costs (financial investments) in producing a particular item by minimising material losses during the grinding process [10].

1.1. Amber Significance and Characteristics

Research on amber, also called "the gold of the north", is conducted by various companies and research institutions specialising in geology, gemmology, archaeology and chemistry. One renowned institution engaged in research on amber is the Institute of Geological Sciences, Polish Academy of Sciences (PAN). This institute performs detailed geological, mineralogical and chemical analyses aimed at understanding the processes of amber formation and its properties. Additionally, research on amber is carried out by private gemmological laboratories that specialise in mineral and gemstone analyses. These laboratories often provide services related to identifying the origin of amber, assessing its authenticity and analysing inclusions inside it, which can provide information about its history. Because amber is also a significant subject of archaeological research, institutions such as archaeological museums and universities conducting archaeological studies often engage in amber analyses, especially if it is found in an archaeological context. It is worth noting that research on amber encompasses diverse scientific fields and requires collaboration among experts from various disciplines to obtain a fuller picture of its origin, properties and history [11].

Amber is used in the jewellery [12], in visual arts [13] or even as a healing agent in folk medicine [14]. Amber was such a desirable commodity, as evidenced by the recorded traces of the existence of an amber trade route between Northern and Southern Europe [15]. Next to hard coal and salt, amber is recognised as a raw material associated with Poland, inextricably linked to the culture and history of this country [16].

Poland is the world's largest supplier of amber. It is often referred to as the global capital of amber, making amber a part of our national heritage. The Amber Route used to be one of the main international trade routes in ancient times. Our scanning technology does not provide direct protection for amber but allows for its optimal utilisation while minimising losses during processing.

Amber is a hard mineral, and more precisely, a fossilised resin from coniferous trees of the *Pinus* genus and sometimes resinous deciduous trees (from the legume group), as shown in Figure 1. It occurs in many diverse forms and shapes. They depend mainly on the location of the resin exudation, the shape and size of the fissure, the season, sunlight exposure, the condition and age of the tree and the history of the amber itself. The colour of amber is not constant and changes over time from white (rarest, most valued) light yellow to orange and from red to reddish-brown [17–19].



Figure 1. Comparison of amber [Property of the Amber Museum in Gdańsk, Poland].

Sometimes, inclusions (remnants of plants or insects from the Cretaceous and Cenozoic periods) can be found inside the solidified resin, making such specimens the most valuable, Figure 2 [20].

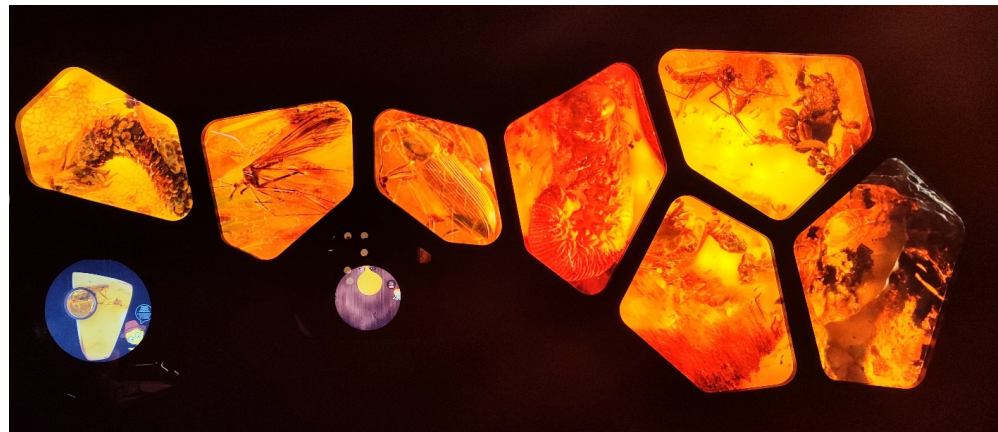


Figure 2. Examples of inclusions in amber [Property of the Amber Museum in Gdańsk, Poland].

1.2. Traditional Methods of Examining Amber Structure

The process of creating jewellery begins with preparatory work, during which the designer analyses the material characteristics of the gemstones. These types of exhibits are often collected in the form of private collections. An example of such exhibits is shown in Figure 3. The exhibits come from the private collection of Dr Elżbieta Miłoś.



Figure 3. Examples of amber necklaces from the private collection of Dr Elżbieta Miłoś.

Previous research methodologies regarding amber have focused on gathering information about its properties, volume analysis, hardness and optical parameters, Figure 4 [21].



Figure 4. A research stand for testing the character of amber—property of the Amber Museum in Gdańsk, Poland.

They provided general descriptions of the studied material and served as a source of information to support the decision-making process regarding its processing. Over time, additional methods and tools were used for general assessment (for example, the Mohs scale for the quick approximation of mineral hardness) and for a detailed evaluation of this property (sclerometers) [22,23] alongside refractometers to determine refractive index [24,25] and an intense assessment of materials (tomographs and equal baseline camera array for voxel grid creation corresponding to density and inclusion distribution [8]). Complete gemstone identification typically requires multiple tests and techniques, such as spectroscopy, density measurement and the observation of microscopic features.

The process of collecting basic data and assessing the quality of the material generates initial ideas and concepts based on the shape of the stone. When selecting a stone for

processing, the challenge is to determine its dimensions in a way that minimises production waste. Additionally, it is important to consider whether the chosen amber (stone) can utilise the visual potential of a given design. These challenges in stone selection significantly impact the work's process, technology selection and the final value of the jewellery. So far, this process has involved creating prototypes, which is time-consuming and complex depending on the project and level of detail [9].

The authors of this work propose using modern methods for analysing gemstones in the field of gemmology. These modern methods aim to overcome the limitations of individual techniques and provide a more comprehensive approach to gemstone analysis and identification [26].

2. Methodology and Research

A comprehensive 3D scanning methodology for amber is presented in Figure 5.

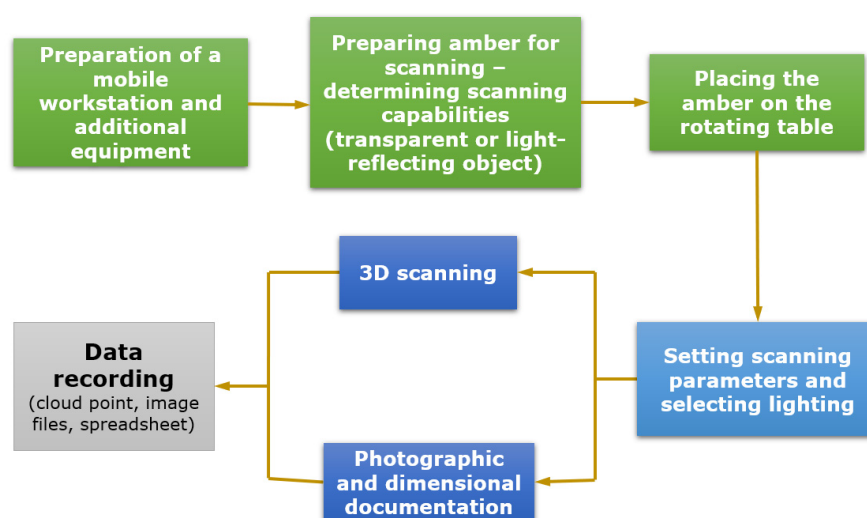


Figure 5. Scanning methodology.

The technology proposed by the authors to support the processing of amber is three-dimensional scanning technology. The scanning setup consists of a handheld scanner using structured light, such as the Artec Spider, a laptop, and a turntable—Figure 6a. The basic parameters of the scanner are as follows:

- Blue light technology scanner.
- Light source: blue LED.
- Three-dimensional resolution, up to 0.1 nm.
- Three-dimensional point accuracy, up to 0.05 nm.
- Data acquisition speed up to 1 million points/s.
- Texture resolution 1.3 MPX (full-colour 3D replicas).
- Working distance 0.2–0.3 m.

Three-dimensional scanning and subsequent data processing require the use of a high-performance laptop. Its basic specifications are as follows: 12-core CPU, 16 GB RAM, 4 GB VRAM and 512 GB SSD. The software used for scanning and data processing was Artec Studio 15.

In the initial scanning phase, it is necessary to select a suitable group of stones that potentially meet the requirements of shape, dimensions and inclusions. Such a group of stones should be both workable and structurally dense enough not to change shape during subsequent operations. Due to the limitations of structured light scanners in scanning transparent and light-reflecting surfaces, the surface of amber was dulled with talc to avoid any additional calculations related to the phenomenon of refraction [9,27].

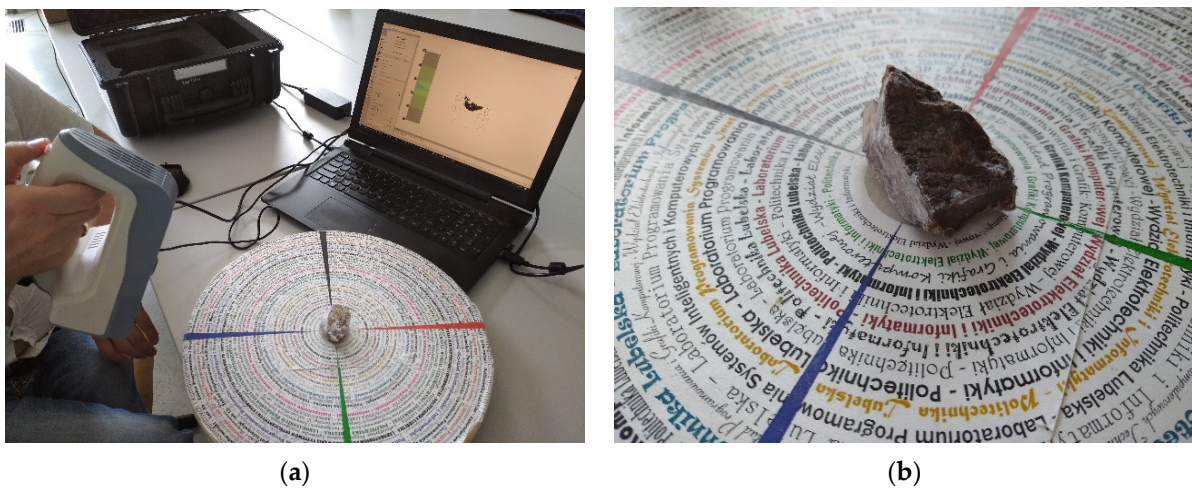


Figure 6. View of the handheld scanner scanning station: (a) general view, (b) view of amber on the rotating table.

The models were placed on a turntable, as shown in Figure 6b. The use of a turntable facilitates the complete scanning of the model from all angles. The process of scanning a single component of amber required several to a dozen individual scans, which were then assembled into a complete model during the post-processing stage. The data were collected at a rate of 30 frames per second. The scanning was conducted under natural daylight without the use of additional lamps [28].

The scanning data of object surfaces was saved in the form of a point cloud. During scanning, each scan was subjected to an initial visual assessment. Moreover, the amber was documented through photographic means, and the fundamental dimensions were measured using calipers to verify the precision of the 3D scan. Other properties of amber (Appendix A), such as density distribution, clarity and colour, fraction or weight, were omitted.

2.1. Processing Scanned Models

The data (post-)processing workflow is a multi-stage process, as depicted in Figure 7.

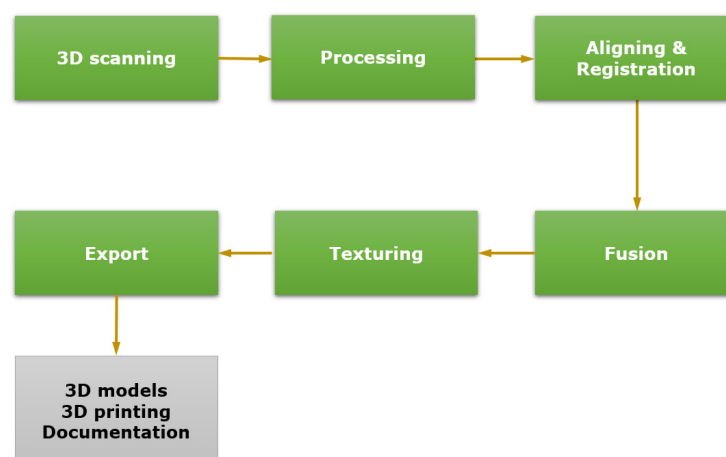


Figure 7. Stages of point cloud processing.

Scanning involved acquiring several to a dozen individual scans that collectively covered the entire surface of the scanned object. The data were imported into Artec Studio 15 software in the form of point clouds with (x, y, z) coordinates and textures.

The first stage of data processing involves aligning each scan to the coordinate system and cleaning it from artefacts, such as scanned fragments of the table, reflections and unwanted elements (Figure 8).

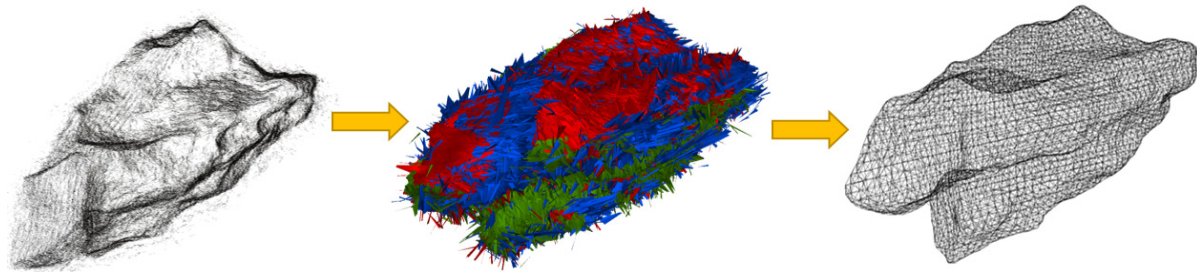


Figure 8. Post-processing steps, from the left: point cloud of an individual scan, alignment of scans, generated mesh model.

In the next stage, Aligning and Registration, involved aligning and merging individual scans to form a unified whole. Automatic alignment options can be used, but the manual selection of common points on the scans is often necessary, requiring at least three pairs of such points. Registration involves bringing the scans into a single coordinate system and optimising their alignment.

The fusion stage involves triangulating the scans after alignment. The Sharp Fusion algorithm was applied to achieve sharp edges in the model. The result was a 3D mesh model of the amber composed of triangles. In the case of missing parts in the mesh, a hole-filling procedure was performed.

For visualisation purposes, the texturing stage involved applying the captured texture to the mesh model. A texture resolution of 2048×2048 ppi was used, and brightness and contrast values of the texture display could be adjusted. The final stage was the export of 3D mesh models of the amber.

The OBJ or STL formats were used, which archived the geometry of the models, serving as their digital documentation. In the case of the STL format, it enabled 3D printing.

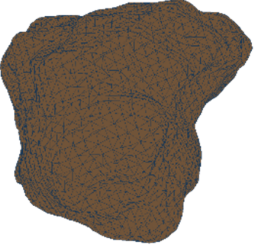

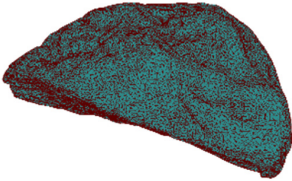

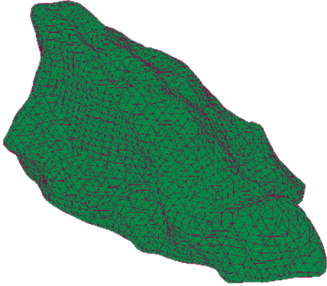

2.2. Results of the 3D Scanning Process

The 3D scanning and subsequent data processing resulted in digital 3D models of the amber specimens. Table 1 presents the outcomes in the form of mesh models and models with applied texture and their measures. Amber 2 was exceptionally difficult to scan due to the high porosity of the surface, which is why it required a larger number of scans. The scans themselves had to take longer than Amber 1 and 3. As a result, for a constant number of scans 30 fps at the same resolution, an approximately three times denser mesh was produced for Amber 2. The mesh analysis of all models showed the same representation of the surface detail of each object.

The obtained models serve as digital documentation of amber geometry, enabling the planning of amber processing while taking into account the optimal utilisation of the material, such as verifying cross-sections along defined cutting planes.

To present the optimisation process of the processing workflow, the most challenging stone among the available ones was selected—Amber 3. In the vector graphics program Rhinoceros3D, a simplified diamond-shaped model (truncated hexagonal asymmetric bipyramid) was developed for the stone-amber. This model was then copied multiple times, and each copy was scaled down according to a graduated scale. For this purpose, four scaled models were selected. The models of the jewellery were set as solid objects, while the scanned amber model was set as mesh. This allowed for spatial visualisation of the intersecting solids.

Table 1. Volume and surface area of the 3D amber models obtained in Artec Studio.

Object Name	3D Mesh Model	3D Textured Model	Model Triangles	Model Volume [mm ³]	Model Surfaces Area [mm ²]
Amber 1			10,790	13,759	4006
Amber 2			41,448	17,695	4343
Amber 3			8362	11,495	3142

The mesh of the amber model has an irregular and asymmetric shape, which makes it difficult to overlay the solids. Hence, during this process, four perspectives were employed, namely the top view, front view, right view and perspective view. Working in this arrangement allowed the processed amber model to be placed within the unprocessed amber model. Figures 9–12 illustrate the process of overlaying the spatial models of dodecahedrons and the scanned Amber 3 model.

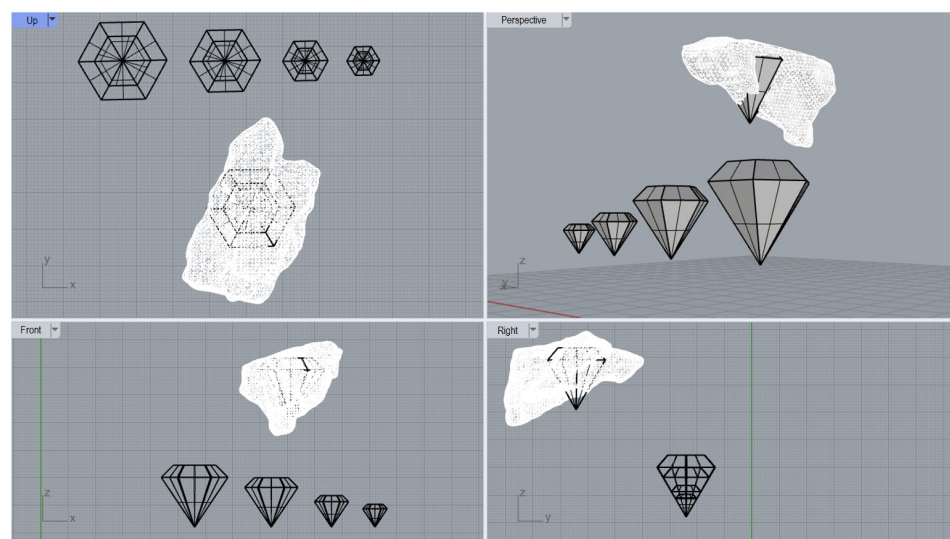


Figure 9. Spatial views in the process of aligning solids (1).

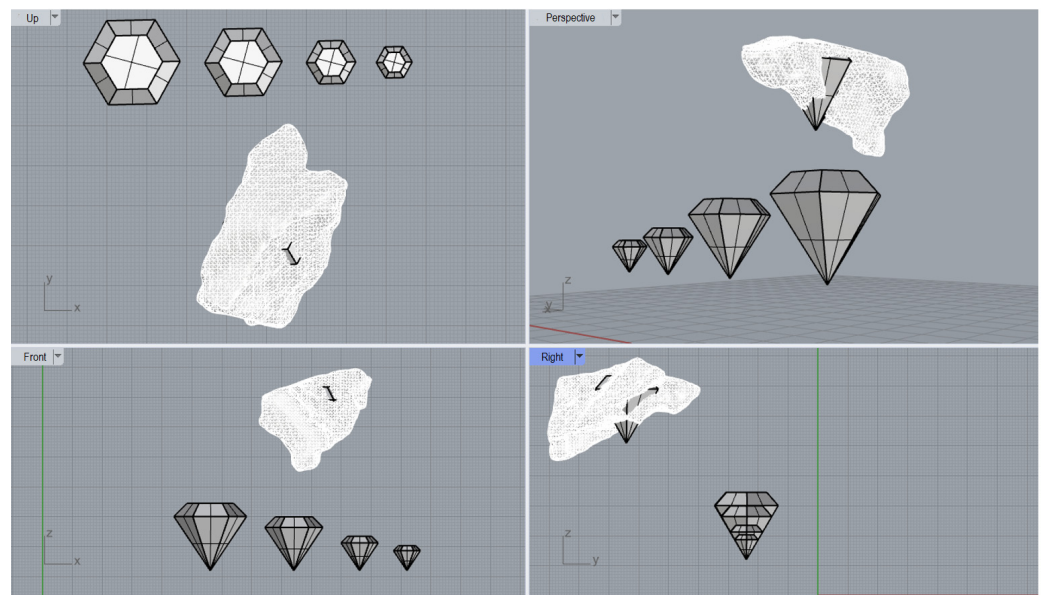


Figure 10. Spatial views in the process of aligning solids (2).

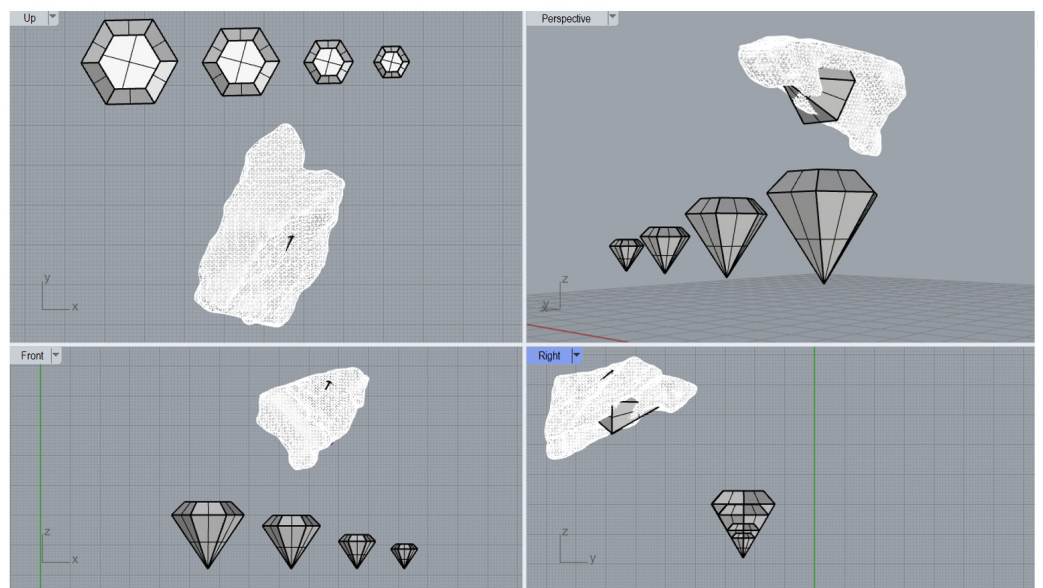


Figure 11. Spatial views in the process of aligning solids (3).

In Figure 12, the optimal position of the diamond model within the mesh of the unprocessed amber is observed. The allowances for grinding were considered during the alignment of solids, which is why the edges of the models do not touch each other directly. Based on the obtained alignments of solids, it is possible to determine how to make cuts in the stone and how to secure it in the holders of saws and grinders. The use of 3D scanning technology and vector graphics provided information for each of the stones about the material losses that could occur during processing. A computational method based on Boolean algebra was used for this purpose. By performing mathematical operations based on volume differences, a comparison of material losses was obtained—Tables 2–4. In each table, Solid No. 6 represented the most favourable alignment model of the diamond model regarding the amber stone.

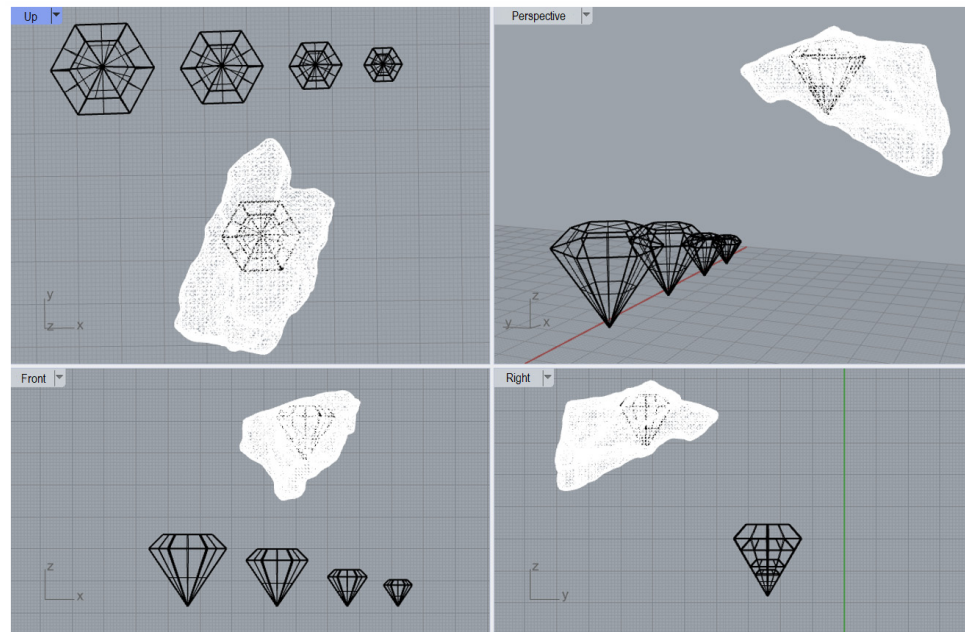


Figure 12. View of the final alignment of solids.

Table 2. Summary of results regarding material losses related to the utilisation of Amber No. 1.

Number of the Solid	Gem Model		Amber No. 1	
	Scale [%]	Volume [mm ³]	Amber Volume [mm ³]	Material Waste Obtained [mm ³]
Solid 1	100	11,984	13,759	—
Solid 2	80	9587.2		—
Solid 3	60	7190.4		6568.6
Solid 4	40	4793.6		8965.4
Solid 5	20	2396.8		11,362.2
Solid 6	75	8988		4771

Table 3. Summary of results regarding material losses related to the utilisation of Amber No. 2.

Number of the Solid	Gem Model		Amber No. 2	
	Scale [%]	Volume [mm ³]	Amber Volume [mm ³]	Material Waste Obtained [mm ³]
Solid 1	100	11,049	17,695	—
Solid 2	80	8839.2		—
Solid 3	60	6629.4		11,065.6
Solid 4	40	4420.2		13,274.8
Solid 5	20	2210.1		15,484.9
Solid 6	67	7404		10,291

Prism number 6, included in each table, represents the most favourable matching model of the dodecahedron regarding the amber stone.

This method is implemented at Golden Amber, the world’s largest supplier of amber raw materials located near Królewiec/Königsberg. The company is involved in both amber extraction and processing.

Table 4. Summary of results regarding material losses related to the utilisation of Amber No. 3.

Number of the Solid	Gem Model		Amber No. 3	
	Scale [%]	Volume [mm ³]	Amber Volume [mm ³]	Material Waste Obtained [mm ³]
Solid 1	100	2050		—
Solid 2	80	1640		9855
Solid 3	60	1230	11,495	10,265
Solid 4	40	820		10,675
Solid 5	20	410		11,085
Solid 6	86	1763		9732

3. Summary and Conclusions

This paper provides information on the utilisation of the 3D modelling process for jewellery design. It compares traditional methods used in gemstone processing and proposes innovative methods utilising 3D scanners and graphic technologies. This study demonstrates that modern jewellery design and stone processing methods significantly contribute to reducing material waste and financial losses. The capabilities of the Rhinoceros 7 software allow for the design of various prototypes with options for saving, editing, scalability and customisation, making it possible to create personalised and unique jewellery designs for each customer. Rhinoceros software enables the creation of diverse jewellery models and the direct export to an STL file format. With this software, any model can be scaled and edited, which is a time-consuming process with traditional techniques. The design capabilities provided by Rhinoceros and Artec Studio allow for the production of customised prototypes in a significantly shorter time tailored to individual customer needs. Compared to traditional jewellery design methods, creating a personalised design is much more cost-effective. The proposed solution may help to strengthen the intangible cultural heritage of amber craftsmanship by relieving craftsmen from at least some hard work so that they can devote the saved time to perfecting the final work stages.

The benefits of using modern technologies in amber processing include the following:

- The rationale behind the incorporation of amber into our research is underpinned by its status as a vital cultural heritage of Poland. Amber serves as a fundamental material for jewellery production by the collaborating companies and enjoys global recognition as a distinct Polish product. It is imperative to note that amber diverges from crystalline structures as it comprises predominantly resin, resulting in polymerisation rather than crystallisation. Within amber, inclusions can be dichotomised into the following two distinct categories: favourable inclusions, encompassing items such as insects, plant matter and water droplets, which appreciably augment the value of amber. Conversely, the second category comprises unfavourable inclusions, including sand, impurities and fractures, leading to a depreciation in the overall value of the amber specimen.
- Improved precision: the advancement of precision is facilitated by modern technologies, such as 3D scanning and modelling, which enable highly precise measurements and calculations, thereby ensuring the precise shaping and cutting of the amber material.
- Waste reduction: the 3D modelling software—Rhinoceros 7 can be utilised to optimise the placement of cutting patterns and designs on the amber, minimising material waste (both suitable for production but less profitable particles (amberoid—pressed amber) and unsuitable dust) and maximising the utilisation of the raw material.
- Time efficiency: the use of modern technologies speeds up the overall processing time. Three-dimensional scanning eliminates the need for manual measurements, while computer-aided design software enables quick adjustments and modifications to the designs [29].

- Enhanced design possibilities: advanced software programs like Rhinoceros provide a wide range of design options and allow for intricate and detailed creations. This enables the production of more complex and unique jewellery pieces using amber.
- Cost savings: Through efficient material usage and reduced processing time, the application of modern technologies can lead to cost savings in the overall production process. Additionally, the ability to create customised designs on-demand minimises inventory costs and reduces the risk of unsold stock. The largest amber processing companies are located in China and Taiwan, and they are also interested in incorporating our method into their workshops. The benefits of this method are self-evident. Reduced waste during processing results in lower material losses, and amber is sold by weight, similar to gold being sold by grams.
- Preservation of original material: the use of non-intrusive 3D scanning techniques aids in preserving the integrity of the original amber material by minimising physical handling and the risk of damage.
- Improved documentation and replication: digital models and records created through 3D scanning and modelling provide comprehensive documentation of the amber pieces. This enables the easy replication of designs and facilitates the production of consistent and identical jewellery pieces.

The next stage of research may be to consider other features, such as the density distribution, clarity or weight, of the tested object in the multi-criteria evaluation process and the financial balance in the process of minimising losses during the decomposition of the facility. Another development may be to increase the level of interaction with scanned models using mixed reality software and technologies such as X-ray [9,30].

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The characteristic features and properties of amber include the following:

- Colour—ranging from light yellow to “amber” brown.
- Transparency—transparent, translucent, opaque.
- Streak—white.
- Density—1.
- Hardness on the Mohs scale—2.0–2.5.
- Cleavage—absent.
- Melting point—287–300 °C.
- Refractive index—1.539–1.542.
- Gravity: 1.05–1.1 g/cm³

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