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Erasmus+ Programme Key Action 2 Cooperation Partnerships for Higher Education (KA220-HED)
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European Network for Additive Manufacturing in Industrial Design for Ukrainian Context

AMAZE

AMAZE e-book for developing of complex design industrial parts

Diana Băilă, Andrei Dumitrescu, Nicolae Ionescu, Bogdan Abaza, Zaharia Cătălin, Adam Patalas, Paweł Zawadzki, Remigiusz Łabudzki, Natalia Wierzbicka, Igor Fodchuk, Mariana Borcha, Yuriy Sobko, Volodymyr Romankevych, Yevheniia Novak, Nataliia Vatamaniuk, Sergio Vizcaino, Beatriz Gloria Bonilla Garcia, César Arcadio Bonilla Garcia

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MODULE 1

Additive Manufacturing

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Authors	**Andrei Dumitrescu, Nicolae Ionescu, Bogdan Abaza, Diana Băilă**

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1.1. The Importance of Industrial Design

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1.1. The Importance of Industrial Design

In this part, the term industrial design always has the meaning of product aesthetics, and the two terms will be used interchangeably.

The world market experiences a constant evolution in the economic, financial, political, social, and technological system, which puts industrial design at an advantage. This evolution is characterized by the following processes:

- generalized globalization (very few territories are not affected by the economic influence of some companies and organizations located even many thousands of kilometres away);
- fierce competition (to acquire a cutting edge, companies invest large funds in different directions, such as technological, marketing, etc.);
- accelerated technological progress (high-level technologies launched by large companies become technically and financially accessible to medium and small companies in just a few years);
- the generalization of quality systems (very few companies and organizations today "afford" not to invest in the development of an effective quality system);
- the sophistication of the public (each market segment or niche wants products precisely tailored on its needs, expectations, and desires).

The result of this market evolution is twofold:

- A company's competitors have an almost identical product on the market with the same guaranteed quality and with an approximately equal price.
- Potential customers want to be able to choose the right product quickly and easily for themselves. They can make the product choice based on brand awareness and industrial design [1].

What was presented above has shown that industrial design is important. But how important is it? Is it equally important for all product classes? A research [2] carried out taking into

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account the Locarno Classification indicated that industrial design is most important for personal and family products, because product aesthetics act as a vector for personal and family own values. In the second category of importance were the products used for professional purposes, and in the last - the products employed for hobby and smoking. These are just guidelines to estimate the importance of industrial design and every product manager and every design representative in top management should perform her/his own research to assess the importance of industrial design attributed by her/his market segments in order to know how much to invest in the development of product aesthetics.

1. *Industrial Design – Vector for Product Meaning*

It is widely assumed that industrial designers create product aesthetics according to their own will and inspiration. There would be no constraints and no objectives. This assumption is wrong, because the industrial designer has the task of attributing the product a certain meaning through its shape, colours, textures, and details. The product meaning is established by the manufacturer and is in agreement with the values, expectations and characteristics of the market segment targeted by the manufacturer. For example, a production company targets a market segment characterized by mature age, high education level and high income, and as human values – respect, tradition, and sense of accomplishment. Consumers belonging to that market segment will want that product to respect (to some extent) tradition, look appropriate for their age, and visually indicate quality and even luxury. At first sight, conferring the required meaning by means of product aesthetics seems difficult and complicated. Things are greatly simplified by the application of communication theory in industrial design.

The ***communication theory*** assumes the existence of a sender who emits a message. The message expresses a certain reality, called context. Depending on the properties of the medium through which the message is transmitted, an adequate message encoding is carried out (with the help of a transmitter) in codes capable of being transmitted through that medium to the destination's receiver [3]. The transmission of codes can be disturbed by noise,

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preventing the receiver from decoding the message to make it accessible to destination. Therefore, decoding should detect and correct possible errors. Ideally, the initial message should be identical to the one that reaches the destination. In order to achieve this, it is necessary that the decoding process should be exactly the reverse of the encoding process, and that the transmitted codes are appropriate for the medium through which the message is transmitted. All three processes (encoding, transmission, decoding) can be affected by noise from outside the environment (Figure 1).

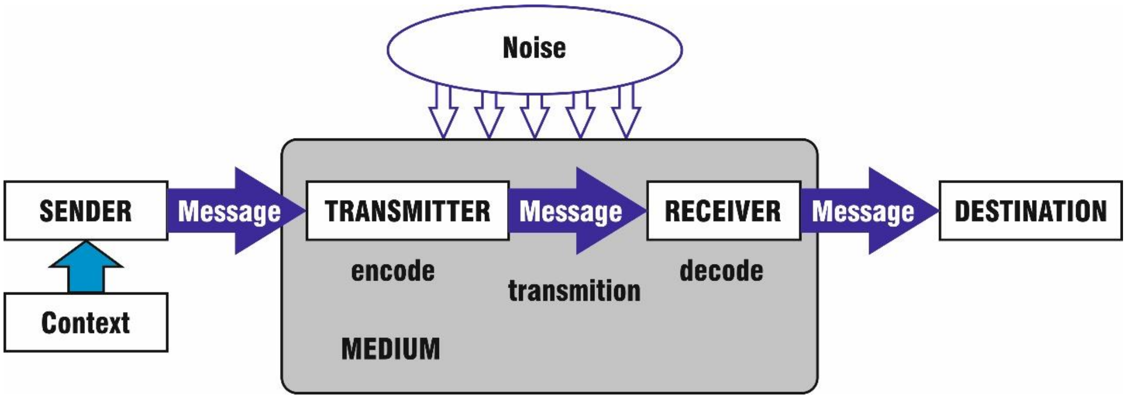

Figure 1. Communication Theory [3]

In industrial design, the communication theory is transposed as follows (Figure 2): The industrial designer formulates a message about a certain context (for example, about the values and expectations of the market segment). She/he encodes the message using the product language elements, namely the product shape, its colours, etc. The message is perceived and decoded by the human sensory organs and the areas on the cerebral cortex associated with them. Decoding and, above all, understanding the message causes the user / observer to react. Reactions can be: a) cognitive; b) affective; c) behavioural [3].

Cognitive reactions are the aesthetic impression ("How beautiful the object is"), the identification of the product's functionality and the association of a product with a certain meaning ("Is it of quality?", "Is it luxurious?", "Does it suit me?"). Affective reactions are: admiration, rejection, amusement, disgust, melancholy, etc. Mainly, there are two human

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behavioural reactions to a product: approach and avoidance. The former indicates interest and can be completed by purchasing the product. The latter represents the failure of the designer, manufacturer, and marketer to attract the interest of the potential buyer.

The process of decoding and understanding the message is influenced by "specific noises": perceptual disorders ("colour-blindness", myopia, deafness, etc.), a background similar to the dominant colour of the product and the observation time of the product (sometimes too short to notice all details).

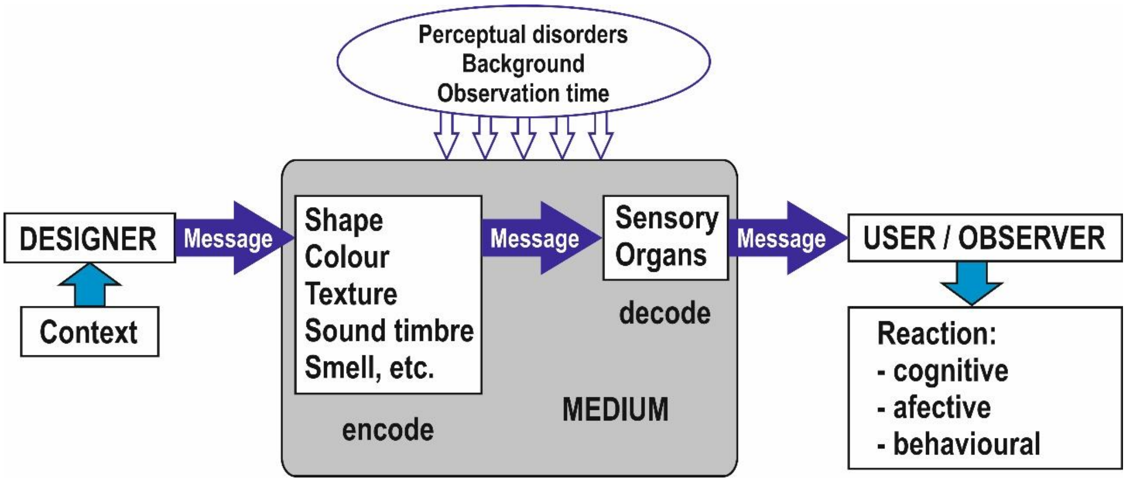

Figure 2. Communication Theory in Industrial Design Field [3]

A simplified example of the application of communication theory in industrial design field is shown in Figure 3. The designer receives an order from a manufacturer specifying that the product should look elegant but have a cheerful note. Added to this is the designer's belief that products should have a professional look. Then, the designer encodes the meaning in aesthetic elements: elegance is conferred by the colour black, cheerfulness by the orange colour, and professionalism by the prismatic appearance (straight edges and right corners).

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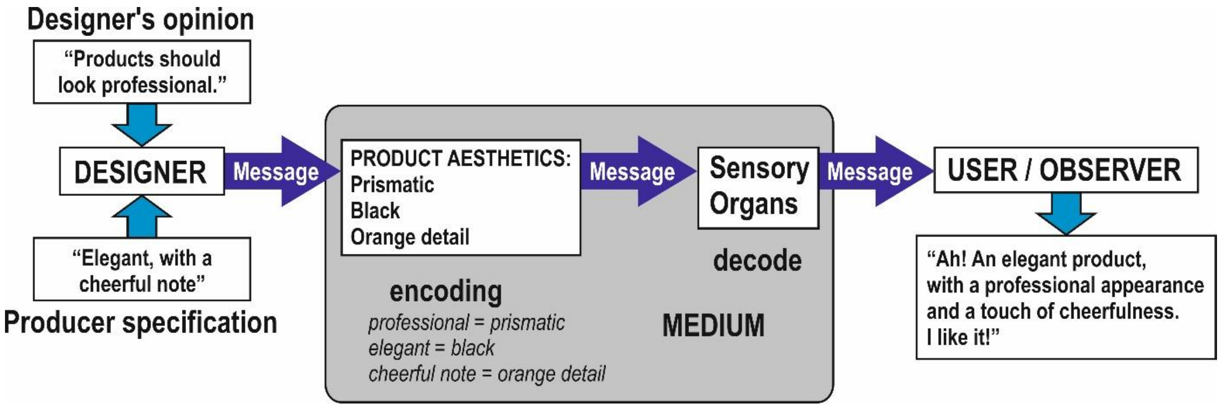

Figure 3. Communication Theory in Industrial Design (example)

2. Technological Conditioning of Industrial Design

A product (and more precisely its parts) is made of different materials using different technologies. Each material can be processed by several technologies, but not by absolutely any technology. Technologies and associated materials are chosen according to their contribution to the following goals: a) obtaining the designed shape; b) reaching the prescribed precision parameters; c) ensuring the functional parameters (resistance, hardness, etc.); d) obtaining an aesthetic in line with the values and requirements of the market segment.

As mentioned above, not all materials are processed by all technological processes. Here are some examples: Natural wood cannot be processed by electro erosion, and ordinary ceramics cannot be manufactured by cutting. Moreover, each processing method requires certain characteristics of the shape to ensure that the processing will take place efficiently. In some cases, non-compliance with these imposed requirements leads to the impossibility of processing the part using the respective process. Due to the existence of this shape-material-process correlation, technology professionals easily identify the processing method by which a part was made. The shape-material-procedure correlation has been materialized into the scientific concept of manufacturability.

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Manufacturability is the set of formal characteristics of a part, made of a specified material, which indicates the ease or difficulty of its manufacture through a certain technological process.

For example, parts made of plastic materials that are obtained by mould injection should have slightly inclined vertical walls in order to be easily removed from the mould. The value of the inclination angle varies between 30' and 3°. The inclination angle is a manufacturability characteristic.

Unlike mould injection, additive technologies have fewer manufacturability conditions imposed on the shape of the parts and allow obtaining much more varied shapes. But there are still technological limitations: the maximum size of the part depends on the plates of the 3D printer, high processing time, lower and variable strength in the part body, average dimensional accuracy, etc.

In any case, the industrial designer should document herself/himself on the manufacturability associated with the processing technology and material of the part, especially when designing for the first time with that material.

3. Industrial Design and the Human Being

There is a tendency to reduce the complex relationship between the human being and the product only to the relationship between the user and the object of her/his activity. It is obviously a wrong approach in its simplification. Considering the complexity of the relationship between human being and product, it can be appreciated that the human being can be placed in one of the following postures: creator (designer of the product at level of specifications and drawings); producer (manufacturer of the product); buyer; owner; user; and observer.

From the perspective of this work, the focus is on the buyer posture. The buyer is the person who decides, based on objective and subjective criteria, to purchase a product. The buyer purchases the product for her/his own use, to be used by others or to offer it as a gift.

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The factors that influence consumer behaviour are [4]: a) cultural; b) social (group, family, social role, and status); c) personal (age and life cycle stage, occupation, income, lifestyle, and personality); d) psychological (motivation, perception, learning, beliefs, and attitudes). But any marketing or sales specialist can easily operate with these factors, so it is not necessary to focus on these details.

Considering product aesthetics, a complex characteristic that combines a person's interest and competence in industrial design field becomes important. This complex feature was introduced by Bloch et al. [5], who named it Centrality of Visual Product Aesthetics (CVPA), and which indicates "the level of significance that visual aesthetics hold for a particular consumer in her/his relationship with products". By applying this concept and the associated methodology, one can identify people with high level of CVPA and those with low level of CVPA. Obviously, people with high CVPA are the ones who are interested in purchasing a product with a remarkable design (high level of product aesthetics). Apart from the fact that these people have an innate inclination for beautiful objects, they have also acquired (formally, but especially informally) considerable knowledge in product aesthetics [6].

It thus becomes important for the industrial designer and product manager to determine the CVPA level for the market segment they target. Centrality of Visual Product Aesthetics (CVPA) can be estimated with the help of the following construct [6], using Likert scales:

Aesthetic Pleasure and Loyalty

I enjoy seeing displays of products that have superior designs.

A product design is a source of pleasure for me.

I am proud of my product brands.

Response

Sometimes the way a product looks seems to reach out and grab me.

When I see a product that has a really great design, I feel a strong urge to buy it.

I like to think that the products that belong to me express my identity.

I love products that have the same personality as mine.

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Acumen

Being able to see subtle differences in product designs is one skill that I have developed over time.

I see things in a product design that other people tend to pass over.

I have the ability to imagine how a product will fit in with designs of other things I already own.

Product Involvement

I like to find out how a certain product is made.

I like to make detailed comparisons between products of the same kind.

I read carefully the articles written by experts about the products that interest me.

Price Indifference

I am not interested in the products that have the lowest price in their category.

The low price of a product probably hides major quality deficiencies.

4. *Design Methods for Product Aesthetics*

Conceiving the product aesthetics must always start from the needs and desires of the consumer and more precisely from the needs and desires of the market segment targeted through the launch of the new product.

Necessity (need) is the humans' and other living beings' state determined by the lack of an object, phenomenon or relationships indispensable for survival, fulfilment of social functions, or achievement of a satisfaction state.

Desire is the state of mind of an individual who tends to possess a certain object or to have a certain relationship with other beings.

As mentioned in the definition, necessity is associated with the "functioning" of man as a biological being and as a social being. Desire is related to the imaginary self-projection of man in an ideal situation. Human desires are generated by culture, advertising, and the perceived image of oneself.

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Designing the product aesthetics is an integral part of the product design process and starts from the very conceptual design stage. A quality product cannot be made, if the aesthetics design is not carried out simultaneously and in correlation with the design of the other aspects of the product: mechanical, electrical, electronic, etc.

Designing product aesthetics does not mean the application of a single method and above all it does not mean the rigid performance of stages and phases “by numbers”. Designing product aesthetics is not at all like designing a gearbox.

Another aspect that differentiates the design of product aesthetics from the technical design is the relationship with innovation. If the maximum use of innovation is aimed at in technical design, in the design of product aesthetics innovation should be introduced sparingly, because the public is quite conservative and needs to discover familiar visual elements to which it can relate. Thus appeared the recommendation expressed suggestively by the famous designer Raymond Loewy [7]: "Most advanced, yet acceptable" [by market].

It can be considered that the methods and techniques used in the complex process of generating product aesthetics fall into four broad categories:

- documentation methods;
- creativity methods;
- auxiliary design methods;
- actual design methods.

4.1. Documentation Methods

The industrial designer (individual or within the design team) receives a set of information to guide her/him in the process of designing the product aesthetics. This set of information has various names in specialized literature or within companies: brief, theme-programme, etc. Starting from the information included in the initial set (which is always incomplete), the industrial designer must document herself/himself in order to create a complete information system based on which to design the product aesthetics.

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In order to perform the documentation phase, the designer has at her/his disposal a series of methods and techniques:

- competition analysis (using tables or multidimensional scaling);
- historical research;
- questionnaire;
- interview;
- focus group;
- observing the product in use;
- empathy diagram;
- sentence completion test.

Among the methods and techniques listed above, historical research is quite important for product aesthetics.

The ***historical research*** is carried out (in the minimal case) by making a small catalogue with significant products of the respective class, chronologically ordered. To deepen the research, information about the material, technology, etc. can be added to the product images. There can also be highlighted the products with great success on the market, as well as those which, although innovative from a technological or aesthetic perspective, were more or less significant failures.

Historical research helps the industrial designer to better understand the product and its aesthetic aspects. Historical research can indicate, when carried out thoroughly, the general direction of evolution of the respective class of products. The method can be a basis for understanding the philosophies, cultural implications, and emotional qualities of previous products.

The results of the historical research represent material for discussion between the industrial designer and colleagues or between the industrial designer and the other members of the design team. Later, these results can constitute a reference point in the concept evaluation.

If the targeted market segment possesses knowledge of aesthetics (high level of CVPA), the industrial designer can play with the historical formal elements to give the observers the intellectual satisfaction of discovering them.

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4.2. *Creativity Methods*

Creativity methods have been in the attention of specialists and general public since at least the middle of the last century. Creativity methods were invented by many researchers, and the ones that became classic were derived in several variants. Since the vast majority of professionals have applied a creativity method at least once, it is recommended that everyone should apply the method she/he is used to and only when the method proves ineffective, she/he should try another one.

Here is a short list of creativity methods:

- brainstorming;
- synectics;
- six thinking hats;
- lateral thinking process.

Since a very large number of ideas are generated following the application of a creativity method, it is recommended that new ideas should be classified in the following categories:

- useful ideas, directly applicable;
- useful ideas, but not for the organization;
- useful ideas, but not for that moment;
- ideas that still need to be processed;
- interesting, but impractical ideas;
- worthless ideas;
- impossible ideas.

4.3. *Auxiliary Design Methods*

Auxiliary design methods do not allow obtaining any directly applicable result in the design process, but they considerably facilitate this process. These methods and techniques allow the deepening of knowledge about the product, aesthetics, typical consumer, etc. and stimulates the industrial designer's imagination.

Auxiliary design methods and techniques that can be used by industrial designers are:

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- character profiling;
- scenario method;
- mind map;
- 9 windows technique;
- cultural matrix;
- mood board.

A representative technique for auxiliary design methods is the ***Mood Board***. A Mood Board is basically a cardboard on which are pasted images that visually incorporate the idea or the concept of a product, service, or corporate identity. Mood Board is a collage of visual elements that involve a good mood for the creator or the person who benefits from the result of the design process. The Mood Board does not have a standardized format. A model to follow in creating a Mood Board is presented in the Figure 4.

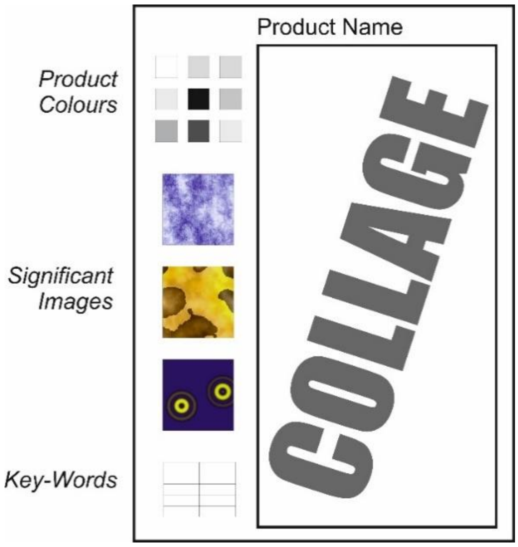

Figure 4. Mood Board (model) [3]

Pasted images can be:

- actual images of favourite products, beloved beings, treasured places, etc.;
- colour samples;
- words (word, font, font size, colour);

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- two-dimensional fragments of packaging (wrapping paper, fragments of plastic or paper bags, etc.);
- (roughly) two-dimensional fragments of objects.

Image sources are:

- magazines;
- books;
- catalogues;
- digital images.

Of course, the Mood Board can also be created in a digital version, but it is not as effective, because the three-dimensionality, the shine, and the different texture of the different materials, etc. are lost.

4.4. Actual Design Methods

In popular culture, designing product aesthetics means a sublime moment of inspiration enjoyed by the talented designer. Perhaps such an approach can give acceptable results in the case of very simple products, with a minimal shape and consisting of a single piece. In the case of complex products, such an approach has no chance of success.

Based on the information contained in the specialized literature, a methodology can be sketched that, at the same time, presents a high degree of generality and covers the entire design process. Such a methodology for designing the product aesthetics would include the following steps:

- defining and clarifying the design problem;
- identification of consumer needs;
- identifying the technical, economic, and ergonomic functions of the product;
- identifying the other functions of the product;
- evaluation of functional, technological, and economic constraints;
- information and documentation;
- incubation of solutions;
- applying creativity methods;
- generation of multiple new solutions to the design problem;

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- selecting the optimal solution;
- developing and detailing the optimal solution;
- testing the optimal solution;
- production of physical models or prototypes;
- testing physical models or prototypes;
- improving the solution.

It should be emphasized that no specific design method covers the above sketched methodology in its entirety. During the product design and development process, several methods and techniques from different areas should be applied (documentation, creativity, actual design, etc.).

To design the product aesthetics, one or more of the methods and techniques included in the following list can be applied:

- Morphological Chart;
- Shape Grammar;
- Designing Product Semantics;
- Product Metaphor Generation;
- Design for Experience;
- Design for Emotion;
- Designing Product Personality;
- Kansei Design;
- Design Thinking;
- Participatory Design (Co-Design);
- Designing for Behaviour Change.

Designing Product Semantics [8] is an example of a method that can be successfully applied to the design of product aesthetics, taking into account the communication theory in design. The phases of the methodology are described below:

- establishment of the objectives and general restrictions related to product;
- identification of the product context of use;
- generation of a list of attributes required to be associated with the product to fulfil the semantic objective;

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- generation of a list of attributes to be avoided;
- analysis, grouping and ranking of attributes;
- search for concrete solutions that materialize the considered attributes;
- assessment, selection, and semantic integration of feasible solutions;
- assessment of the selected solutions from the point of view of technical-economic restrictions.

Establishment of the objectives and general restrictions related to product consists in determining the semantic character that should be communicated to the market segment to which the product is intended. The semantic character can be indicated by a single word or, preferably, by a complete description. Examples of such words are: elegance, high technology, contemporary, traditional, futuristic, etc.

As part of identification of the product context of use, the following aspects are recorded and analysed: a) the opinions of users and buyers (if the buyer is not the product user); b) trends manifested in the field and c) progress in neighbouring fields.

Next it is the generation of a list of attributes required to be associated with the product in order to fulfil the semantic objective. The use of adjectives is recommended. Here are some examples of desirable attributes for a truck cab: mechanical, full of energy, controlled force, reliable, etc. It should be paid attention to the fact that the attributes refer to the way the product looks and not to the way it works.

Generation of a list of attributes to be avoided prevents the designer from deviating from her/his goal. Logically, avoidable attributes are antagonistic to desirable attributes. It is recommended that avoidable attributes pair with desirable ones. It is exemplified by the expressions: “full of energy, but not brutal” and “sophisticated, but not complex”. The avoidable attributes can also result from the semantic history of the product and from the market analysis.

Sometimes the attributes are too numerous, and their operation becomes difficult. That is why attributes are grouped into families. Thus, for example, “repetitive, interconnected, integrated and interchangeable” are grouped under the name “modulated”. The ranking aims

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to order the attributes according to their contribution to the fulfilment of the semantic objective.

Afterwards, concrete solutions will be sought to materialize the considered attributes. The solutions will be expressed in terms of shape, colour, texture and material. For example, let us consider that the desirable attributes are strong and precise, and those to be avoided are brutal and imprecise. A prismatic shape is recommended, but not with sharp edges. The colours can be black, dark neutral greys or dark metallic shades. The texture will be smooth, even mirror. The material will be metallic.

As a result of the previous stage, it resulted a set of solutions that conform to the attributes. It is time to assess, select and semantically integrate the generated solutions according to the semantic objective and the context of use.

A new assessment phase follows, in which the criteria are the technical-economic restrictions. The solutions that can present an extremely interesting semantic content, but which cannot be applied due to the low technology of the form or because of the too high production costs, will be eliminated.

5. Assessment Methods for Product Aesthetics

Assessment means to establish the value in a systematic manner, based on objective and clear criteria. Usually, the assessment of product aesthetics means the appraisal of the product appearance against a certain list of criteria. Several issues can occur:

- Evaluators are not motivated in performing a correct evaluation.
- Evaluators are reluctant to honestly express their opinion, believing that they will be assessed based on what they express.
- (often) Likert scales are used, and numbers stimulate the left hemisphere of the brain.
- The wrong designation of a positive or negative character for the attributes associated with certain criteria.
- The list of criteria is not well chosen (includes unclear or irrelevant criteria).

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The assessment performed by design critics is welcome for magazine articles and blogs or for award juries. However, if the assessment is made by the manufacturing company to improve the appearance of its own products, it is recommended to involve representatives of the market segment, because they know what they want and, in the end, they will purchase the company's products.

Often, non-professional evaluators are impressed by the organization and environment created for the assessment and censor their opinions, unjustifiably believing that they are in danger of being laughed at if they express some of their opinions honestly. This situation is avoided by using projective methods in which evaluators express the assessment of fictional characters in relation to the product aesthetics.

It is known that product aesthetics is the field of the right hemisphere of the human brain - the artistic hemisphere. But by assigning grades (numbers), the left hemisphere is activated, the one that cannot correctly evaluate product aesthetics. That is why it is recommended to use attributes and not numbers.

There are absolutely no positive and absolutely no negative aesthetic attributes. For example, a product is appraised using proportion criterion, with the indication that "proportionate" means a ratio close to the golden section (1.618). If a static product has a ratio of, say, 2.5 (disproportioned) with a large horizontal dimension, this does not mean that "disproportioned" is a negative attribute. Therefore, it is recommended that the attributes be set as positive or negative depending on their contribution to the fulfilment of the product purpose and to the materialisation of the values of the considered market segment.

Wishing to be outstanding, certain authors in the product aesthetics field launch new assessment criteria. An example of such a criterion is “tectonics”. Let us imagine that somebody is assessing the tectonics of a car... It is obvious that this criterion is unclear. The specialized literature includes numerous criteria systems. Without being the only effective system of criteria, it can be used the following system, which resulted from a research carried out with the involvement of consumers [9]:

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- functionality;
- ergonomics;
- harmony;
- balance;
- proportion;
- compactness;
- elegance;
- complexity;
- neatness;
- novelty ratio;
- originality;
- distinctiveness.

6. *Conclusions*

The product aesthetics has lately become important following the evolution of the global market. Industrial design is used, along with the brand, by consumers to make the purchase decision. Product aesthetics is not equally important for all product classes, and the product manager should determine the importance of industrial design for her/his product to know how much to invest in product aesthetics.

Since assigning a meaning to the product is a difficult process, communication theory is applied in product aesthetics. The product becomes the medium of communication, and the aesthetic elements (shapes, colours, textures, smells, etc.) are the codes that carry the message from the industrial designer and manufacturing company to the user and observer.

Technology is conditioning product aesthetics by the fact that each material can only be processed through a limited number of technological processes, and each process has a series of constraints that limit the industrial designer in her/his activity.

In relation to industrial design, man can be placed in different postures. The posture of the consumer is important to study because each market segment has its own characteristics,

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including interest and competence in industrial design (Centrality of Visual Product Aesthetics).

Conceiving the product aesthetics is a complex process which requires the application of different design methods from different fields (documentation, creativity, support and actual design).

Assessing product aesthetics should be carried out in a systematic manner using objective and clear criteria. There should be avoided issues related to evaluators' motivation and self-censorship, excessive use of numbers, preconceptions regarding what is a positive/negative attribute and quality of applied criteria.

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1.2. Additive Manufacturing - Fabrication

Contents

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1.2. Additive Manufacturing – Fabrication

1.2.1.The principle of Additive Manufacturing technologies

A variety of processes, equipment, and materials are used in the production of a three-dimensional object via additive manufacturing. 3D printing is also known as additive manufacturing, because the numerous available 3D printing process tend to be additive in nature, with a few key differences in the technologies and the materials used in this process.

Some of the different types of physical transformations which are used in 3D printing include melt extrusion, light polymerization, continuous liquid interface production and sintering.

Additive Manufacturing technologies of prototypes (Additive Manufacturing - AM) differ fundamentally from material removal processing technologies (chipping, electroerosion, laser processing) and material redistribution processing technologies (casting, injection, forging, molding), because the parts are obtained by adding as much material as and where needed. [1] These technologies emerged as a result of achievements and advances made in fine mechanics, numerical control, laser technology, computers, computer programs, and grace of new innovative materials. [1-124]

These new manufacturing technologies have started to grow in importance, as well as other products for manufacturers, reducing the time from conception to market, and the costs for assimilating and manufacturing new ones. The specificity of these additive manufacturing processes is their ability to make complex three-dimensional parts and objects, starting from a CAD file, without the need for the use of machine tools or certain devices. [1] The basic element of additive prototyping technologies is the "section". Parts are quantified into sections and made using a repetitive, section-by-section construction process, reducing a three-dimensional problem to a plan. This dimensional reduction leads to a decrease in the precision and quality of the surfaces of scale effects. Making a part using AM technology requires the following steps:

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-realization of the three-dimensional (3D) model of the part, using a computer-aided design (CAD) program;
-transferring the CAD model to the sectioning processor. The most well-known method of sectioning is the approximation of the model with planar triangular elements.
-sectioning the 3D virtual model with planes parallel to the working plane of the rapid prototyping machine and generating orders for the machine's control equipment;
-the actual construction of the part (material, the way to use the material, the supports needed during the construction of the model, the gluing to the previous layer, how a new layer will be added, the marking of the contours for each section, the marking of the area between the outer and inner contour of of a section;
-cleaning and finishing the part (operations in which the supports used in the construction and the excess material are removed).
Additive Manufacturing processes were initially used for the production of prototypes, i.e. in the case of small, unique series production. Soon, however, these Additive Manufacturing processes will directly produce functional parts with high precision and very short manufacturing time, whether metal or from other materials, successfully replacing conventional manufacturing technologies that use expensive machine tools. [1,2] Looking at CAD solid modeling, Additive Manufacturing systems are becoming an important motivating factor for companies that produce solid modeling systems, such as Unigraphics, I-DEAS, Catia, AutoCAD, Pro/Engineer, etc. The models obtained through Additive Manufacturing optimize the design of a new model or the modernization of an existing one, these models allow the physical visualization of the product and improve the communication between the manufacturer and the beneficiary. The models manufactured by these new technologies can be used for various testing modes, of which the most implemented are:
- functional tests;

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- simulation tests;
- control tests;
- manufacturing tests;
- fixing and assembly tests;
- packaging tests.

Testing a product manufactured by Additive Manufacturing technologies depends on three factors material, size and design. The tests carried out must lead to a visual acceptance, an understanding of the construction, the functionality of the product and the finalization of the dimensioning elements. Additive Manufacturing technologies have and will have an important role in many industrial fields, from the field of manufacturing to medicine, aerospace, architecture, automotive, electronics, tooling thus giving the technology a strategic importance for the companies that use these technologies. [1]

Laser Additive Manufacturing is a set of innovative, state-of-the-art technologies that have developed explosively in the last two decades. ALM technologies have begun to be used on an increasingly large scale in industry, especially aerospace, automotive and mold making, respectively in the medical field. Laser Additive Manufacturing technologies provide designers with physical replicas of virtual models built in CAD systems. Almost all CAD systems can produce very faithful images of an object, but a physical model will provide more information about the same object (eg design errors) and is easier to understand. The chapter book presented Laser Additive Manufacturing technologies, specific manufacturing equipment and parameters of ALM manufacturing regimes. The development of SLS, DMLS, SLM, EBM, Laser Design/DMD technologies have made and are making possible customized implants from various biocompatible materials.

1.2.2. Types of Additive Manufacturing technologies

Construction of a model with contemporary methods can take anywhere from several hours to several days, depending on the method used and the size and complexity of the

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model. Additive systems can typically reduce this time to a few hours, although it varies widely depending on the type of machine used and the size and number of models being produced simultaneously.

Finishing

Though the printer-produced resolution and surface finish are sufficient for some applications, post-processing and finishing methods allow for benefits such as greater dimensional accuracy, smoother surfaces, and other modifications such as coloration.

The surface finish of a 3D printed part can improved using subtractive methods such as sanding and bead blasting. When smoothing parts that require dimensional accuracy, it is important to take into account the volume of the material being removed.

Some printable polymers, such as acrylonitrile butadiene styrene (ABS), allow the surface finish to be smoothed and improved using chemical vapor processes based on acetone or similar solvents.

Some additive manufacturing techniques can benefit from annealing as a post-processing step. Annealing a 3D-printed part allows for better internal layer bonding due to recrystallization of the part. It allows for an increase in mechanical properties, some of which are fracture toughness, flexural strength, impact resistance, and heat resistance. Annealing a component may not be suitable for applications where dimensional accuracy is required, as it can introduce warpage or shrinkage due to heating and cooling.

Additive or subtractive hybrid manufacturing (ASHM) is a method that involves producing a 3D printed part and using machining (subtractive manufacturing) to remove material. Machining operations can be completed after each layer, or after the entire 3D print has been completed depending on the application requirements. These hybrid methods allow for 3D-printed parts to achieve better surface finishes and dimensional accuracy.

The layered structure of traditional additive manufacturing processes leads to a stair-stepping effect on part-surfaces that are curved or tilted with respect to the building platform. The effect strongly depends on the layer height used, as well as the orientation of a part

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surface inside the building process. This effect can be minimized using "variable layer heights" or "adaptive layer heights". These methods decrease the layer height in places where higher quality is needed.

Painting a 3D-printed part offers a range of finishes and appearances that may not be achievable through most 3D printing techniques. The process typically involves several steps, such as surface preparation, priming, and painting. These steps help prepare the surface of the part and ensuring the paint adheres properly.

Some additive manufacturing techniques are capable of using multiple materials simultaneously. These techniques are able to print in multiple colors and color combinations simultaneously and can produce parts that may not necessarily require painting.

Some printing techniques require internal supports to be built to support overhanging features during construction. These supports must be mechanically removed or dissolved if using a water-soluble support material such as PVA after completing a print.

Some commercial metal 3D printers involve cutting the metal component off the metal substrate after deposition. A new process for the GMAW 3D printing allows for substrate surface modifications to remove aluminium or steel.

A variety of processes, equipment, and materials are used in the production of a three-dimensional object via additive manufacturing. 3D printing is also known as additive manufacturing, because the numerous available 3D printing process tend to be additive in nature, with a few key differences in the technologies and the materials used in this process. Some of the different types of physical transformations which are used in 3D printing include melt extrusion, light polymerization, continuous liquid interface production and sintering.

The standard ISO/ASTM52900-15 defines seven categories of additive manufacturing (AM) processes within its meaning. They are:

- Vat photopolymerization;
- Material jetting;
- Binder jetting;

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- Powder bed fusion;
- Material extrusion;
- Directed energy deposition;
- Sheet lamination.

The main differences between processes are in the way layers are deposited to create parts and in the materials that are used. Each method has its own advantages and drawbacks, which is why some companies offer a choice of powder and polymer for the material used to build the object. Others sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype. The main considerations in choosing a machine are generally speed, costs of the 3D printer, of the printed prototype, choice and cost of the materials, and color capabilities. Printers that work directly with metals are generally expensive. However, less expensive printers can be used to make a mold, which is then used to make metal parts.

1.2.3. Processes and printers

The variety of processes and equipment allows for numerous uses by amateurs and professionals alike. Some lend themselves better toward industry use (in this case the term Additive Manufacturing is preferred) whereas others make 3D printing accessible to the average consumer. Some printers are large enough to fabricate buildings whilst others tend to micro and nanoscale sized objects and in general many different technologies can be exploited to physically produce the designed objects.

Several 3D printing processes have been invented since the late 1970s. The printers were originally large, expensive, and highly limited in what they could produce.

A large number of additive processes are now available. The main differences between processes are in the way layers are deposited to create parts and in the materials that are used. Some methods melt or soften the material to produce the layers, for example. selective laser melting (SLM) or direct metal laser sintering (DMLS), selective laser sintering (SLS), fused

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deposition modeling (FDM), or fused filament fabrication (FFF), while others cure liquid materials using different sophisticated technologies, such as stereolithography (SLA).

Table 1. Additive Manufacturing technologies and materials

Type	Technologies	Materials
Material jetting	**Drop-on-demand or continuous (single- or multi-nozzle) particle deposition**	**Hot-melt materials (wax, thermoplastic, metal alloy),** dispersed materials (technical ceramics, metals, polymers)
Material extrusion	**Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) and fused pellet fabrication or fused particle fabrication**	**Thermoplastics, eutectic metals, edible materials, rubbers, modelung clay, plasticine**
	Robocasting or MIG wlding 3D printing or Direct Ink Writing (DIW) or extrusion based additive manufacturing of metals (EAM) and ceramics (EAC)	**Metal-binder mixtures such as metal clay, ceramic-binder mixtures (including ceramic clay and ceramic slurries), cermet, metal matrix composite, ceramic matrix composite, metal (MIG welding)**
	Additive Friction Stir Deposition (AFSD)	**Metal alloys**
	Composite Filament Fabrication (CFF)	**Nylon or nylon reinforced with carbon, Kevlar or glass fibers**
Light polymerized	**Stereolithography (SLA)**	**Photopolymer (including preceramic polymers)**
	Digital Light Processing (DLP)	**Photopolymer**
	Continuous liquid interface production (CLIP)	**Photopolymer + thermally activated chemistry**
Powder Bed	**Powder bed and inkjet head 3D printing (3DP)**	**Almost any metal alloy, powdered polymers, paster**
	Electron Beam Melting (EBM)	**Almost any metal alloy including titanium alloys**
	Selective Laser Melting (SLM)	**Titanium alloys, Co-Cr alloys, Stainless steels, aluminium**
	Selective Laser Sintering (SLS)	**Thermoplastics, metal powders, ceramic powders**
	Selective Heat Sintering (SHS)	**Thermoplastic powders**
	Direct Metal Laser Sintering (DMLS)	**Metal alloys**
Laminated	**Laminated object manufacturing (LOM)**	**Paper, metal foil, plastic film**
	Stratoconception	
Powder fed	**Laser Metal Deposition (LMD) or Directed Energy Deposition (DED)**	**Metal alloys**
	Extreme High-speed Laser Cladding (EHLA)	**Metal alloys**
Wire	**Electron Beam Freeform Fabrication (EBF3)**	**Metal alloys**
	Wire-arc additive manufacturing (WAAM)	**Metal alloys**
Freezing	**Rapid Freeze Prototyping (RFP)**	**Water**
3D Bioprinting	**3D Bioprinting**	**STEM cells, biopolimers**

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In case of Laminated Object Manufacturing (LOM), thin layers are cut to shape and joined (e.g., paper, polymer, metal). Particle deposition using inkjet technology prints layers of material in the form of individual drops. Each drop of solid ink from hot-melt material actually prints one particle or one object. Color hot-melt inks print individual drops of CMYK on top of each other to produce a single color object with 1-3 layers melted together. Complex 3D models are printed with many overlapping drops fused together into layers as defined by the sliced CAD file. Inkjet technology allows 3D models to be solid or open cell structures as defined by the 3D printer inkjet print configuration. Each method has its own advantages and drawbacks, which is why some companies offer a choice of powder and polymer for the material used to build the object. Others sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype. The main considerations in choosing a machine are generally speed, costs of the 3D printer, of the printed prototype, choice and cost of the materials, and color capabilities.

Printers that work directly with metals are generally expensive. However less expensive printers can be used to make a mold, which is then used to make metal parts.

1.2.4. Fused Deposition Modeling (FDM)

FDM (Fused Deposition Modeling), in translation Thermoplastic Extrusion Modeling was patented by Stratasys Inc in 1993. [1,18]

Thermoplastic extrusion/melt deposition modeling is the most used additive manufacturing technology due to its simplicity and affordability. It is used in modeling, prototyping but also in production applications. Other names used are:

MEM (Melting Extrusion Modeling), TPE (Thermoplastic Extrusion), FFF (Fused Filament Fabrication).

In this process, the material is applied in small droplets through a diameter nozzle

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small, similar to how a common 2D inkjet printer works, but is layered on a platform to build a 3D object and follows processing through photopolymer solidification using UV rays. [1,18]
The FDM manufacturing process uses two materials: model material and support material. The three-dimensional geometric model in .stl format is taken in the QuickSlice program and processed to obtain the machine control program (SML-Stratasys Modeling Language command file). Principle scheme of the FDM process is shown in figure 1.

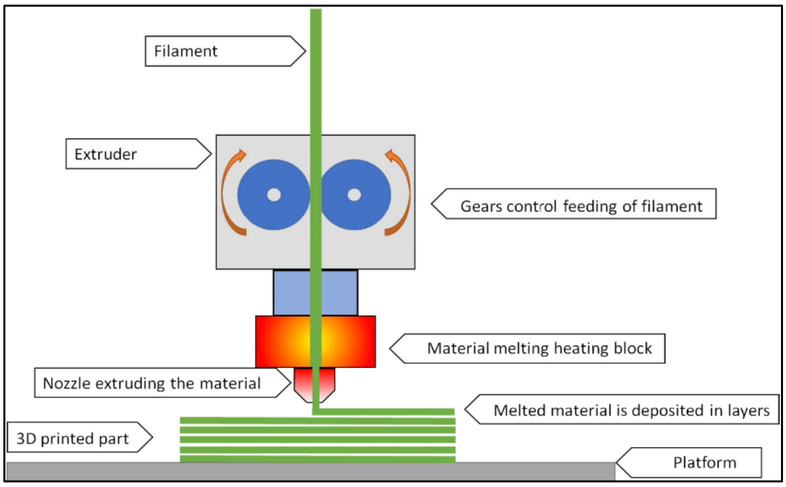

Fig.1. Fused Deposition Modeling (FDM) principle [19]

The Magna Drive manufacturing system has two deposition heads (one for support material, other for part material) that can move independently and has a high-performance system of order to move the deposition heads. This system is very reliable, fast and accurate.
Filament is fed from a large spool through a moving, heated printer extruder head, and is deposited on the growing work. The print head is moved under computer control to define the printed shape. Usually the head moves in two dimensions to deposit one horizontal plane, or layer, at a time; the work or the print head is then moved vertically by a small amount to begin a new layer. The speed of the extruder head may also be controlled to stop and start

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deposition and form an interrupted plane without stringing or dribbling between sections. "Fused filament fabrication" was coined by the members of the RepRap project to give an acronym (FFF) that would be legally unconstrained in its use.

Fig.2. Assembly of parts obtained by the FDM process [20]

Fused filament printing is now the most popular process (by number of machines) for hobbyist-grade 3D printing. Other techniques such as photopolymerisation and powder sintering may offer better results, but they are much more costly. The 3D printer head or 3D printer extruder is a part in material extrusion additive manufacturing responsible for raw material melting or softening and forming it into a continuous profile. A wide variety of filament materials are extruded, including thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), high-impact polystyrene (HIPS), thermoplastic polyurethane (TPU) and aliphatic polyamides (nylon).The advantages of FDM technology consist of very office-

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friendly technology, quiet and safe. Usable objects and parts can be produced, the palette of materials being quite wide. The price of 3D printers (kits and assembled models) as well as consumables (rolls with plastic filaments) is extremely affordable. [1,18,19] The disadvantages of this process are the slow construction speed in the complex geometries case, the possibility of non-uniformly printed areas (layers unglued), low impermeability, poor resolution and accuracy for small parts and details fine (microns). Disadvantages for kits and 3D printers is the long assembly and calibration time (kits), print quality is variable, high scrap rate (in the beginning), very fast small construction for complex parts, parts limited in size due to deformations in printing, unevenly printed areas (unglued layers). The processing precision is of the order of tens of millimeters and is influenced by the precision of the .stl model and the choice of technological processing parameters. [1,18,19] Applications of the FDM process consist in the production of parts and subassemblies, resistant for functional testing, conceptual design as in fig.2, presentation of models and marketing, detail parts for industrial or medical applications, subassemblies from plastic for high temperature applications, very small series productions. Casting forms, matrix prototyping (structural skeletons) can be made for tissue engineering medical applications, rapid prototyping of small parts and tools size.

1.2.5. Laminated object manufacturing (LOM)

Laminated object manufacturing (LOM) is a rapid prototyping system developed by Helisys Inc. (Cubic Technologies is now the successor organization of Helisys) In it, layers of adhesive-coated paper, plastic, or metal laminates are successively glued together and cut to shape with a knife or laser cutter. Objects printed with this technique may be additionally modified by machining or drilling after printing. Typical layer resolution for this process is defined by the material feedstock and usually ranges in thickness from one to a few sheets of copy paper.

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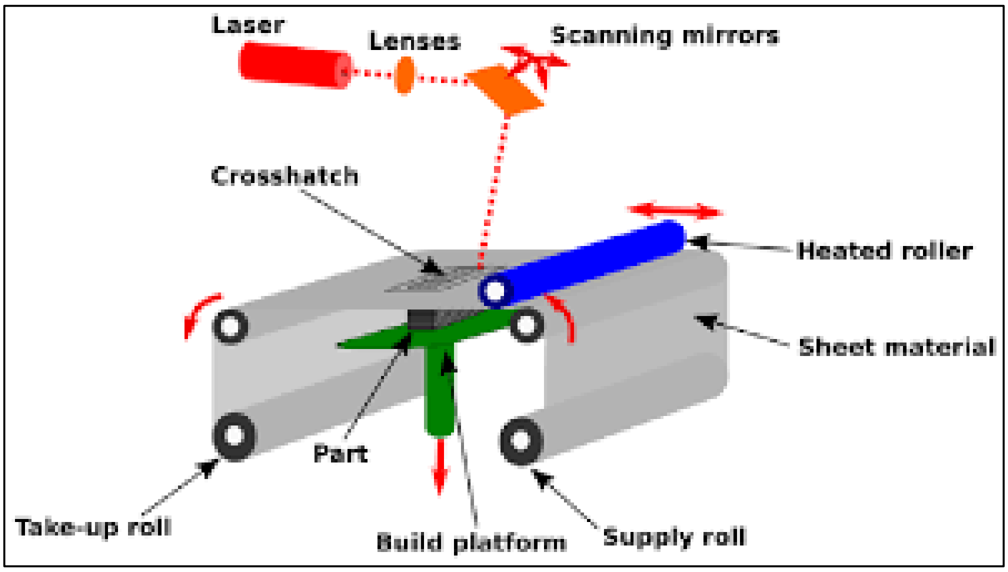

Fig.3. Schema procedeului de fabricaţie LOM [15]

The first stage that must be completed to obtain a part through a process of rapid prototyping is the three-dimensional geometric modeling of the part respectively. The virtual geometric model must then be converted from the native format of modeling program, in a file format supported by the control program of rapid prototyping system. The file format most used for this purpose is the STL (Stereo Lithography) format. In essence, an STL representation is an approximation of the geometric model through a collection of triangular facets. [1.15]

In figure 3, the scheme of the LOM manufacturing process is represented. The virtual geometric model, in .stl format, is taken over by the command program al
machine (LOM Slice) and processed in order to make the physical part. It is sectioned with planes parallel to the working plane of the machine (XOY) in order to obtain the profile of the part at certain Z elevation.

Based on the geometric information obtained from the sectioning of the virtual model and the technological data entered by the operator, the cutting device formed from a laser beam control system, materializes the section. Excess material it is cut by the laser beam, in the form

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of a hatch with the hatching directions parallel to the axes X and Y. After the upper layer is fully processed, the platform is retracted (on Z axis), the material advances one step, the platform rises to bring the new layer of material in the focus plane of the laser beam (working plane of the machine), a heating roller and pressing glues the "n" layer to the "n-1" layer and then the process of materializing the section by cutting. [1.16]

The manufacturing process is repetitive and is completed at the moment when the last one virtual section was physically materialized. The sectioning step along the Z axis is given by the thickness of the material used in the manufacture of the part. The most commonly used material is LOM paper, special paper that has an adhesive layer on one side. The processed paper parts have characteristics and physical appearance similar to the parts made of wood, as in Figure 4. [1.16]

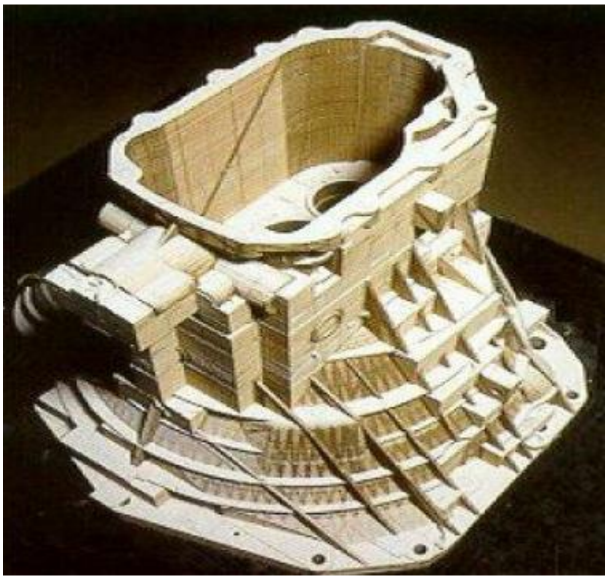

Fig.4. Part manufactured by LOM [17]

Other types of materials can also be used, such as: plastic materials, metallic materials, composite materials and ceramic materials.

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The process is performed as follows:

1. Sheet is adhered to a substrate with a heated roller.
2. Laser traces desired dimensions of prototype.
3. Laser cross hatches non-part area to facilitate waste removal.
4. Platform with completed layer moves down out of the way.
5. Fresh sheet of material is rolled into position.
6. Platform downs into new position to receive next layer.
7. The process is repeated until full model or prototype prepared.

After the last layer has been processed, post-processing takes place, which includes all the operations that are done in order to separate the piece from the excess material, as well as finishing operations.

LOM technology allows the layered manufacturing of the 3D object from layers of paper or plastic that are glued together, one on top of the other and cut with a knife or other a laser. The printing material used can be supplied both in the roll (plastic) and in sheets or sheets (paper).

Initially, the 3D CAD model is converted into cross-sections (slices) of the object and then sent to the printer.

With the help of a laser source or a knife, the printer cuts from the sheet of material solid the layers that will make up the 3D piece.

The rest of the material not used after cutting is finely checkered by the knife (or the source laser) so that at the end of the process it can be removed manually. The finished layer is glued to the previous layer using an adhesive applied to the underside of the sheet.

The cost of equipment using this technology is quite expensive, however they have the great advantage of using extremely cheap consumables (ordinary paper).

The average precision of the processing of LOM parts is of the order of tens of millimeters. In the during lamination, the layers of material neither stretch nor contract, so they do not want introduces stresses that lead to deformation of the model.

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In the case of the LOM process, it is not necessary to build supports to sustain the part during construction, as the excess material in each layer constitutes support for the next layer.

The advantages of LOM technology lie in very cheap printing materials (paper regular A4), good accuracy and precision, allows printing larger models which do not have complicated details. 3D prototypes printed in full color allow a great visual impact. The equipment used for printing does not use powders, chemicals or hazardous post-processing operations. [1.16]

The disadvantages of LOM technology are the limited range of materials, poor mechanical properties of materials, unused material must be removed by hand, material waste quite large and limited print volumes.

Applications of LOM technology are in the field of prototypes, models of architecture, aerospace, mechanical domain. 3D models manufactured by the LOM process are bulky, not highly detailed and require a cheap manufacturing cost.

Color printing has applicability in many areas as: architecture, conceptual design, marketing models, scientific visualization, education.

1.2.6. Stereolithography (SLA)

Stereolithography (SLA or SL) is an additive manufacturing technology known as a manufacturing process by solidifying the raw material in a liquid state due to photopolymerization. Stereolithography was the first process that allowed the generation of a model physically, using model data, directly from the computer. [1.21]

Stereolithography (Fig.5) is an additive manufacturing process that, in its most common form, works by focusing an ultraviolet (UV) laser on to a vat of photopolymer resin. With the help of computer aided manufacturing or computer-aided design (CAM/CAD) software, the UV laser is used to draw a pre-programmed design or shape on to the surface of the photopolymer vat. Photopolymers are sensitive to ultraviolet light, so the resin is photochemically solidified and forms a single layer of the desired 3D object. Then, the build platform lowers one layer and a

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blade recoats the top of the tank with resin. This process is repeated for each layer of the design until the 3D object is complete. Completed parts must be washed with a solvent to clean wet resin from their surfaces.

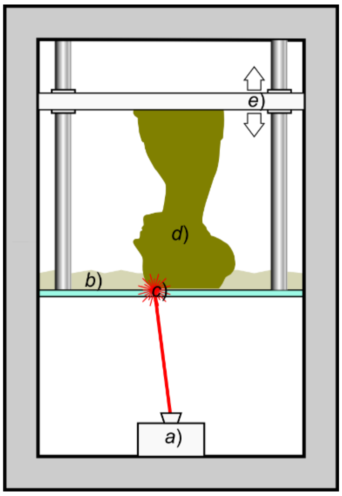

Fig.5. Stereolithography (SLA) principle [124]

It is also possible to print objects "bottom up" by using a vat with a transparent bottom and focusing the UV or deep-blue polymerization laser upward through the bottom of the vat. An inverted stereolithography machine starts a print by lowering the build platform to touch the bottom of the resin-filled vat, then moving upward the height of one layer. The UV laser then writes the bottom-most layer of the desired part through the transparent vat bottom. Then the vat is "rocked", flexing and peeling the bottom of the vat away from the hardened photopolymer; the hardened material detaches from the bottom of the vat and stays attached to the rising build platform, and new liquid photopolymer flows in from the edges of the partially built part. The UV laser then writes the second-from-bottom layer and repeats the process. An advantage of this bottom-up mode is that the build volume can be much bigger than the vat itself, and only enough photopolymer is needed to keep the bottom of the build

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vat continuously full of photopolymer. This approach is typical of desktop SLA printers, while the right-side-up approach is more common in industrial systems.
This technology allows the creation and manufacture of models, prototypes and layered parts, using for solidification, the process of selective photopolymerization, a process that is activated by a light beam and forms bonds between unsaturated molecules forming chains of polymer, figure 5.
This procedure was conceived in 1982 by Charles Hull, and in 1986 it was patented the Stereolithography process. 3D Systems Inc. use this patent for commercialization since 1986. In 1988, the first one was commercialized stereolithography system SLA-1. In 1989, an improved SLA 250 model was presented, and starting from 1990, more productive models are made for voluminous parts, SLA-500 type.

Fig.6. Part manufactured via SLA

Stereolithography requires the use of supporting structures which attach to the elevator platform to prevent deflection due to gravity, resist lateral pressure from the resin-filled blade, or retain newly created sections during the "vat rocking" of bottom up printing. Supports are typically created automatically during the preparation of CAD models and can

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also be made manually, as in figure 6. In either situation, the supports must be removed manually after printing. In figure 7, were used different colored resins in architectural domain for realize the Kretzulescu Palace, manufactured by SLA.

Fig.7. Resins used in architectural domain (Kretzulescu Palace) manufactured by SLA

Other forms of stereolithography build each layer by LCD masking or using a DLP projector.

The liquid materials used for SLA printing are commonly referred to as "resins" and are thermoset polymers. A wide variety of resins are commercially available and it is also possible to use homemade resins to test different compositions for example. Material properties vary according to formulation configurations: "materials can be soft or hard, heavily filled with secondary materials like glass and ceramic, or imbued with mechanical properties like high heat deflection temperature or impact resistance". It is possible to classify the resins in the following categories:

- Standard resins, for general prototyping
- Engineering resins, for specific mechanical and thermal properties

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- Dental and medical resins, for biocompatibility certifications
- Castable resins, for zero ash-content after burnout
- Biomaterial resins, formulated as aqueous solutions of synthetic polymers like polyethylene glycol, or biological polymers such as gelatin, dextran, or hyaluronic acid.

One of the advantages of stereolithography is its speed; functional parts can be manufactured within a day. The length of time it takes to produce a single part depends upon the complexity of the design and the size. Printing time can last anywhere from hours to more than a day. SLA printed parts (Fig.6), unlike those obtained from FFF/FDM, do not exhibit significant anisotropy and there's no visible layering pattern. The surface quality is, in general, superior. Prototypes and designs made with stereolithography are strong enough to be machined and can also be used to make master patterns for injection molding or various metal casting processes.

Although stereolithography can be used to produce virtually any synthetic design, it is often costly, though the price is coming down. Since 2012, however, public interest in 3D printing has inspired the design of several consumer SLA machines which can cost considerably less. Beginning in 2016, substitution of the SLA and DLP methods using a high resolution, high contrast LCD panel has brought prices down to below US$200. The layers are created in their entirety since the entire layer is displayed on the LCD screen and is exposed using UV LEDs that lie below. Resolutions of .01mm are attainable. Another disadvantage is that the photopolymers are sticky, messy, and need to be handled with care. Newly made parts need to be washed, further cured, and dried. The environmental impact of all these processes requires more study to be understood, but in general SLA technologies have not created any biodegradable or compostable forms of resin, while other 3-D printing methods offer some compostable PLA options. The choice of materials is limited compared to FFF, which can process virtually any thermoplastic.

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1.2.7. Digital Light Processing (DLP)

Developed by Texas Instruments, DLP technology has the chip as its main element DMD (Digital Micromirror Device) – an array of micro-mirrors used for fast space modulation of light. [1, 32]

The DLP process is a form of stereolithography, which is used in the services of rapid prototyping. In DLP projectors, the image is created by microscopically small mirrors laid out in a matrix on a semiconductor chip, known as a digital micromirror device (DMD). These mirrors are so small that DMD pixel pitch may be 5.4 µm or less.

The main difference between DLP and SLA is the use of a light projector that solidifies the resin of a photosensitive polymer, compared to a laser as it uses the process of stereolithography.

A DLP printer (Fig.8) projects the 3D cross-sectional image of the object onto the surface of the resin. The resin exposed to the light source hardens while the platform of built of the machine descends, allowing the deposition of a new layer of fresh resin which to be solidified by light. [1,32,33]

Once the part is completely manufactured, post-processing can be done additional, such as removal of the support material, chemical bath and UV drying.

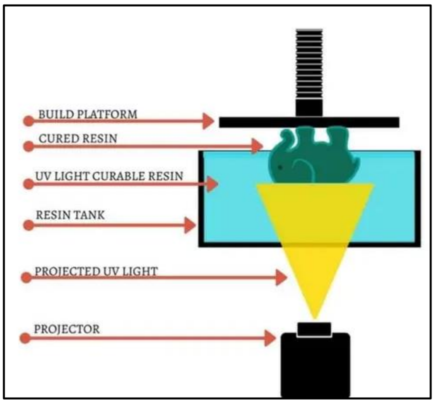

Fig.8. Digital Light Processing (DLP) principle [33]

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The accuracy of the printed parts (Fig.9) is very good. Finishing of printed surfaces is very good. Print speed is good (for multiple objects and complex geometries). The materials used by DLP technology are different types of resins, photopolymers, transparent resins, wax-based polymers.

Fig.9. Parts manufactured by DLP technology

The advantages of DLP technology are fine and precise printed surfaces (use in jewelry industry, dental technology, electronics, architecture, tooling), quite durable prototypes for processing, diverse range of resins including biomedical materials (certificates for use in the medical field) and transparent resins (prototypes in the packaging industry), printers stable with few moving parts. [1,32,33]

The technology enables the prototyping of parts with complex and detailed geometries, great print speed for complex geometries and simultaneous printing of several parts (high productivity). The printed parts can be used as master molds for industries as injection molding, thermoforming and metal casting.

Disadvantages of DLP technology would be more expensive construction materials, price higher printing (for large volumes), requires post-processing operations (UV curing, removal of support material), requires handling of resins.

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1.2.8. Selective Laser Sintering (SLS)

An additive manufacturing layer technology, SLS involves the use of a high power laser (for example, a carbon dioxide laser) to fuse small particles of plastic, metal, ceramic, or glass powders into a mass that has a desired three-dimensional shape.

The laser selectively fuses powdered material by scanning cross-sections generated from a 3-D digital description of the part (for example from a CAD file or scan data) on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed, as in figure 10.

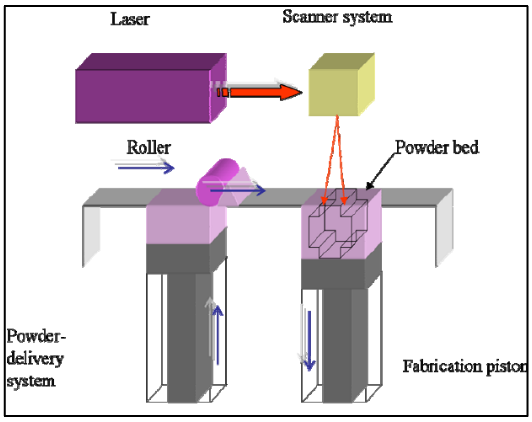

Fig.10. Principle of SLS technology [51]

The SLS selective laser sintering process has been developed and patented over the years 1980 by Dr. Carl Deckard at the University of Texas at Austin. The first equipment of selective laser sintering were commercialized after 1996. [1,37-50]

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Selective Laser Sintering (SLS) processes have been developed after 1992 and is based on design and manufacturing experience gained on stereolithographic equipment (STL) but also on the expansion of technological research on to other groups of materials with mechanical and technological properties closer to the needs of functional assemblies in machine construction (ceramic, ferrous materials and non-ferrous.

Selective laser sintering processes consider a wide variety of materials from which will result in products at a higher level of performance, i.e. with physico-mechanical properties
close to the demands in the organs of usual machines.

Rapid prototyping technology helps identify potential problems appear in the design and conception process. With a prototype one can actually see if two surfaces are joining correctly or if the joining points are lining up as they should.

The DTM Sinterstation 2500 (SLS) rapid prototyping system makes prototypes both for beneficiaries in the industrial environment, but also for humanitarian purposes -medical prostheses in case of accidents, especially skulls, as in figure 11.

Because finished part density depends on peak laser power, rather than laser duration, a SLS machine typically uses a pulsed laser. The SLS machine preheats the bulk powder material in the powder bed somewhat below its melting point, to make it easier for the laser to raise the temperature of the selected regions the rest of the way to the melting point.

In contrast with SLA and FDM, which most often require special support structures to fabricate overhanging designs, SLS does not need a separate feeder for support material because the part being constructed is surrounded by unsintered powder at all times. This allows for the construction of previously impossible geometries. Also, since the machine's chamber is always filled with powder material the fabrication of multiple parts has a far lower impact on the overall difficulty and price of the design because through a technique known as 'Nesting', where multiple parts can be positioned to fit within the boundaries of the machine. One design aspect which should be observed however is that with SLS it is 'impossible' to fabricate a

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hollow but fully enclosed element. This is because the unsintered powder within the element could not be drained.

The quality of printed structures depends on the various factors include powder properties such as particle size and shape, density, roughness, and porosity. Furthermore, the particle distribution and their thermal properties affect a lot on the flowability of the powder.

Fig.11. Sintersation 2500 system [52]

Commercially-available materials used in SLS come in powder form and include, but are not limited to, polymers such as polyamides (PA), polystyrenes (PS), thermoplastic elastomers (TPE), and polyaryletherketones (PAEK). Polyamides are the most commonly used SLS materials due to their ideal sintering behavior as a semi-crystalline thermoplastic, resulting in parts with desirable mechanical properties. Polycarbonate (PC) is a material of high interest for SLS due to its high toughness, thermal stability, and flame resistance; however, such amorphous polymers processed by SLS tend to result in parts with diminished mechanical properties, dimensional accuracy and thus are limited to applications where these

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are of low importance. Metal materials are not commonly used in SLS since the development of selective laser melting.

Sintering in SLS primarily occurs in the liquid state when the powder particles forms a micro-melt layer at the surface, resulting in a reduction in viscosity and the formation of a concave radial bridge between particles, known as necking, due to the material's response to lower its surface energy. In the case of coated powders, the purpose of the laser is to melt the surface coating which will act as a binder. Solid state sintering is also a contributing factor, albeit with a much-reduced influence, and occurs at temperatures below the melting temperature of the material. The principal driving force behind the process is again the material's response to lower its free energy state resulting in diffusion of molecules across particles.

SLS manufacturing applications are used in the aerospace industry, in applications medical, orthopedics, dentistry. The process begins by using CAD files, in the form of .stl file and the 3D part is printed layer by layer, usually having thicknesses between 20 and 100 of micrometers, creating a 2D image of each layer.

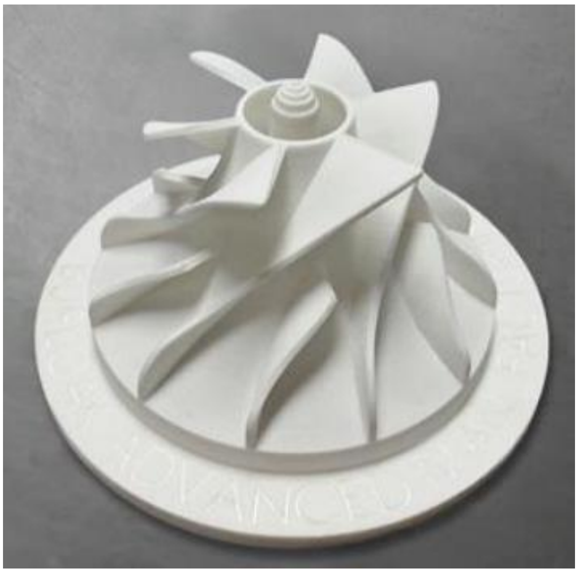

Fig.12. Industrial part with complex forms manufactured by SLS [53]

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The selective laser sintering process has some particularities, namely the metal powders used are pre-treated by conditioning them with a resin or with a polymer, i.e. the powder grains are film-coated, finally obtaining a new powder which contains 75-80% metal and 20-25% resin or polymer.

Another characteristic specific to the selective laser sintering process is the fact that the process takes place in two stages, in the first stage the very raw-green part is made brittle by melting the resin or polymer film of the grains and partially binding a metal particles between them through bridges and the second post-sintering stage in the furnace sintering at temperatures of 1100-1200ºC, producing the welding of metal particles between them and the consolidation of the whole structure. [1:37-52]

The metallic structure obtained is porous, having a density of 70-75%, presenting very good physical-mechanical properties so that these parts can be used as functional parts (sliding bearings, filter elements). [53,54]

In figure 12 is presented an industrial part with complex forms manufactured by SLS.

After the piece has been completed, a rest time (sometimes quite long) for reducing the temperature from tens or hundreds of degrees, the volume of powder what was subjected to processing. Then the piston of the cylinder in which the part was built rises in view of the evacuation of the piece. The final part together with the unsintered powder is transferred into an auxiliary machine equipment, in order to clean and remove excess dust.

The materials used in the selective laser sintering process are particularly various, starting with polyamide powders (DuraForm PA, PA1500, PA2200, PA1300GF, PA3200GF), metal powders (MC3201, DirectMetal 50-VI, DirectMetal 100-VI, RapidSteel 1.0, RapidSteel 2.0), quartz or zirconium-based powders (EOSINT S quartz, EOSINT zircon HT). [1:37-51]

Depending on the type of material to be sintered, there will be different power values of the laser used for sintering, respectively different sintering temperatures.

Selective laser sintering SLS, is a family of methods that can build a solid body from various types of powders (plastic, metal, ceramics including very rare metals or with physical-

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mechanical properties and of special biocompatibility) by solidifying the powder, following exposure successive layers of powders to a laser beam of various powers.

Through these processes, depending on the material, we can obtain a density of up to 100% and material properties comparable to those of conventional methods can be obtained manufacturing. [1:37-51]

Thus, SLS technology can successfully meet new challenges in terms of innovative technologies, in the context of a globalized economy and increased competitiveness.

1.2.9. Direct Metal Laser Sintering (DMLS)

The DMLS manufacturing process is part of LENS (Laser Engineered Net Shaping) from the selective laser melting category. [1,57,58]

Fig.13. Phenix Systems ProX DMP 100 Dental [59]

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The DMLS process has been developed and researched down to the manufacturing system level by the EOS company from Germany, since 1995.

This company made the most famous DMLS sintering equipment in the world and is one of the best performing sintering manufacturing companies.

A very diverse number of materials are available to be used with high-tech EOSINT M270 systems, offering a wide range of e-Manufacturing applications.

EOS CobaltChrome MP1, is a cobalt-chromium superalloy powder that was special optimized for processing on this type of high-tech systems. [1,57,58]

Other materials are also available for EOSINT M systems, including a special cobalt-chromium-molybdenum alloy for dental restorations.

The DMLS manufacturing process is identical to that of SLM selective laser melting, because it starts from the same 3D model of the part, which is sectioned into sections with thicknesses of 20 µm, forming the sequence of sections necessary for the physical materialization of the 3D model virtual. The very small thickness of 20 µm of the material section allows good sintering and leads to an increase in dimensional accuracy and the quality of the machined surfaces of the part, relative to other similar processes. [1,57,58]

In case of SLS technology, the metallic powders are not filmized, and the process is carried out in one step. In figure 12 is presented Phenix Dental ProX DMP 100 Systems.

However, when using low laser powers of 50 W a post treatment is required, by placing the part in a sintering furnace at a temperature between 800-900ºC for half an hour, for the increase in hardness and the improvement in mechanical and corrosion resistance.

In rapport with the SLM selective laser melting process, DMLS process used for manufacturing only metal alloys.

The metal powders that can be used in manufacturing through DMLS, include a large variety of materials including implantable or general-purpose stainless steel, superalloys cobalt chrome, inconel 625, inconel 718, AlSi10Mg aluminum alloys, titanium alloys- Ti6Al4V.

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Laser power on Phenix Systems manufacturing equipment varies from 50-500 W, which provides the energy needed to melt the powder layer for the materialization of a section.
Phenix Dental Systems use stainless steels 316L (ST4404D), hard tool steels (ST2709B), Co-Cr superalloys (ST2724G), Ti alloys, precious metals and non-ferrous alloys. [1,57,58,59]
The ProX DMP 100 Dental manufacturing system from figure 13 is used at rapid fabrication by direct metal laser sintering. This procedure allows direct production of fixed or removable prostheses from Co-Cr.
The machine is equipped with a platen from stainless steel, having circular or rectangular form. In this case, the platen has square form with the dimensions 100x100 mm and allows to print, only small parts, as in figure 14. [1,57,58,59]
After each use due to the high temperatures of 1300-1600^{o}C, the metallic powders adhere on the platen, respectively the supports of the welded parts remain, and the platens must to be changed or reused.

Fig.14. Platen of ProX DMP 100 Dental

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All materials intended for DMLS process have special physical and mechanical qualities, better than cast or forged materials, so they are recommended for biomedical implants, parts for design, architecture, robotics, tooling, aeronautical or automotive industry. In figure 15 is presented analogue dental implants manufactured via DMLS.

Fig.15. Analogue dental implants manufactured via DMLS

The properties of biocompatibility, corrosion resistance and low specific gravity, combined with the infinite possibility of 3D geometric modeling recommend this manufacturing process as a working tool of the future of micro-mechanical, mechatronic and robotics. [1,57,58,59]

1.2.10. Selective Laser Melting (SLM)

SLM selective laser melting has been grouped under the process category of "laser sintering" although this is improper, recognized because the process melts the powder, unlike selective laser sintering (SLS) and direct metal laser sintering (DMLS), which are true sintering processes. A similar process is electron beam melting (EBM), which uses a beam of electrons as an energy source. [1.62]

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The Fraunhofer Institute from Aachen patented this process of selective laser melting in 1995. Patent authors Dr. W. Meiners and Dr. D. Fockele not only have researched and patented this process, but they also contributed to the establishment of companies that produce and today these systems.

This process only processes metal powders of great diversity (powders of titanium and its alloys, alloy steel, stainless steel, tool steel, Co-Cr alloys, aluminium), having a very fine powder granulation below 20 µm. The powder used is obtained by atomization, having spherical granulation. [1.62]

Fig.16. SLM500 HL system [64]

Most SLM machines use working enclosures with dimensions of 250x250x350 mm, and the larger machines have enclosure dimensions of 500x500x500 mm.

Selective laser melting SLM is an additive manufacturing process, similar to the SLS selective laser sintering process, but at a higher level than it.

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The room in which the procedure is carried out contains a well-controlled atmosphere of inert gas, argon or nitrogen, at the oxygen level below 500 parts per million. [1.62]

Once each layer has been distributed, each 2D section of the geometry is melted by selective melting of the powder. This is done with a high-power laser beam, usually a ytterbium Yb fiber laser (100-200 W). In figure 17 is shown pre-assembled micro-turbojet engine of Inconel 718 manufactured by SLM.

Fig.17. Pre-assembled micro-turbojet engine of Inconel 718 manufactured by SLM [122]

Parts obtained by SLM technology do not require post-sintering treatment in furnace, the density of the part is almost 100% and it has practically mechanical properties identical to the properties of parts obtained by classical processes such as casting.

Parts with complex geometric shapes and details can be made with this technology (cooling channels for active die elements, for example) that are difficult to achieve through classic technologies. Figure 16 shows the SLM500 HL system. [64]

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This technology has manufacturing applications in aerospace, automotive, architecture or medicine fields (creates the possibility of manufacturing the customized orthopedic implants from biocompatible Ti materials) and is being pioneered. [1,62,63]

The ability to produce parts extremely quickly, economically and flexibly, it allows the manufacture of individual parts or batches, which in turn allow identification design or manufacturing issues at an early stage of development of the product, and the time to market is shortened. This new technology is used in top fields, fields of engineering and medicine, both for civil and military purposes.

The world's most advanced engineering entity, NASA, uses the technology EOSINT M270 Titanium Version.

1.2.11. Electron Beam Melting (EBM)

Electron-beam additive manufacturing, or electron-beam melting (EBM) is a type of additive manufacturing, or 3D printing, for metal parts. The raw material (metal powder or wire) is placed under a vacuum and fused together from heating by an electron beam. This technique is distinct from selective laser sintering as the raw material fuses having completely melted.

Metal powders can be consolidated into a solid mass using an electron beam as the heat source. Parts are manufactured by melting metal powder, layer by layer, with an electron beam in a high vacuum.

This powder bed method produces fully dense metal parts directly from metal powder with characteristics of the target material. The EBM machine reads data from a 3D CAD model and lays down successive layers of powdered material. These layers are melted together utilizing a computer-controlled electron beam. In this way it builds up the parts. The process takes place under vacuum, which makes it suited to manufacture parts in reactive materials with a high affinity for oxygen, e.g. titanium. The process is known to operate at higher temperatures

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(up to 1000 °C), which can lead to differences in phase formation though solidification and solid-state phase transformation.

Currently commercial materials for EBM include commercially pure Titanium, Ti-6Al-4V, CoCr, Inconel 718, and Inconel 625.

Other notable developments have focused on the development of process parameters to produce parts out of alloys such as copper, niobium, Al 2024, bulk metallic glass, stainless steel, and titanium aluminide.

1.2.12. Powder bed and inkjet head 3D printing

This technology was first developed at the Massachusetts Institute of Technology and patented in 1993. Binder jet 3D printing, known variously as "Powder bed and inkjet" and "drop-on-powder" printing, is a rapid prototyping and additive manufacturing technology for making objects described by digital data such as a CAD file.

Fig.18. Zprinter310 Plus system

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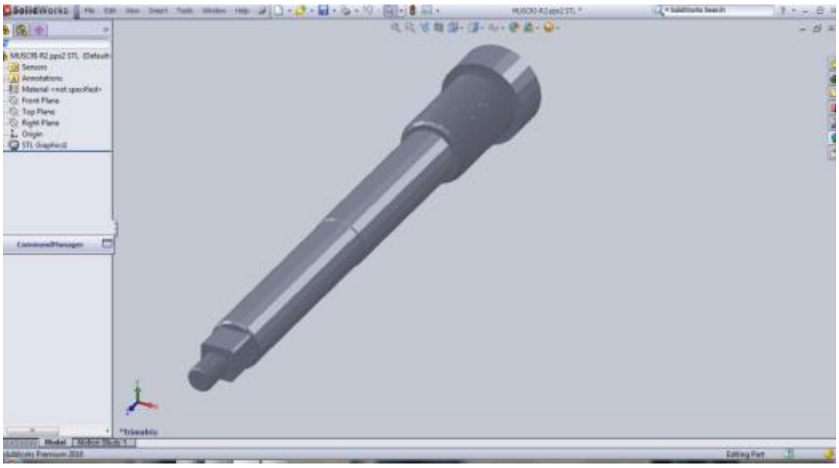

Fig.19. stl. file of the shaft

Parts printed using the binder jetting process are inherently porous and have an unfinished surface, as unlike powder bed fusion the powders are not physically melted and are joined by a binding agent. While the usage of a binding agent allows for high melting temperature (e.g. ceramic) and heat-sensitive (e.g. polymer) materials to be powdered and used for additive manufacturing, binder jetting parts require additional post-processing that can require more time than it takes to print the part, such as curing, sintering, and additional finishing.

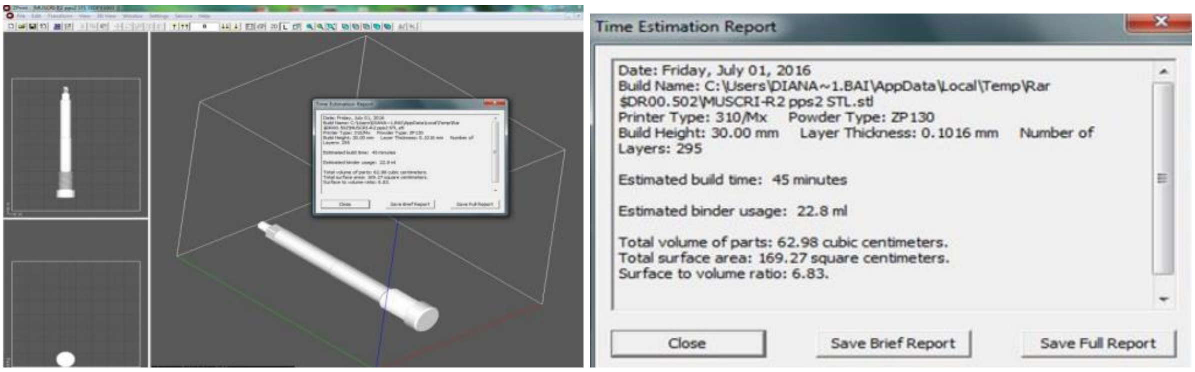

Fig.20. Estimation of time and consumption of powder and binder required for 3D printing

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In figure 18 the part obtained by 3D printing using the ZPRINT 310 Plus system, after cleaning and impregnation with resin and hardener. In figure 19 is shown the stl file for the shaft.
The ZPRINT 310 Plus software estimates the time required for 3D printing (45 min) for shaft part, tells us how much powder (62.98 cm^3) and binder (22.8 ml) are consumed during printing, as in fig.20. The software permit also to view the 2D sections layer by layer print, as in fig.21.

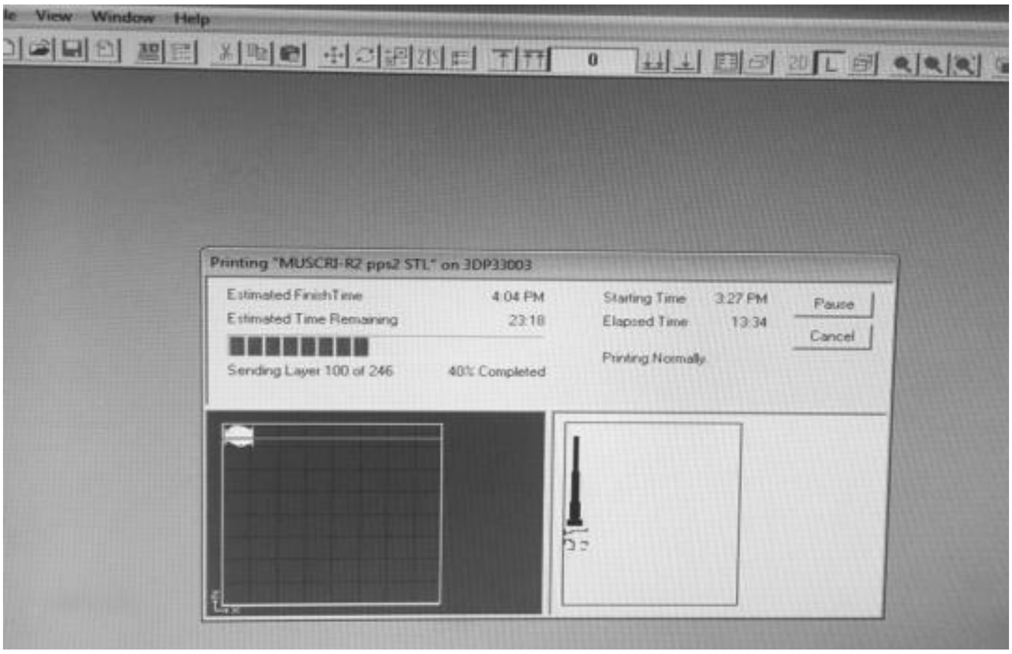

Fig.21. View of the 2D sections layer by layer during the printing process

It is noted that the powder has a fine granulation of the order of microns of 20-50 µm, with rounded grains, with a range of quite large particle size fractions.

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In figure 22 is presented the shaft model part manufactured from calcium carbonate powder by Binder Jetting using Zprint 310 Plus system.

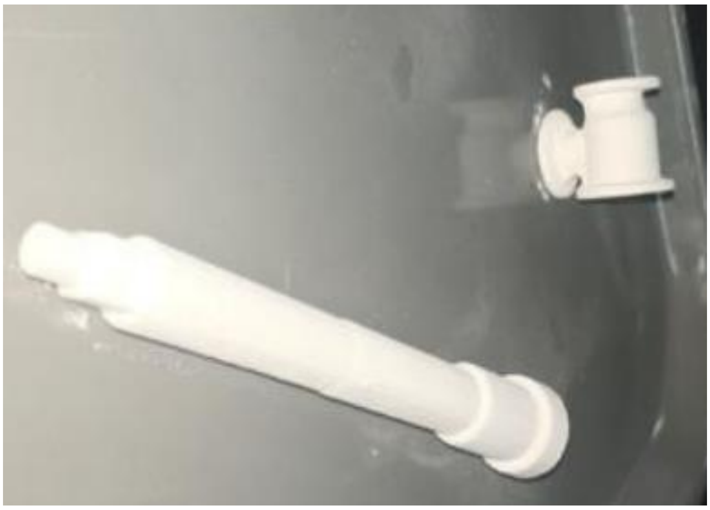

Fig.22. Industrial part manufactured by Binder Jetting using Zprint 310 Plus system

1.3.Plastic materials used in Additive Manufacturing

ABS and PLA are the most common FDM (Fused Deposition Modeling) printed materials and are typically similar in cost. ABS has superior mechanical properties but is harder to print compared to PLA. PLA is ideal for 3D prints where aesthetics is important.

Table 3. 1. The mechanical properties of Acrylonitrile Butadiene Styrene (ABS)

Properties	Values	Units
Density	1.0-1.4	g/cm3
Poisson's Ratio	0.35	-
Shear Modulus G	1,03-1,07	GPa
Melting Temperature	200	ºC
Glass transition temperature	105	ºC
Thermal Conductivity	0,25	W/m-K

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Extruded Temperature	200-230	ºC
Heat Deflection Temperature, 1,81 MPa	81	ºC
Young's modulus	1,79-3,2	GPa
Tensile Strength	29,8-43	MPa
Compressive Strength	76-78	MPa
Elongation at Break	10-50	%
Flexural modulus	2,1-7,6	GPa
Hardness Shore D	100	
Izod Impact Strength	58	kJ/m2
Yield Strength	28-120	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	-	-
Melt flow	12-23	g/10min
Rockwell Hardness	R102-R104	

Due to its lower printing temperature is easier to print with and therefore better suited for parts with fine details. ABS is best suited for applications where strength, ductility, machinability and thermal stability are required. ABS is more prone to warping. The mechanical properties of ABS are presented in Table 3.1. [1-86]

Other materials used frequently in FDM technology are the filaments of Polyethylene Terephthalate PET $(C_{10}H_8O_4)_n$ and Polyethylene Terephthalate Glycol (PETG). The mechanical properties of PET material are presented in the Table 3.2 and the comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and HIPS is shown in the Table 3.4. In table 3.3 are shown the mechanical properties of PLA for 3D printed material.

Table 3.2. The mechanical properties of Polyethylene Terephthalate PET $(C_{10}H_8O_4)_n$

No	Mechanical and chemical properties	U.M.	Value (unit)	Obs.
1	Density	g/cm^3	1.455 – cristalin 1.37 - amorphous	1.38 – at 20ºC
2	Tensile Strength	N/mm^2	74-cristalin 55-amorphous	-
3	Compressive Strength	N/mm^2	125	-
4	Flexural strength	N/mm^2	90	-
5	Torsion strength	N/mm^2	-	-

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6	Shear strength	N/mm^2	-	-
7	Elongation at break	%	50-cristalin 150-300 - amorphous	-
8	Ball penetration hardness	Kg/m^3	1370	-
9	Rockwell Hardness	-	R100-cristalin R90-amorphous	-
10	Charpy shock resistant (uncracked)	kJ/m^2	3.6	-
11	Charpy shock resistant (cracked)	kJ/m^2	2.5	-
12	Melting temperature	ºC	260	-
13	Glass transition temperature	ºC	67-81	-
14	Notch test	kJ/m^2	3.6	-
15	Vicat Temperature(VST)	ºC	82	-
16	Extruded temperature	ºC	220-250	-
17	Liniar expansion coefficient	-	7	$(*10^{-5}K^{-1})$
18	Specific Heat	cal/gºC	0.28	$(JK^{-1}*kg^{-1})$
19	Thermal conductivity	W/mK	0.15-0.24	-
20	Boiling point	ºC	350	-
21	Volume resistivity	Ω*cm	$4*10^{16}$ – cristalin $2*10^{16}$ - amorphous	-
22	Surface resistivity	Ω	10^{13}	-
23	Water absorption (ASTM)	%	0.5-0.6 – cristalin 0.6-0.7 -amorphous	/24h
24	Viscosity	cP	75000-90000	Low-viscosity PET at high-viscosity PET
25	Dielectric rigidity	kV/mm	16	-
26	Melt flow	g/10min	35,08	230ºC
27	Young's Modulus (*E*)	MPa	2800-3100	-
28	IZOD Impact strength	J/m2	140	-

Table 3.3. The mechanical properties of PLA (Polylactic Acid)

Properties	Values	Units
Density	1.25	g/cm3
Poisson's Ratio	0.36	-
Shear Modulus G	2.4	GPa
Melting Temperature	173	ºC
Glass transition temperature	60	ºC
Thermal Conductivity	0.13	W/m-K
Extruded Temperature	160-220	ºC
Heat Resistance	110	ºC

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Young's modulus	3.5	GPa
Tensile Strength	61.5	MPa
Compressive Strength	93.8	MPa
Elongation at Break	6	%
Flexural strength	88.8	MPa
Hardness Shore D	85	A
Impact Strength	30.8	kJ/m2
Yield Strength	60	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	yes	-

Table 3.4. Comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and HIPS

Polymers	HIPS			ABS			PLA		
	OV	SD	SEx̄	OV	SD	SEx̄	OV	SD	SEx̄
MFI (g/10 min)	7.5 ± 0.20	0.16	0.11	8.76 ± 0.16	0.13	0.09	13.52 ± 0.11	0.09	0.06
Young's modulus (MPa)	112.5 ± 0.12	0.09	0.06	175 ± 0.11	0.09	0.06	47.9 ± 0.10	0.08	0.05
Yield stress (MPa)	3.44 ± 0.21	0.17	0.12	0.49 ± 0.21	0.17	0.12	0.27 ± 0.16	0.13	0.09
Glass transition temp (°C)	100.41 ± 0.16	0.13	0.09	109.76 ± 0.2	0.16	0.11	62.57 ± 0.21	0.17	0.12
Peak load (N)	80.8 ± 0.11	0.08	0.06	207 ± 0.2	0.16	0.11	282.4 ± 0.20	0.16	0.11
Peak strength (MPa)	4.21 ± 0.16	0.13	0.09	10.78 ± 0.11	0.09	0.06	14.71 ± 0.16	0.13	0.09
Peak elongation (mm)	1.9 ± 0.20	0.16	0.11	4.75 ± 0.16	0.13	0.09	5.13 ± 0.16	0.13	0.09
Percentage elongation at peak (%)	3.0 ± 0.11	0.09	0.06	6.0 ± 0.15	0.12	0.08	7.0 ± 0.10	0.08	0.05

In the SLA (Stereolithography) and DLP (Digital Light Processing) technologies are used photocurable vinyl- or epoxy- functional oligomers for photopolymerization.

In table 5 are presented the mechanical properties of Bisphenol A Ethoxylate Diacrylate resin. Other resins used in SLA manufacturing are the polyurethane resins. In figure 4 can remark the SEM image for the resin sample. [1-86]

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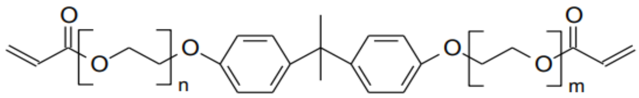
Table 5. The mechanical properties of Bisphenol A Ethoxylate Diacrylate

Bisphenol A Ethoxylate Diacrylate



n + m ~ 4

INTRODUCTION

EBECRYL 150 is an ethoxylated bisphenol A diacrylate commonly used as reactive diluent in UV/EB cure applications. EBECRYL 150 can improve the cure response, hardness, and chemical resistance of UV/EB curable coatings and inks while maintaining good adhesion, and without imparting brittleness.

PERFORMANCE HIGHLIGHTS

EBECRYL 150 is characterized by:

- High reactivity
- Moderate viscosity
- High refractive index

UV/EB curable formulated products containing EBECRYL 150 are characterized by:

- Hardness
- Chemical resistance
- Good adhesion
- Improved wetting

The actual properties of UV/EB cured products also depend on the selection of other formulation components such as oligomers, additives and photoinitiators.

SPECIFICATIONS[1]	VALUE
Acid value, mg KOH/g, max.	5
Appearance	Clear liquid
Color, Gardner scale, max.	2
Viscosity, 25°C, cP/mPa·s	1150-1650

TYPICAL PHYSICAL PROPERTIES	
Density, g/ml at 25°C	1.14
Flash point, Setaflash, °C	>100
Functionality, theoretical	2
Refractive index (n_D at 20°C)	1.5294
Vapor pressure, mm Hg at 20°C	<0.01

TYPICAL CURED PROPERTIES[2]	
Tensile strength, psi (MPa)	6300 (43)
Elongation at break, %	9
Young's modulus, psi (MPa)	180000 (1241)
Glass transition temperature, °C[3]	41

Characteristics of the powder particles used in additive laser manufacturing, using different standards,-are shown in Table 6.

Table 6. Standards (ASTM, ISO, EN) for powder properties used in additive manufacturing [86]

AM Powder characteristics	Powder Type	Symbols	Techniques	ASMT Standard	ISO Standard	EN Standard
Size and shape	Metallic powders	Φ [μm]	SEM	B822	13322	-
Specific density	Metallic powders	$\rho_{specific}$ [g/cm^3]	Gas pycnometer	B293	12154	-
Apparent density	Non-free flowing metallic powders	ρ_{app} [g/cm^3]	Hall apparatus	B212	3923/1	3923

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Apparent density	Non-free flowing metallic powders	ρ_{app} [g/cm^3]	Carney apparatus	B417	3923/1, 4490	4490
Apparent density	Metallic powders	ρ_{app} [g/cm^3]	Arnold meter	B703	-	-
Apparent density	Refractory metals and compounds	ρ_{app} [g/cm^3]	Scott volumeter	B329	3923/2	-
Tap density	Metallic powders	P_{tapped} [g/cm^3]	BT-1000	B527	3953	3953
Average particle size	Metallic powders	d_{60}	Fisher sub-sieve sizer	B330, C72	10070	-
Powder sieve analysis	Metallic powders	-	Sieve analysis equipment Westmoreland	B214	4497,2591	24497
Particle size distribution	Metallic powders and related compounds	d_{10}, d_{60}, d_{90}	Light scattering	B822	13320, 24370	-
Flowing rate	Free-flowing metallic powders	Flow time (s) for 50g	Hall apparatus	B213	4490	4490
Envelope specific surface	Powder bed under steady flow	S_v [m^2/g]	Measurement of air permeability	-	10070	196-6

The main mechanical characteristics of Ti6Al4V powder are: elastic limit 0.2% $Rp_{0,2}$= 815 MPa, elongation at break = 10%, Vickers hardness = 375 HV , elastic modulus = 229 GPa, mass density = 8,336 g/cm^3, corrosion resistance < 4 μg/cm^2, and thermal expansion coefficient = 14,5×10^{-6} K^{-1}.

The SINT-TECH company and ISO 9001 and ISO 13485 standards propose a range of powders suitable for the process developed by Phenix Systems. This powder range was selected to guarantee an optimized result for implementation with the “PX” range and the former “PM” range systems produced by Phenix Systems. [1-86]

The Co-Cr alloy powder (ST2724G) used for DMLS manufacturing presents the chemical composition: 54.31 %Co; 23.08%Cr; 11.12% Mo, 7.85% W, 3.35% Si, and Mn, Fe < 0.1%. [35-41]. Table 7 presents the mechanical characteristics of the Co-Cr powder used for the DMLS manufacturing process.

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Table 7. Mechanical characteristics of Co-Cr powder

Minimum layer thickness	20 μm
Surface roughness	Ra=10 μm, Ry=40-50 μm Ra=0,39 μm, Rz=1,6 μm After polishing Rz<1 μm
Density with standard parameters	8,3 g/cm³
Mechanical properties	
Tensile strength	1100MPa
Yield strength	600 MPa
Elongation at break	20%
Young’s modulus	200 GPa
Hardness	35-35 HRC
Fatigue life	>10 million cycles
Thermal properties	
Maximum operating temperature	1150 °C

In Table 8 are presented the mechanical properties of the materials used in Selective Laser Melting technology.

Table 8. Properties of metallic materials used in SLM technology [82]

Material	Property	Value
Inconel 625	Density	8.44 g/cm³
	Yield strength	460 MPa
	Modulus	205.8 GPa
	Density	4.43 g/cm³
TiAl64V	Yield strength	880 MPa
	Modulus	193 GPa
	Density	8 g/cm³
Stainless steel	Yield strength	205 MPa
	Modulus	193 GPa
	Density	2.67 g/cm³
AlSi10Mg	Yield strength	240 MPa
	Modulus	70 GPa

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MODULE 2

Smart (Intelligent) Materials

Project Title	**European Network for Additive Manufacturing in Industrial Design for Ukrainian Context 2023-1-RO01-KA220-HED-000155412**
Output	**IO1 - AMAZE e-book for industrial design for complex parts**
Module	**Module 2 Smart (Intelligent) Materials**
Date of Delivery	**March 2024**
Authors	**Adam Patalas, Paweł Zawadzki, Remigiusz Łabudzki, Natalia Wierzbicka Igor FODCHUK, Mariana BORCHA, Yuriy SOBKO, Volodymyr ROMANKEVYCH, Yevheniia NOVAK**
Version	**FINAL VARIANT, *date***

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1 Introduction to Smart Materials

1.1 Definition and characteristics of smart materials

Smart materials, also known as intelligent or advanced materials, lack a singular definition. They can be described as materials able to revert to their original shape under specific stimuli or as advanced materials displaying intelligent reactions to environmental changes. The classification of smart materials is based on their properties, distinguishing between active and passive categories (Bahl et al., 2020). Smart Materials (SMs) refer to materials that exhibit systematic changes in their behavior in response to specific stimuli, which can be modified. Millennia ago, humans utilized various materials for diverse purposes, leading to improvements in their quality of life.

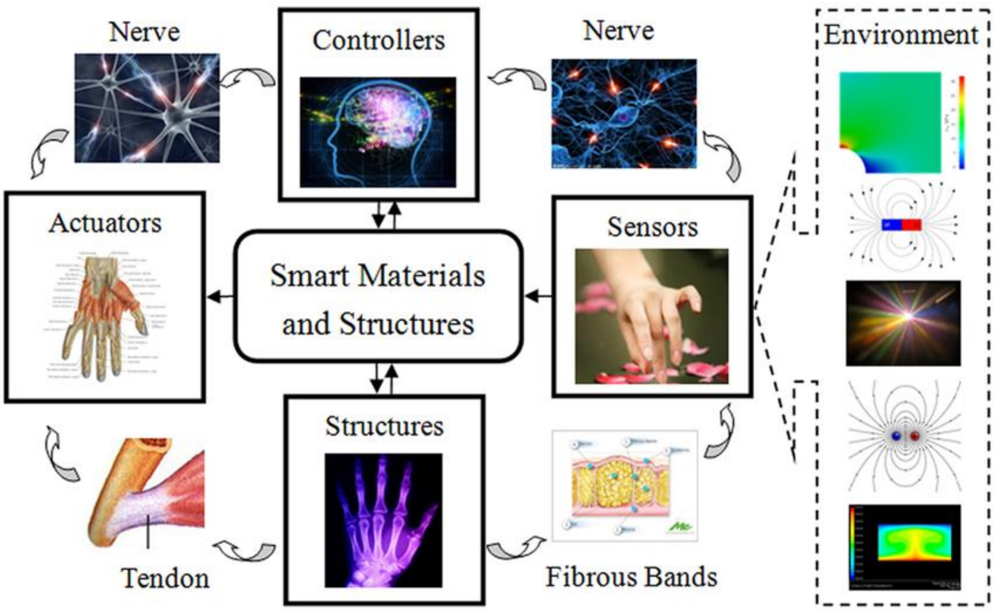

Fig. 1. Smart materials and structures (Sun et al. 2016).

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Civilizations were even categorized based on material discoveries, such as the Stone Age and the groundbreaking Bronze Age, marked by the durability and hardness of bronze. Over the past two decades, significant strides in science and technology have enabled the synthesis of new materials, primarily categorized into Polymers, Ceramics, Metals, and Smart Materials (Maheswari, 2022). Smart materials are multifunctional substances that exhibit responsiveness to external stimuli, undergoing changes in properties such as shape, color, or size. These materials find diverse applications across numerous industries, including aerospace, automotive, medical devices, and energy harvesting (Syrett et al., 2010).

The popularity of Smart Materials is on the rise due to their diverse applications compared to conventional materials. These unique materials can alter their properties, such as changing shape with the addition of heat or instantly transitioning phases when exposed to a magnet. The emerging era of Smart Materials is poised to profoundly impact humanity. Some can adapt their properties to the environment, while others possess sensory capabilities. Certain Smart Materials can undergo self-repair, and some even exhibit self-degradation. The extraordinary capabilities of Smart Materials are anticipated to influence every facet of civilization.

1.2 Importance in engineering applications

Smart materials can possess self-healing properties, encompassing both chemical (reversible and polymeric) and non-chemical systems. In the realm of architecture and transportation, smart materials like chromogenics are utilized for large area glazing in buildings, automobiles, planes, and specific types of electronic displays (Syrett et al., 2010). Printed technologies play a pivotal role in processing multifunctional smart materials. Examples include piezoelectric, piezoresistive, magnetostrictive, shape memory polymers, pH-sensitive, and chromic system materials. This utilization extends the functionalities of these materials to various applications. (Oliveira et al., 2018)

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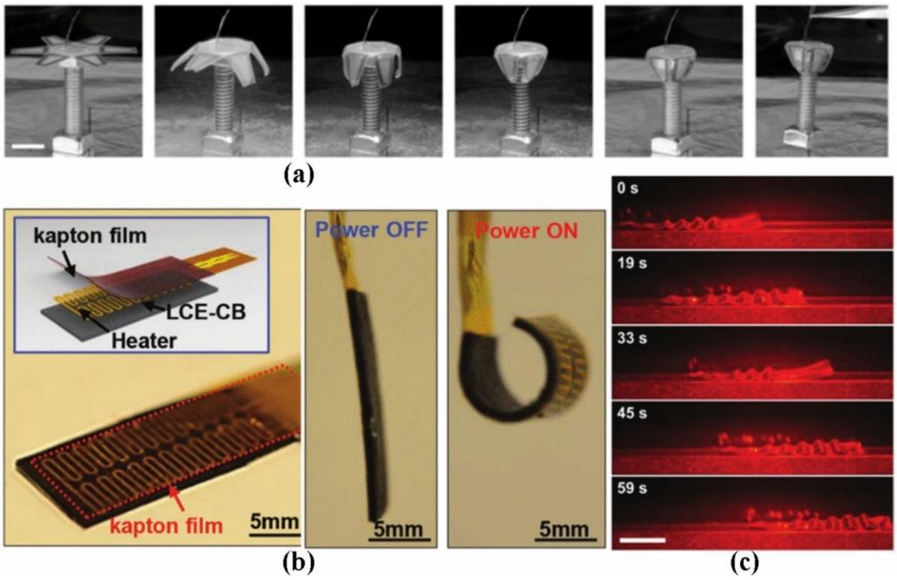

Fig. 2. Applications of thermally responsive actuators/devices in the robots: a A gripper made of thermoplastic polystyrene sheets for grasping objects under the light; b A fully soft robot mimicking an inchworm that can sense the environment and crawl the body adaptively c An LCE light-driven soft robot for mimicking caterpillar locomotion (Hao et al., 2022)

Materials like shape memory alloys, piezoelectric materials, and magnetostrictive and ferromagnetic shape memory alloys fall under the umbrella of smart materials. These substances exhibit changes in shape, color, or size in response to external stimuli, showcasing versatility in their applications. (Maheswari, 2022) Further, smart materials respond to externally supplied driving forces, such as those seen in shape memory alloys or electro- and magneto-rheological fluids. This property enables a dynamic change in shape or state based on specific stimuli. (Manfredi, 2023) Functionality is a key aspect of smart materials, as they can sense and respond to a range of environmental conditions or stimuli, including optical, electrical, magnetic, mechanical, thermal, and chemical signals. This adaptability makes them highly relevant in various technological applications. (Mano, 2008; Shafranek et al., 2019) These materials possess unique features like self-sensing, self-adaptability, memory

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capabilities, and manifold functions, making them particularly significant in industries such as aerospace. The aerospace sector benefits from the specialized properties of smart materials in creating advanced and efficient systems. (Wang et al., 2023) Characterized as complex materials, smart materials are employed in a wide array of products, spanning household goods, automotive components, and medical devices. Their adaptability and responsiveness contribute to the enhanced performance and functionality of these products. (Bogue, 2014)

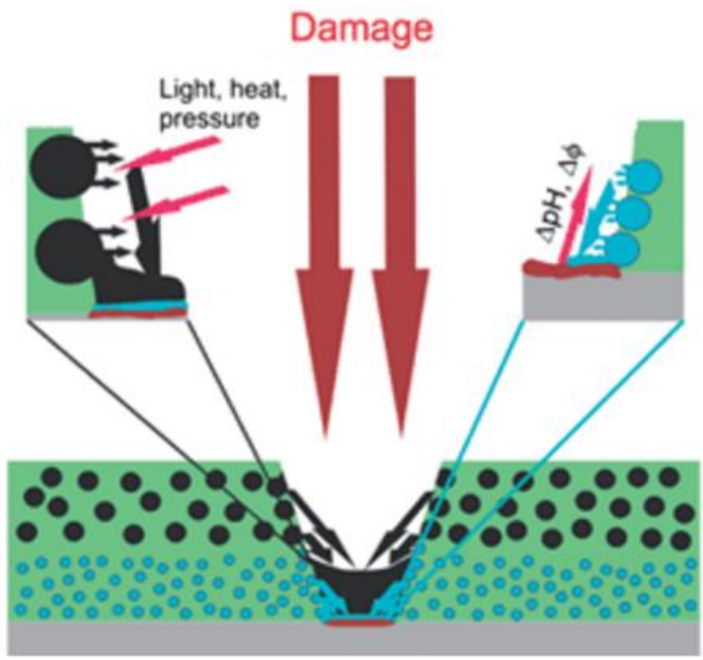

Fig. 3. Schematic representation of Self-healing mechanism (Singh et al., 2023)

In essence, smart materials are substances with altered properties under controlled conditions, responding to stimuli and generating useful effects, including signals, across a multitude of fields. Their applications extend to vibration energy harvesting, seismic applications, and the development of self-sustainable wireless sensor networks. (Valliappan & Qi, 2001)

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2 Classification of Smart Materials

2.1 Active vs. Passive smart materials

Smart Materials are classified based on their characteristics, distinguishing between Active and Passive types.

Active Smart Materials have the ability to alter their geometric and material properties when subjected to electric, thermal, or magnetic fields, endowing them with an inherent capacity to transduce energy. Active smart materials represent a category of technological substances designed to respond and adapt to external stimuli or alterations in their surroundings. These materials possess the capability to actively modify their properties, which may include alterations in shape, color, or conductivity, in direct response to particular triggers. These triggers can span a range of stimuli, encompassing physical, chemical, or electrical influences.

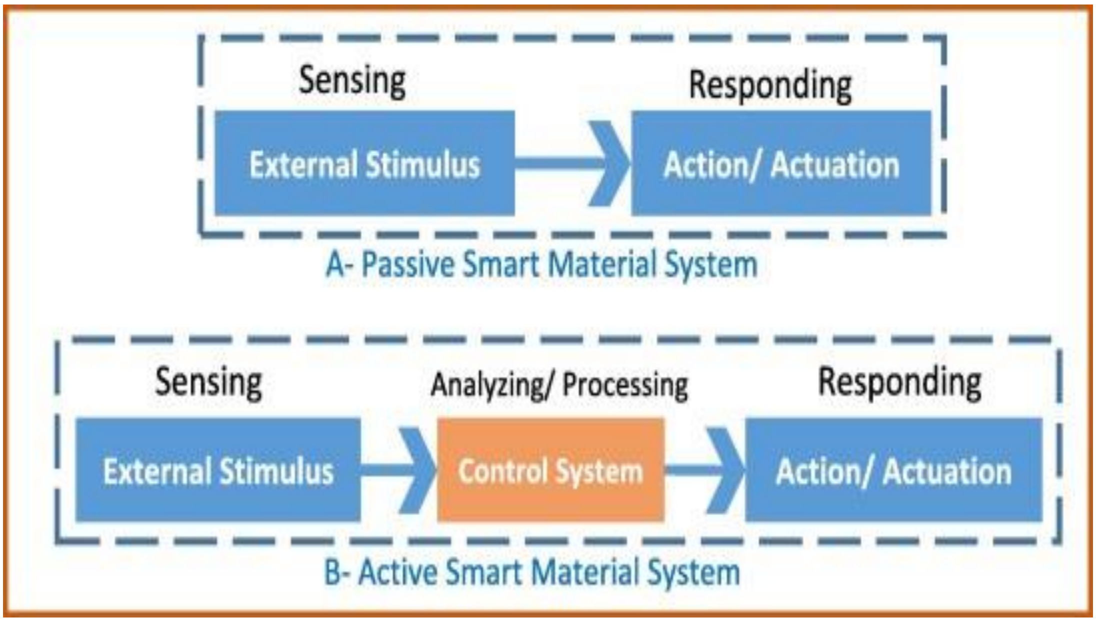

Fig. 4. Passive smart material system, B – Active smart material system (Yahya and Hoda, 2019)

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In contrast, Passive Smart Materials lack this inherent energy transduction capability. Passive smart materials, in contrast, do not undergo active changes in their properties in response to external stimuli. Rather, they exhibit inherent characteristics that enable them to passively respond to alterations in their environment. These materials are engineered with specific properties that contribute to improved performance or functionality, and they achieve this without relying on external triggers to initiate the changes.

Passive smart materials possess the ability to transmit a specific energy type, such as optical fibers transmitting electromagnetic waves. Conversely, active materials are further categorized into two types. The first type remains unchanged when exposed to external stimuli, as seen in photochromatic glasses that only change color in sunlight. The second type can convert one energy form (thermal, electrical, chemical, mechanical, and optical) into another. For example, piezoelectric materials can generate an electric charge under external strain (Bahl et al., 2020).

2.2 Types: piezoelectric, shape memory alloys, magnetostrictive materials, etc.

- **Shape Memory Alloys (SMAs)**

  Shape Memory Alloys constitute a unique class of metal alloys capable of recovering apparent permanent strains when heated above a specific temperature. The distinctive properties of SMAs stem from a phase transformation occurring between two phases upon heating/cooling.

- **Piezoelectric Materials**

  The term "piezoelectricity" combines "piezo," a Greek term meaning pressure, and "electricity," referring to electric charges. Piezoelectric materials convert mechanical energy into electrical energy and vice versa when subjected to stress or strain. Piezoelectric actuators, in turn, convert electrical signals into mechanical movement, commonly employed in adjusting mirrors, lenses, and various automotive components.

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- **Magneto-Rheological Fluids (MRFs)**
  Magneto-Rheological Fluids change their rheological properties, such as stress and viscosity, in response to a magnetic field. Also known as Magneto-Sensitive Smart Materials, MRFs exhibit visco-elasticity, magnetic properties, lightweight composition, controllable modulus, and excellent sound absorption.
- **Electro-Rheological Fluids (ERFs)**
  Electro-Rheological Fluids consist of small particles suspended in an electrically insulating fluid. When an electric field is applied, they swiftly form a solid-like structure in the direction of the field. ERFs display characteristics like stiffness, variable damping coefficient in an electric field, high dielectric constant, interfacial bond strength, consistent rheology, and dielectric properties.

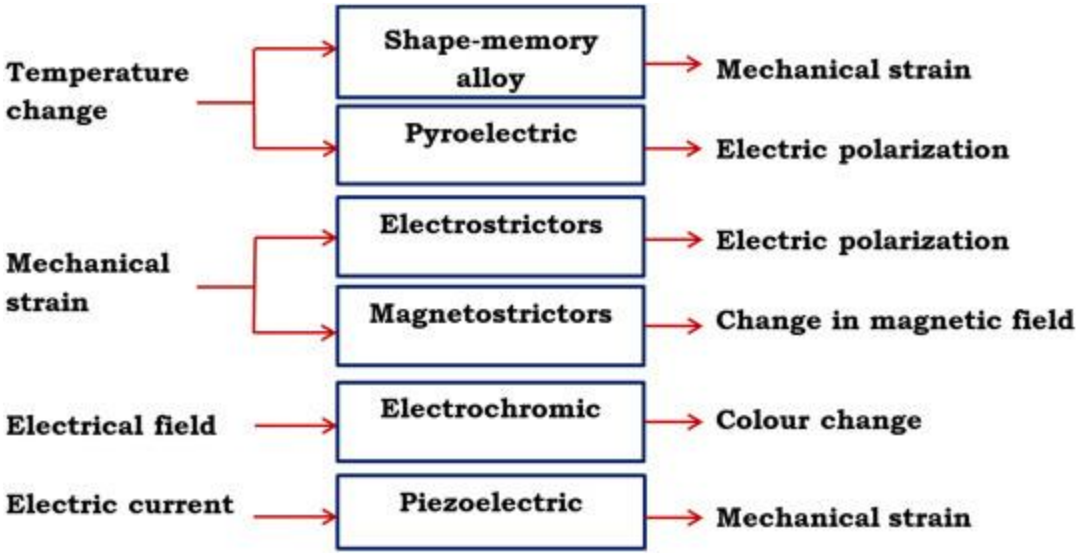

Fig. 5. Effect of external stimulus on some SMs. (Shehata et al., 2022)

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3 Types of Smart Materials

3.1 Piezoelectric materials

The smart materials showcase extraordinary properties setting them apart from conventional materials. They exhibit transiency, responding to various external stimuli; immediacy, with rapid response times; self-actuation, the ability to autonomously alter appearance and shape; selectivity, offering a divided and expected response; directness, with responses confined to the activating event; shape-changing capabilities, adjusting form based on external stimuli; self-diagnostic features, automatically detecting surface cracks; and self-healing characteristics, capable of autonomous repair when damaged or repairable (Bahl et al., 2020).

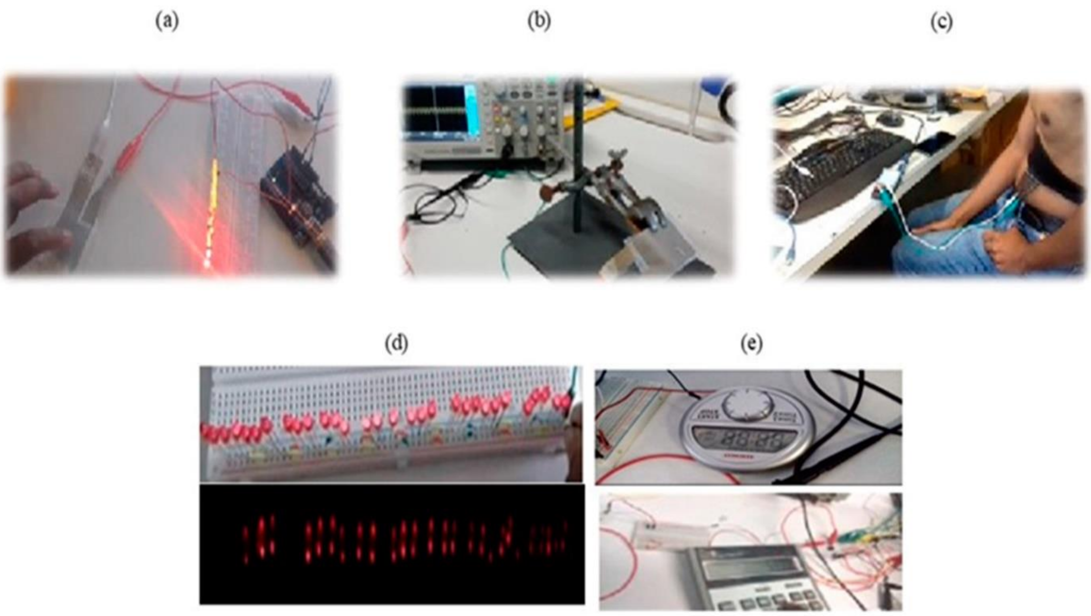

Fig. 6. Demonstration of the PSTS as (a) a touch sensor; (b) water droplets for voltage generation; (c) breathing detection; (d) a PSTH lightening 32 LEDs in the dark (bottom) and at daylight (top); and (e) stored energy powering electronics such as a timer and calculator in operation.(Hossain et al., 2022)

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Piezoelectric materials find application in various devices and systems, showcasing their versatile capabilities. In the realm of lighters or portable sparkers equipped with a piezo fuze, a sudden and intense pressure is employed to generate voltage. This generated spark is then used to ignite the gas, providing a reliable ignition mechanism.

A piezo motor, on the other hand, operates based on the alteration in the mechanical shape of a piezoelectric material when subjected to tension. This material, in response, generates ultrasonic or acoustic vibrations, facilitating linear or rotary motion. The innovative design and functionality of piezo motors make them valuable components in various mechanical systems.

In the field of music, piezo elements play a crucial role, particularly in acoustic instruments. These elements are integrated into stringed instruments such as guitars and violins. In this context, the dynamic deformation and vibrations of the strings are effectively converted into a small alternating voltage. This conversion process contributes to the production of sound, demonstrating the adaptability and significance of piezoelectric materials in musical applications(Maheswari, 2022).

3.2 Shape Memory Alloys (smas)

Shape Memory Alloys find extensive applications across diverse fields such as Biomedical, Aerospace, Robotics, Automotive, and more. The incorporation of Shape Memory Alloys in robotics dates back to the 1980s. In the realm of robotics, various categories exist, each defined by distinctive movement techniques and applications. Examples include jumpers, crawlers, fish-like robots, walkers, flower-inspired robots, medical robots, and biomimetic robotic hands.

Muscle wire, composed of a NiTi alloy, is capable of stretching up to 8% of its length and recovering fully. When a small electric current is applied, the wire undergoes increased hardness and reverts to its original length with a reasonable force.

The integration of muscle wire with a micro-controller circuit gives rise to a notable application known as a 'Robotic Hand.' In this robotic hand, stretched muscle wires are affixed

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to the base of each finger. When a current is introduced to the muscle wire, it contracts to its natural length by pulling on the ordinary wire. The micro-controller is programmed to produce five outputs with switch on and off options, enabling coordinated movement of the hand's fingers(Maheswari, 2022).

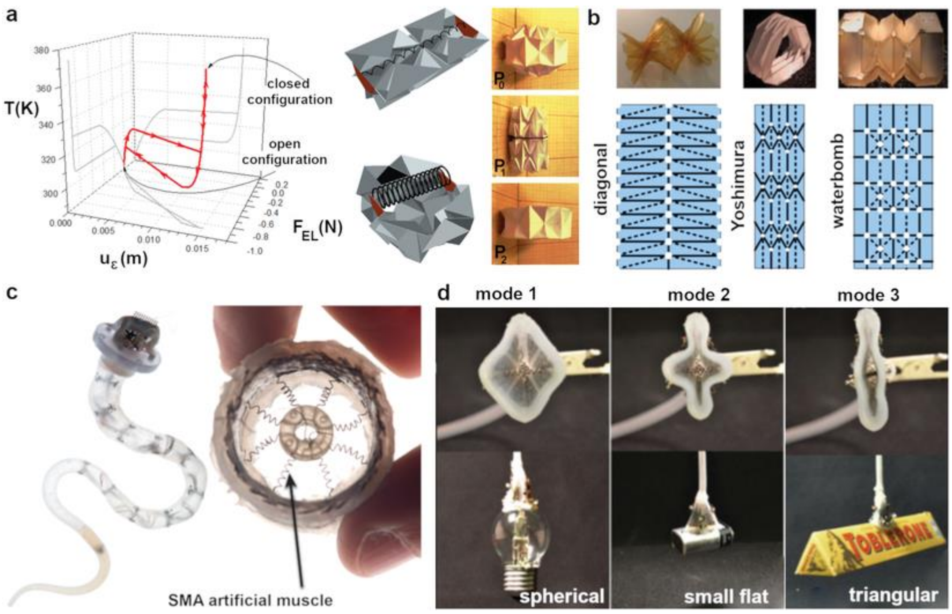

Fig. 7. Shape memory alloys (SMAs) in twisted configurations. a) An origami wheel powered by SMA spring coils cycles between open and closed configurations. Reproduced with permission. b) The peristaltic motion of worms is replicated with origami-inspired design, powered by SMA spring coils. c) An aquatic robotic arm based on SMA coil mimics the motion of octopus tentacles. d) A suction gripper is prepared from SMA to pick up objects of different geometries. (McCracken et al., 2020)

Numerous potential areas have been suggested by researches, but the predominant focus in SMA research has been on metallurgical properties rather than the design perspective. It is

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emphasized that for effective utilization of SMA applications, a closer collaboration between material scientists and engineering designers is crucial. This is due to the specialized nature of information provided by material scientists, making it challenging for design engineers to directly comprehend. The primary challenges in designing SMA actuators are not solely the limitations of SMAs but also the effective communication of information. For instance, outlined three main challenges for SMA actuator design: (1) acquiring a simple and reliable material model, (2) increasing actuator stroke, and (3) deriving design equations to assist engineers in sizing the actuator (Jani et al., 2014).

Hence, the establishment of an efficient information platform or database for SMA applications becomes crucial to reduce development time and costs, minimize the risk of product failure, and effectively identify potential applications through patent screening and analysis. Achieving an optimal design for SMA actuators involves providing design engineers with suitable procedures and guidelines.

3.3 Magnetostrictive Materials

Magneto-Rheological Fluids (MRFs) find extensive applications across various industries, including the automotive sector, civil engineering, household appliances, and biomedical applications. In the automotive industry, MRFs are utilized for their unique rheological properties, providing adjustable damping in shock absorbers and enhancing vehicle performance.

In household appliances, particularly in washing machines, MRF dampers play a crucial role in reducing vibrations during the spin cycle. This application contributes to improved stability and efficiency in washing machines.

However, the integration of semi-active control in household applications is still in the early stages of development. Current discussions primarily revolve around areas of research focused on tub dynamics at low spin and the resonance frequency of the main drum. This work, in

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contrast, concentrates specifically on addressing vibrations induced by high rotational velocities, marking a distinct focus on a crucial aspect of the technology's application in household appliances(Maheswari, 2022).

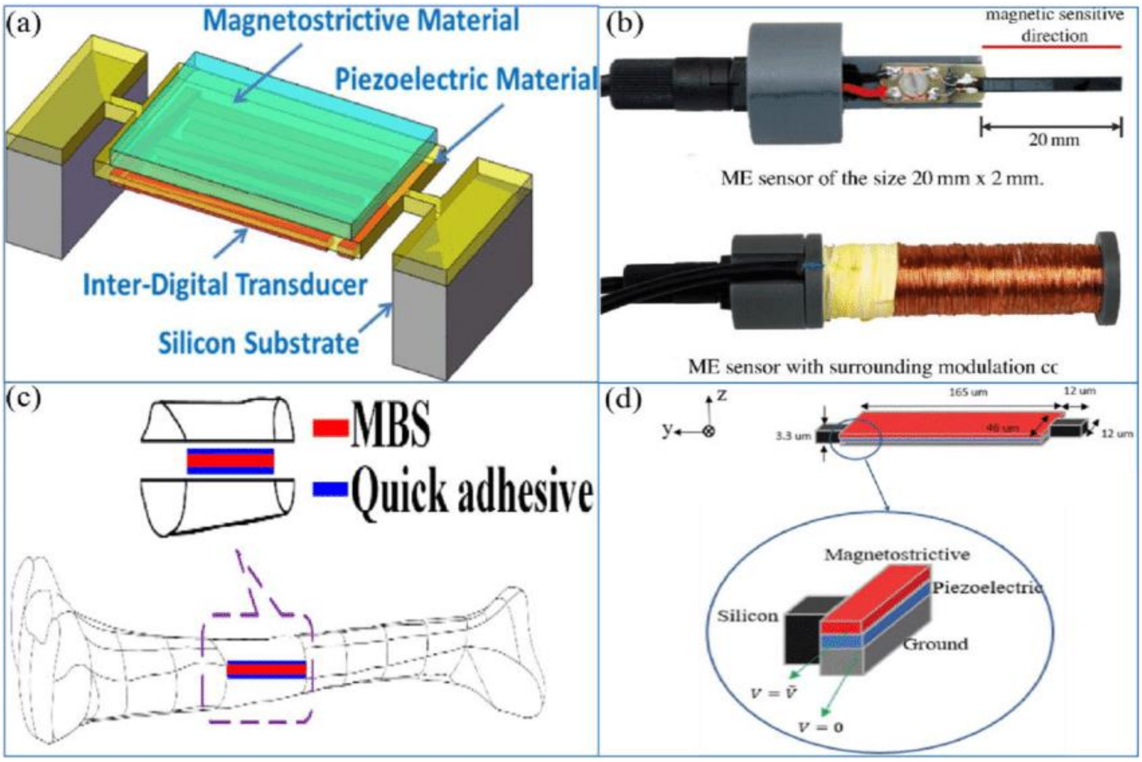

Fig. 8. The applications of magnetostrictive materials in biomagnetic field measurement and wireless implantable devices. (a) 3D schematic of the MEMS resonant magnetic field sensor based on AlN/FeGaB bilayer nanoplate resonator. (b) The ME sensor used for measuring R-waves in human heart. (c) Model for monitoring and evaluating the degradation rate of artificial bone and MBS refers to magnetoelastic-based sensor. (d) ME heterostructure consisting of a piezoelectric AlN film and a magnetostrictive FeGaB film. (Gao et al. 2021)

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3.4 Electroactive Polymers (eaps)

Electroactive Polymers (EAPs) refer to polymers that undergo alterations in their size, shape, or volume when exposed to a robust electrical field. Within the realm of "active materials," which includes piezoelectrics, thermo-elastic polymers, shape memory alloys and polymers, or magnetostrictive materials, electroactive polymers distinguish themselves by their considerable potential for active deformation, rapid response, low density, and enhanced resilience. Notably, they exhibit qualities of being highly lightweight, cost-effective, resistant to fractures, and flexible (Finkenstadt, 2005). Electroactive polymers (EAPs) exhibit large property changes in response to electrical stimulation, enabling applications like mimicking biologic systems and sensors.(Bar-Cohen & Zhang, 2008)

Based on their operational principles, Electroactive Polymers (EAPs) can be classified into two primary categories: ionic and electronic EAPs.

- Ionic EAPs operate through the displacement of ions during electrical stimulation, resulting in a change in shape or volume. An advantageous feature is their responsiveness to low voltages, typically ranging from 1 to 2V. However, since ions move within an electrolyte, these EAPs require constant wetness. They are commonly used as bending actuators with robust bending capabilities but exhibit a relatively slow response speed. Due to the challenging production of stable material configurations, they tend to be costly and are not typically available commercially.
- On the other hand, electronic EAPs function under strong electric fields, where electrostatic forces induce an electromechanical change in the material's shape. Typically applied as planar actuators due to significant in-plane deformations, they operate in dry conditions but necessitate high activation voltages in the range of several kilovolts. Electronic EAPs respond rapidly, display relatively large activation stresses, and can maintain the induced displacement under DC activation("Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges, Second Edition," 2004; Finkenstadt, 2005).

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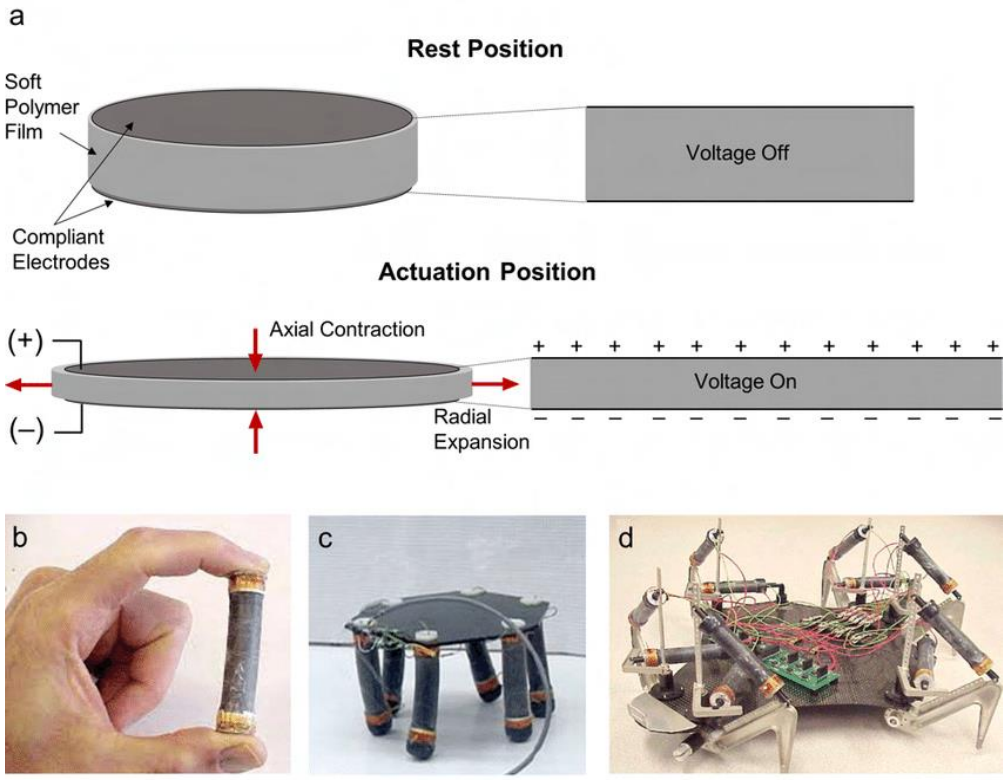

Fig. 9. Electro-Active Polymers (EAPs). (a) Operating principle of dielectric elastomer actuators (DEAs). When a bias voltage is applied across an elastomer (soft polymer) film coated on both sides with compliant electrodes, Coulombic forces compress the film in the axial direction and expand it radially. (b) One degree of freedom multifunctional electroelastomer roll (MER) actuator fabricated with two prestrained films rolled around a compressed central spring (the spring is located at the center of the roll and covered by the films). (c) MERbot, a robot using a 2-DOF MER for each of its six legs. (d) FLEX 2 robot using MER actuators from b. (Higueras-Ruiz et al., 2021)

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4 Smart Materials in Biomedical Engineering

The examination of SMART (Self-Healing, Multifunctional, Adaptive, Responsive, and Tunable) materials in the realm of biomedical applications reveals a landscape abundant in potential, innovation, and challenges. These materials, inspired by natural processes and meticulously crafted, have the potential to redefine the boundaries of contemporary healthcare. They are expected to usher in a new era of medical treatments that are customized, highly flexible, and exceptionally effective. The advancements in SMART materials have demonstrated their transformative capabilities across various facets of biomedicine (Kumar et al., 2023).

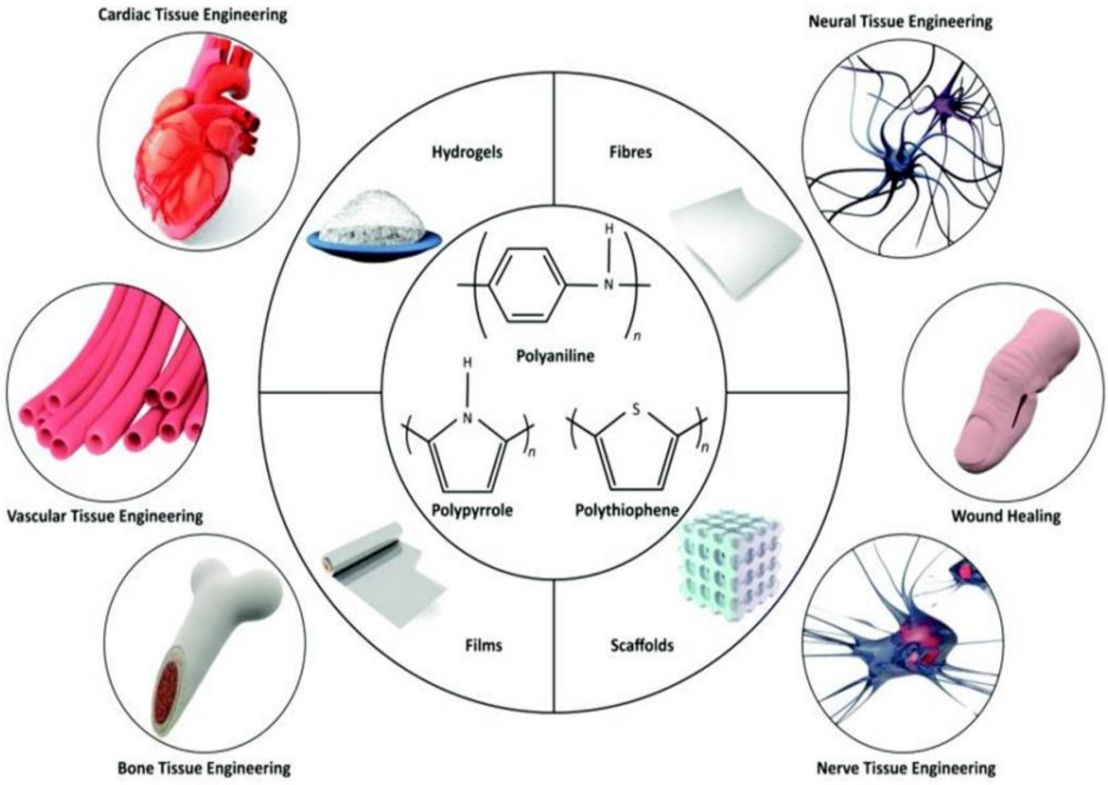

Fig. 10. Use of smart sensors in biomedical application (Tissue engineering) (Fernandes et al., 2019)

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The strides made in materials science have led to the creation of inventive solutions to address complex medical issues. These include materials that can self-heal, emulating natural regenerative processes, and multifunctional materials that seamlessly integrate diagnostics and therapies. Each of these breakthroughs presents distinct opportunities for addressing intricate medical challenges. Materials with the ability to adapt and respond to external stimuli offer precise control over drug delivery and tissue engineering. Additionally, responsive materials enable real-time health monitoring through wearable devices(Kumar et al., 2023).

The enhanced biocompatibility and integration of SMART materials contribute to their adaptable characteristics, broadening their potential applications in fields such as implants, prosthetics, and personalized medicine. Ongoing developments in this field hold the potential to revolutionize medical practices and enhance the overall efficacy of healthcare solutions(Kumar et al., 2023).

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5 Integration of Smart Materials in Electronics

1.1. Flexible electronics and smart textiles

The term "Smart Textiles" encompasses a vast domain of research and products aimed at enhancing the functionality and versatility of conventional fabrics. These textiles, ranging from fibers and filaments to woven, knitted, or non-woven structures, possess the capability to interact with their environment and users. By merging textiles with electronics, known as e-textiles, the development of smart materials capable of a myriad of functions becomes possible, surpassing the constraints of rigid electronic products prevalent today. Smart Textiles not only hold the potential to enhance social welfare but also offer avenues for significant savings in welfare budgets.

Smart Textiles exhibit a high degree of intelligence, categorized into three subgroups:

- Passive Smart Textiles: Primarily equipped with sensors, these textiles detect signals from the environment or user.
- Active Smart Textiles: Apart from sensing, these textiles react to stimuli, incorporating both actuator and sensing functions.
- Very Smart Textiles: These advanced textiles not only sense and react but also adapt their behavior to varying circumstances.

Sensors serve as the nervous system of passive smart materials, detecting signals crucial for their functioning. Actuators, on the other hand, respond to detected signals either autonomously or through a central control unit, forming the backbone of active smart materials. Fabric-based sensing, extensively researched in biomedical and safety sectors, has yielded various applications, including electrocardiogram (ECG), electromyography (EMG), electroencephalography (EEG), temperature sensing through thermocouples, biophotonic sensing via luminescent elements, and movement detection through shape-sensitive fabrics, among others.

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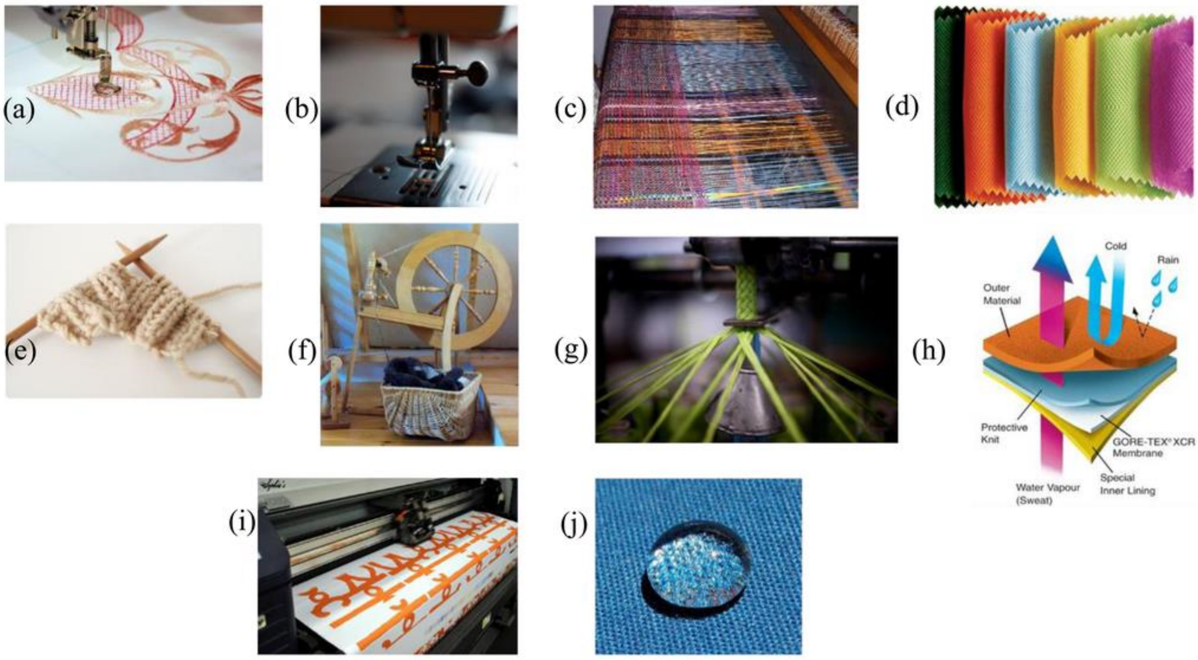

Fig. 11. Different kinds of textile/fabric manufacturing and treatment. (a) Embroidery; (b) sewing; (c) weaving; (d) non-woven; (e) knitting; (f) spinning; (g) breading; (h) coating/laminating; (i) printing and (j) chemical treatment. (Stoppa M., 2014)

Active functionalities encompass diverse capabilities such as power generation or storage, human interface elements, radio frequency (RF) functionality, and assistive technologies. Addressing the significant design challenge of powering smart fabrics, various methods such as piezoelectric elements for energy harvesting from motion or photovoltaic elements have been explored. Human interfaces are classified into input devices, including capacitive patches and shape-sensitive fabrics, and annunciation or display devices like fabric speakers and electroluminescent yarns. Fabric-based antennas represent a straightforward application of Smart Fabrics, utilizing conductive yarns integrated into non-conducting fabrics to create functional antennas. The study of intelligent textiles initially focuses on smart materials, progressing to explore how these materials can be incorporated into textile structures. Various technologies including embroidering, sewing, non-woven textile methods, knitting,

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weaving, spinning, braiding, coating/laminating, printing, and chemical treatments facilitate the integration of smart materials into textile structures, offering specific features such as controlled hydrophobic behavior. In essence, the journey of intelligent textiles begins with the study of smart materials and evolves into the exploration of their seamless integration into textile structures through a myriad of technological processes.

5.1 Wearable technology

Wearable sensing systems encompass two primary categories: electronic devices affixed to fabrics and chemical sensors seamlessly integrated into textiles. The latter category, though challenging, offers an intriguing avenue for creating "smart" textiles with fully integrated sensing capabilities. One approach involves fabricating colorimetric sensors, utilizing halochromic dyes to induce noticeable color changes in the fabric. These sensors have found utility in various occupational settings, such as alerting workers to potentially hazardous chemical leaks without relying on external power sources. However, they exhibit drawbacks such as relatively low stability and pH sensitivity, particularly evident at high gas concentrations. To address this limitation, most textile sensors are designed with a large surface area, achieved through techniques like electrospinning, to enhance pH responsiveness.

For instance, Agarwal et al. developed universal pH sensing nanofibrous sensors using a variety of halochromic dyes combined with Nylon 6. Pakolpakçıl et al. formulated pH-indicating nanofibrous sensors by employing natural halochromic dyes with sodium alginate and polyvinyl alcohol. Guinovart et al. pioneered the fabrication of an electropolymerized polyaniline (PANi)-based conducting polymer for bandage-based wearable potentiometric sensors, targeting wound pH monitoring. Kassal et al. innovated with a wireless RFID-based smart bandage incorporating covalently modified cellulose particles and a pH indicator dye within a biocompatible hydrogel for optical pH determination. Moreover, nanofibrous sensors fabricated via electrospinning and sol-gel methods demonstrated effectiveness in detecting gaseous NH3 and HCl, as evidenced

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by studies conducted by Getmeyer et al. and research by Jeevarathinam et al. and Suleymanov et al., which harnessed the aggregation-induced emission of dyestuff.

Furthermore, wearable sensing systems hold immense potential in revolutionizing healthcare. Continuous monitoring of physical activities in obese individuals, for instance, can incentivize active lifestyles, thereby reducing the need for extensive clinical interventions. Similarly, long-term monitoring of physiological data aids in the diagnosis and treatment of cardiovascular diseases. Commercial technologies for such monitoring encompass parameters like heart rate, oxygen saturation, blood pressure, body temperature, respiratory rate, and galvanic skin response, albeit some may be discomforting. Consequently, ongoing clinical studies are validating wearable sensor platforms to enhance the clinical management of patients with conditions like congestive heart failure.

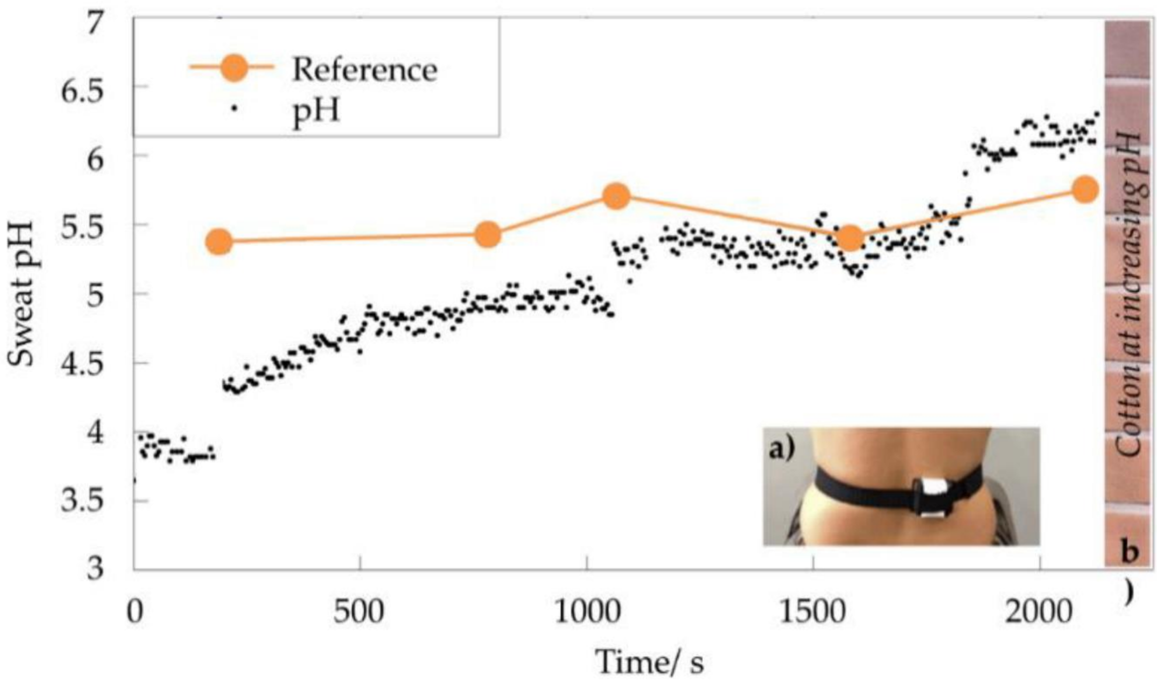

Fig. 12. Comparison between five local skin pH (reference pH) and on-body continuous sweat pH measurements during physical activity (Caldara M., 2016)

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Projects like LiveNet, developed by the MIT Media Laboratory, illustrate the integration of diverse sensors including 3D acceleration, electrocardiogram (ECG), electromyogram (EMG), and galvanic skin conductance for monitoring symptoms of Parkinson's disease and detecting epileptic seizures. Similarly, "LifeGuard," a custom data logger, has been designed for monitoring individuals' health status in extreme environments, both terrestrial and spatial, with promising results. Notably, advancements in non-invasive brain activity monitoring using functional near-infrared spectroscopy (fNIRS) under projects like ASTONISH have demonstrated significant potential, as evidenced by recent patents.

Funded by the European Commission, projects such as AMON have developed wrist-worn devices capable of monitoring ECG, blood pressure, blood oxygen saturation, and skin temperature to aid in the management of cardio-respiratory conditions. Other noteworthy projects supported by the European Commission, including MyHeart, WEALTHY, and MagIC, are centered on developing wearable sensor-equipped garments for monitoring individuals' health in home and community settings. These initiatives signify the burgeoning potential of wearable sensing systems in revolutionizing healthcare management and improving quality of life.

5.2 Future directions in electronic applications

In the era of advancing technologies shaping our daily lives, the foundation of these innovations lies in smart materials and sophisticated manufacturing techniques. Smart materials represent a new class of functional materials capable of sensing and responding to various environmental stimuli, including optical, electrical, magnetic, mechanical, thermal, and chemical signals. By dynamically reacting to changes in their surroundings, these materials emulate biological intelligence, showcasing abilities such as self-deformation, self-diagnosis, self-response, self-adaptation, and even self-repair.

Today, smart materials have evolved into a burgeoning multidisciplinary scientific domain and stand as a prominent international academic discipline. Functional devices, built upon the

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principles of smart materials, integrate modern information technology to process sensory data and execute feedback commands. A defining trait of devices based on smart materials is their ability to sensitively and aptly respond to external stimuli. However, it's crucial to note that the mere amalgamation of smart materials doesn't suffice to create functional devices; instead, their inherent smart properties must be intricately woven into preconceived structures through precise and scientific processes of compounding or assembly.

Presently, the integration of smart materials with structural design predominantly revolves around micro/nanostructures. Micro/nanostructuring from smart materials serves as a fundamental prerequisite for achieving function-oriented microdevice integration and applications. In this context, micro/nanofabrication technology remains the dominant force driving advancements in science and technology, owing to its pivotal role in the development of novel applications.

Lithography-based strategies currently dominate micro/nanofabrication, particularly in fields like optics, electronics, and biology. However, while effective, lithography-based methods pose limitations in directly patterning smart materials into functional structures. These methods typically involve patterning photoresist on target substrates, followed by the deposition of smart materials onto the patterned substrate through various techniques like magnetron sputtering or vacuum evaporation. Although these methods have yielded promising results, they offer limited options for patterning smart materials.

Recognizing the need to explore alternative manufacturing methods for smart materials-based devices, researchers are delving into diverse approaches beyond lithography-based technologies. Among these, additive manufacturing techniques, notably printing, emerge as promising avenues. Printing offers unparalleled universality, diversity, and stability in patterning smart materials, poised to revolutionize micro/nanomanufacturing and device integration technologies.

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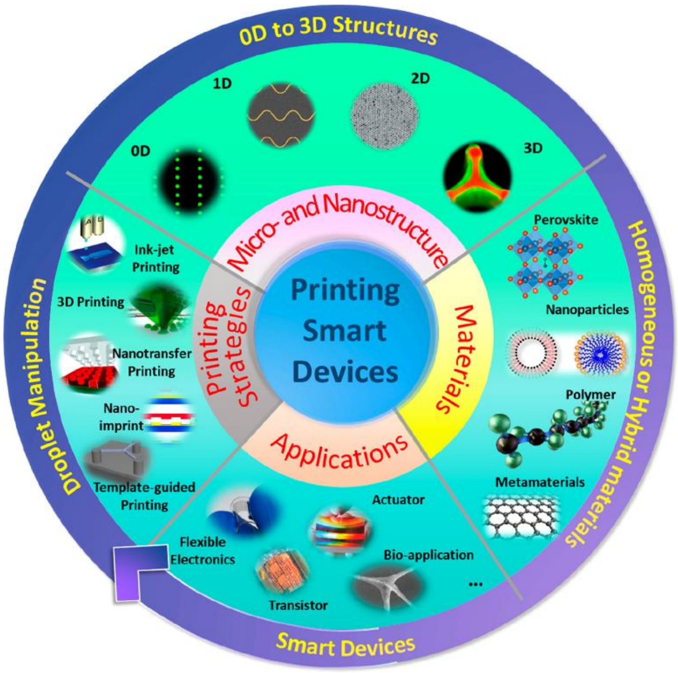

Fig. 13. Smart micro- and nanostructured devices: printing strategies, printable smart materials, micro/nanostructures, and smart device applications. (SU M., 2022)

Recent years have witnessed remarkable strides in designing and constructing printable smart materials and devices, facilitating a myriad of applications in communication, sensing, actuation, and imaging. To propel the practical application of printed smart devices across engineering fields such as aerospace, biomedicine, intelligent robotics, and smart electronics, interdisciplinary endeavors are imperative. This comprehensive review explores recent advancements in printing strategies for smart materials, along with the diverse applications of printed smart devices across various sectors. Emphasizing the direct integration of different functional materials into flexible devices, we delve into the creation of printable smart materials, technologies for printing designed micro/nanostructures, smart devices, and emerging intelligent applications. Furthermore, we address key challenges and opportunities in this field, proposing solutions to realize the printing of multimaterial smart devices efficiently.

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6 Smart Materials in Structural Engineering

6.1 Ultra-high strength composites

Ultra-high strength composites (UHSC) are materials of high structural strength and density. They are made as a special dispersed product with a compressive strength of 150 N/mm^2. The tensile strength of ultra-high strength composites with steel fibres can be up to 15 N/mm^2, and the flexural strength up to 50 N/mm^2 [1-4]. UHSC is a high-tech material that allows creating fairly durable and corrosion-resistant concrete structures (Jayakumar, 2004).

Fig. 14 Ultra-high strength composites

The structure of an ultra-high strength composite is formed during physicochemical reactions that are accompanied by the binding of free water to the clinker minerals of cement and the formation of a saturated solution of crystalline hydrates and their subsequent crystallization. Due to the complexity and insufficient knowledge of these physicochemical processes, there are different theoretical interpretations of their nature and sequence. The first work on the development of an ultra-high strength composite began in the seventies in the United States of America (Martirena et al., 2004). High-strength concrete was first used in 1997 in the expansion (completion - reconstruction) of the Cattenom nuclear power plant in

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France (Wille et al., 2011). The introduction of cast cement mixtures of high homogeneity, viability, and high-strength composites based on them is impossible without the use of polyfunctional modifiers (PFMs). The most effective PFMs are complexes based on superplasticizers (SP) and highly dispersed additives such as microsilica and metakaolin (Fodchuk et al., 2020). At the same time, comprehensive studies of the mechanisms and dynamics of structural changes in UHSC during the course of physical and chemical processes, that occur when superplasticizers are introduced, are required.

6.1.1 Principles of high structural strength and density composites

The development of high-strength concrete mixtures is usually based on modifying the microstructure of the concrete matrix with fine aggregates (Fodchuk et al., 2020; Jayakumar, 2004; Martirena et al., 2004; Wille et al., 2011; Vandenberg & Wille, 2019; Sumariuk & Fodchuk, 2021; Grice, 2005). Grain packing density plays a decisive role in the formation of a composite with ultra-high structural strength and density. Among the technological fillers that exhibit high pozzolanic activity and binding properties, special attention is paid to amorphous condensed microsilica with a microsphere size of 0.1-0.3 µm. The presence of microsilica helps to accelerate the hydration of the alite and belite phases of cement and optimizes the density of grain packing (Fodchuk et al., 2020). This leads to a higher density of the concrete matrix, as well as the generation of a large amount of calcium silicate hydrate (C-S-H) (Fodchuk et al., 2020). An effective modifier is also metakaolin, a product of dehydration of kaolin clay (natural hydroalumina), which densifies the microstructure of the concrete matrix during the hardening of hydrate formations (Fodchuk et al., 2020). Another quality of metakaolin is its pozzolanic activity, which has combined aluminate-silica nature (Fodchuk et al., 2020). According to previous studies (Sumariuk & Fodchuk, 2021; Grice, 2005; Ma et al., 1999; Setiadi et al., 2006; Le Saout et al., 2006; Lager et al., 2005; Ferro et al., 2003; Medvescek et al., 2006), a gel of alumina hydrate Al(OH)3 may form at an early stage of interaction in the system of aluminium and calcium oxides and water (Al2O3-CaO-H2O). Subsequently, depending on the hydrogen content of the medium and other factors, Al(OH)3 crystallizes into high-base calcium hydroaluminates 4CaO-Al2O3-nH2O, hydrogarnets, hydrogenite C2ASH8, and low-base calcium hydrosilicates.

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At the same time, research aimed at clarifying the physicochemical processes that determine the mechanical characteristics (tensile and compressive strength) of a concrete composite modified with a complex of fine additives play an important role.

One of the important directions of the predicted formation of the optimal meso- and macrostructure of concrete is the method of selecting the optimal particle size distribution of polyfractional aggregate, which is based on the analysis of the equations of ideal curves Fuller, Andreassen, Funk, and Dinger (Marsh, 1984). At the same time, a study by Zhang (2007) indicates that this method gives only an approximate composition of the maximum packing of grains by aggregate. Since these equations describe the "ideal" sieving curve for systems with a spherical grain shape and do not take into account possible deviations of shape for real systems. It is considered that this factor can be adjusted using the grain shape coefficient, which is determined by the ratio of the surface area of the ball to the surface area of a grain of equal volume (Marsh, 1984).

This section presents the results of the study of the mechanisms of structure formation in concrete composites, modified with a complex of fine additives, with a compressive strength exceeding 115 MPa. X-ray diffraction, X-ray spectral analysis and electron microscopy were used to determine the composition and products of hydration. Investigations were also performed to clarify the physical and chemical processes that determine the mechanical characteristics (tensile and compressive strength) of concrete composite.

Obtaining reliable information in research is possible only with the use of an integrated approach to planning and conducting experimental tests. A comprehensive approach has a factor space that includes a number of variables. One such variable that affects the reliability of the experimental results is the consistency of the quality characteristics of used materials.

6.1.2 Composites, modified with a complex of fine additives based on microsilica and metakaolin

Fine modifiers made on the basis of domestic raw materials were used in this work. The main physical and mechanical properties are given in Tables 1-4.

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Tables 1 Physical and chemical properties of microsilica according to the manufacturer's certified laboratory

Property	Value
Mass fraction of condensed microsilica in terms of dry residue, not less than, %	97
Shape and average particle size, µm	0,1-0,3
Bulk density, kg/m³	220±0,1
Relative density, g/cm³	2,24±0,1
Specific surface, cm²/g	12000±100
Mass fraction of SO2, %	91,4
Mass fraction of free alkalis (Na2O, K2O), %	1,6
Mass fraction of CaO, %	1,3
Mass fraction of SO3, %	0,3
Pozzolanic activity, mg Ca(OH)2/g	1575

Determination of the effective microsilica content.

The concrete specimens were made and tested in accordance with the requirements of DSTU B V.2.7-214:2009, EN 12390-1:2000 "Concrete. Methods for determination of strength by control specimens". Concrete specimens are made in inventory metal moulds of size 10*10*10 cm³, which meets the requirements of DSTU B V.2.8-38:2011, EN 206-1:200. The mixtures of the concrete mixtures are shown in Table 2. All samples were stored at a relative humidity of 95% and a temperature of 20°C. The test data are shown in Fig. 15. and Fig. 16.

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Table 2

Composition of concrete mixture per 1 m^3

No	Water (kg)	Cement (kg)	Sand (kg)	Fractional crushed stone, mm			Microsilica (kg)	Layer (kg)
				2-5	5-10	10-20		
				(kg)				
1	141	360	751	199	443	1021	-	3,6
2	141	360	751	192	443	1021	9	3,6
3	141	360	751	181	443	1021	18	3,6
4	141	360	751	163	443	1021	36	3,6

The arithmetic mean of the series of samples was used to plot a graph of the strength of the samples (Fig. 2).

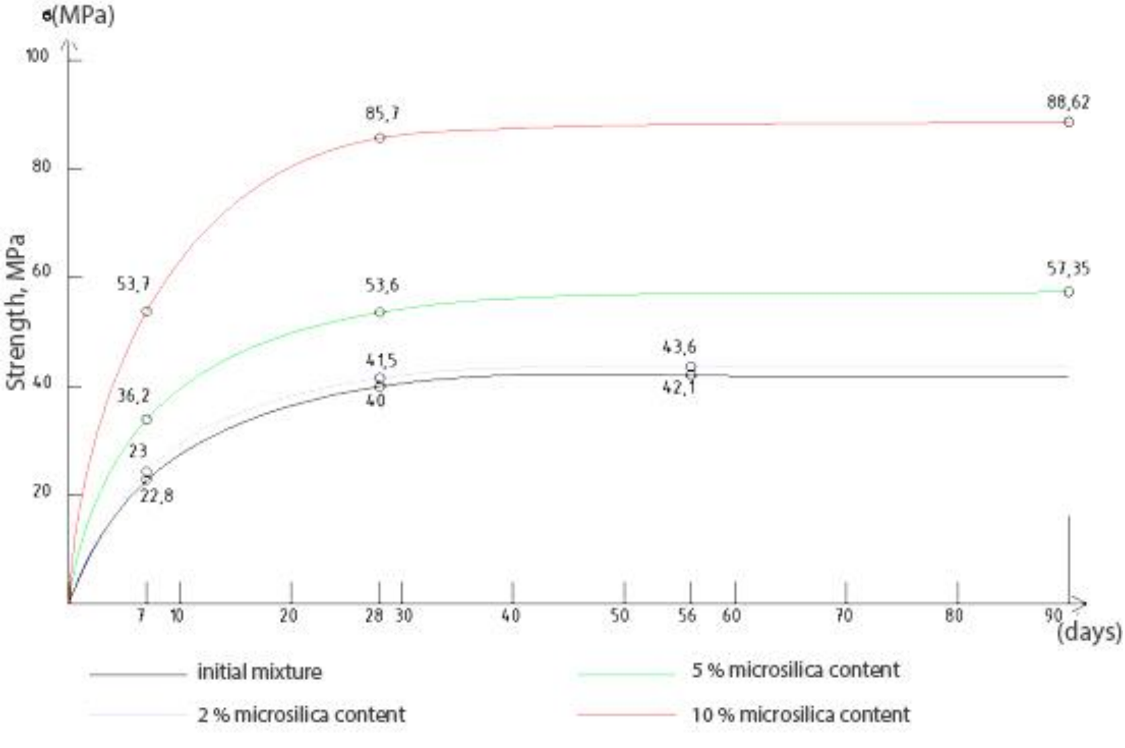

Fig. 15. Compressive strength of samples

Microsilica content of up to 2% does not provide a significant increase in strength, while addition up to 5-10% leads to a significant increase in strength.

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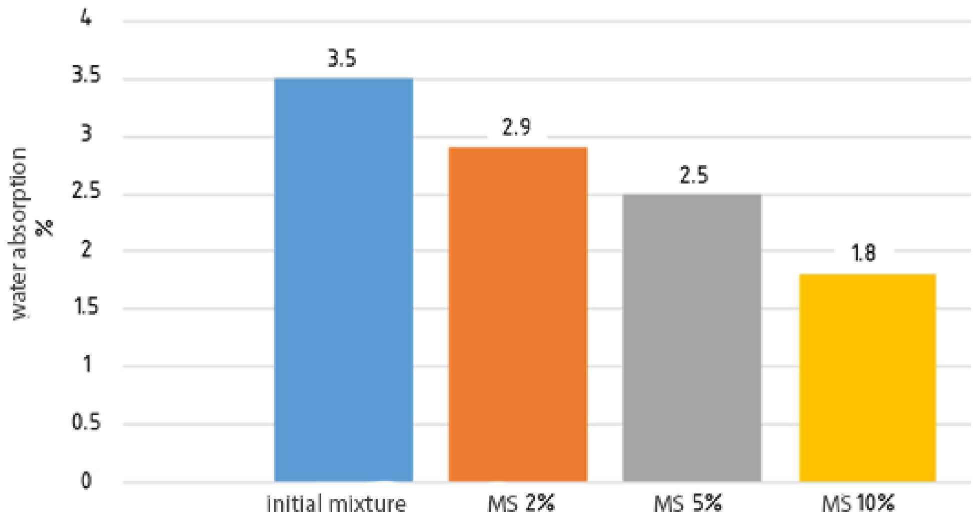

Fig. 16. Water absorption of concrete samples

Water absorption of concrete samples decreases with increasing microsilica content, which is explained by the dispersity of microsilica that fills the micropores and compacts the cement matrix with calcium hydrosilicates. This result confirms the existing scientific research in this area.

Table 3

Composition of chemical compounds according to the certified laboratory of the manufacturer.

Supplement	Chemical composition in %					Grain size	Density
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO		
Microsilica	96	0,10	0,08	0,65	0,16	0,1-0,3 µm	280-350 kg/m²
Metakaolin	51,4	0,8	42	-	-	10-40 µm	1250 kg/m²

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Table 4

Composition of chemical compounds in cement from a certified laboratory of the manufacturer.

Chemical composition in %					
SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3
96	5	5,1	64,2	1,2	0,2

Table 5

Physical and chemical properties of metakaolin

Property	Value
Shape and average particle size, %	Lamellar 5-30 μm
Bulk density, kg/m³	352
True density, g/cm³	2,59
Relative density, g/cm³	2,24±0,1
Specific surface area, cm²/g	3000±100
Residue on sieve № 0.08, %	0,7
Mass share of SiO_2	51.4
Mass share of Al_2O_3	42
Mass share of Fe_2O_3	0,6
Mass share of TiO_2	0,5
Pozzolanic activity, mg Ca(OH)2/g	1275

Determining the effective content of metakaolin.

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Four experimental concrete mixtures were used for physical and mechanical tests: №1 (original) and №2, 3, 4 – modified with a complex fine additive based on metakaolin with a corresponding dosage amount of 2, 5, 10%. The compositions of the mixtures are given in the table. Several series of cube-shaped samples with dimensions of 10*10*10 cm³ were made and kept under normal conditions (at a temperature of 20 °C and relative humidity of 95%). The test data are shown in Fig. 17.

Table 6

Concrete mixtures per 1 m³

Name of materials	Composition №1 Initial mixture	Composition №2 2% of metakaolin	Composition №3 5% of metakaolin	Composition №4 10% of metakaolin
Portland cement PC I-500	360	360	360	360
River sand	751	751	751	751
Crushed granite fraction 2.5-5 mm	199	192	181	163
Crushed granite fraction 5-10 mm	443	443	443	443
Crushed granite fraction 10-20 mm	1021	1021	1021	1021
Superplasticiser	3,6	3,6	3,6	3,6
Metakaolin	-	7,2	18	36
Water (l)	141	141	141	141

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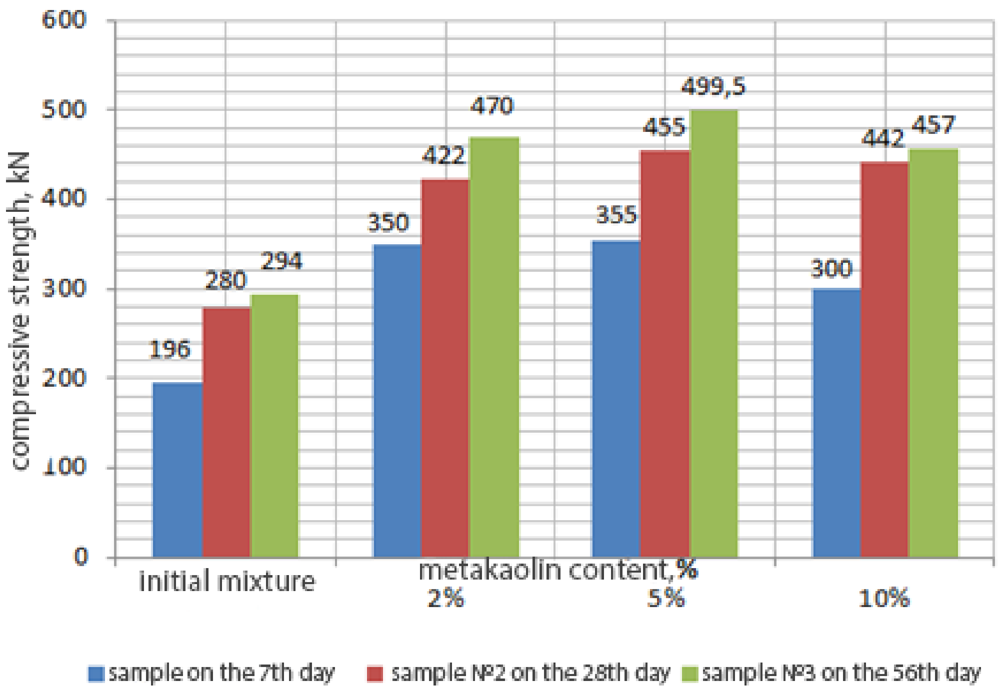

Fig. 17. Strength test results of concrete mixtures

Samples of concrete composites were aged for 7, 28, 90 days under normal conditions and the results of mechanical tests were obtained as shown in Fig. 17.

Metakaolin was added to concrete mixtures together with a polycarboxylate-based superplasticiser to compensate high water requirement.

Mixing technology

All components were added and mixed from smaller to larger fractions and thoroughly mixed with gradual modification with fine additives, which ensured a more even distribution of aggregates and fillers in the mixture (Fig. 18).

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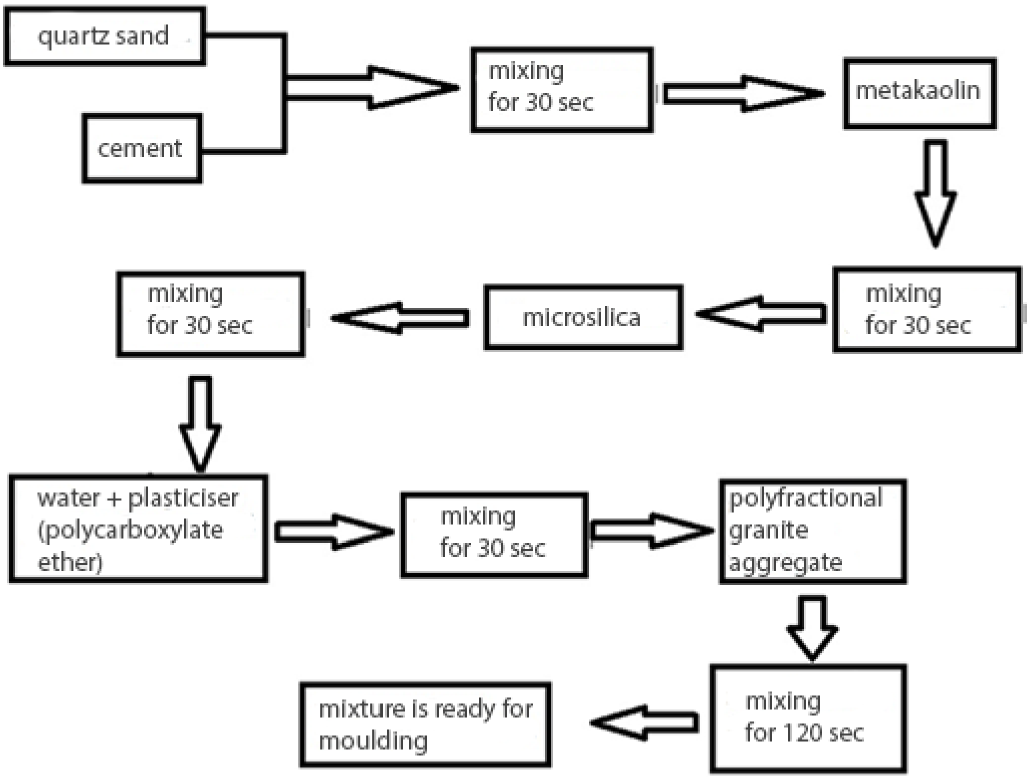

Fig. 18. Mixing technology of the mixture

Water with polycarboxylate plasticiser was added to the mixture after mixing the dry fraction. Such mixing of the dry composition distributes the larger micron, cement and pozzolanic particles with smaller submicron particles and promotes the densest possible packing, causing at the same time physical and chemical activation of the powdered additives. The water-cement ratio was 0.26.

6.2 Samples and research methods

A prerequisite for the production of high-strength concrete is the substantiation of the cause-and-effect relationships of structure formation and the discovery of new approaches to chemical modification of the concrete mixture (Marsh, 1984). However, there are a number of factors that can affect physical and mechanical properties of concrete. First of all, it is

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microcracks caused by autogenous shrinkage (Poole et al., 2007). This significantly reduces the resistance of concrete to aggressive environments and defects in the interfacial transition zone between the cement matrix and large aggregates (Marsh, 1984).

Among the technological factors that affect the formation of a concrete matrix of high structural strength and density is modification with a complex of fine modifiers based on amorphous condensed silica with a specific surface area of ≈250 m^2/g (Marsh, 1984). In particular, work by Marsh (1984) investigated the effect of a complex of different nanofillers on their physical and mechanical parameters and the formation of a denser structure of cement stone. It is noted that, as a rule, the structure of high-strength concrete is formed mainly from low-base calcium hydrosilicates (CSH-I) and such structural models of cement gel as Genite (Ca9H22O32Si6) and Tobermorite (Ca2H3O11Si3) (Marsh, 1984). In the study conducted by Marsh (1984), authors show that highly active pozzolans lead to a decrease in porosity and calcium hydroxide (Ca(OH)2) content. This, in turn, affects the generation of calcium hydrosilicates.

The peculiarities of the formation of the microstructure of concrete fractures without and with the addition of ultrafine modifiers were investigated by scanning electron microscopy (Hitachi SU 70, Zeiss EXO 50 microscope) and X-ray diffraction (Link - 860 analysis, Oxford Inca Energy 450) in this section. The influence of the phase composition of the formed compounds on the character of crack opening in the process of composite fracture was analysed.

Two experimental concrete mixtures were used for physical and mechanical tests – №1 (original) and №2 – modified with a complex of fine modifiers based on microsilica and metakaolin. The composition of the mixtures is shown in Table 6. Several series of cube-shaped samples (10*10*10 cm^3) were made and stored under normal conditions (at 20°C and 95% relative humidity).

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Fig. 19. Cubic samples of 10*10*10 cm³ size

The compressive strength of the samples of mixture No. 1, created on the basis of the analysis of analytical curves describing the formation of the optimal meso- and macrostructure of the concrete composite (Sumariuk & Fodchuk, 2021), was approximately 61 MPa. At the same time, the compressive strength of the samples was approximately 120 MPa for mixture No. 2. The recommendations of the German and Ukrainian standards DIN EN 1045, DSTU B V.2.6-156:2010, which recommend the compositions of the main components and the size of aggregates and their percentage content, were used to predict the meso- and macrostructure of the modified concrete (Fodchuk et al., 2020).

The compressive strength was determined using a hydraulic press "TEST MAK" 2000kN, with the samples being loaded continuously at a rate that ensures an increase in the design stress in the sample until its complete failure within (0.6 ± 0.4) MPa/s. The analysis of the microstructure features of concrete cracks was carried out using a scanning electron microscope Hitachi SU 70, Zeiss EXO 50 using a CCD-detector. Elemental analysis of the objects was carried out by means of energy dispersive X-ray spectroscopy (Link – 860, Oxford Inca Energy 450 for energy dispersive X-ray analysis and SIMS analysis).

Structural studies of the phase composition of cement and cement stone samples were carried out on a X'Pert PRO MRD diffractometer in a single-crystal scheme for CuK*1a

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radiation. Pre-ground samples and a fine powder cement were sieved through a sieve with a mesh diameter of ~ 8 μm for the purpose of ploting the calibration graphs.

The experimental X-ray data were processed using the Match3 software; the experimental X-ray diffraction patterns were compared with theoretical ones calculated using the Rietveld method for data reliability (Fodchuk et al., 2020).

6.2.1 Analysis of the microstructure of composites of different structural strengths and densities

Fig. 20 and Fig. 21 show fragments of scanning electron microscopy images, and Tables 7 and 8 contain X-ray spectral analysis data in the areas of the sample sections marked with numbers.

The list of elements and their percentage content indicates the presence of calcium hydrosilicates and aluminates, as well as calcium hydroxide in the concrete matrix. It is noteworthy that the content of the main components of the area 7 bounded by the lines in Fig. 20 and Fig. 21 for samples №1 and №2 is almost the same. In the local grains, the percentage of the main elements is also the same, in particular, in grains 3 and 4 in Fig. 20 and 1, 2 and 3 in Fig. 21. At the same time, the intergranular zones 1 and 2 (Fig. 20) have a significantly (two times) lower carbon content and a higher calcium content than the corresponding zones 5 and 6 in Fig. 8. At the same time, the ratio of calcium to silicon is almost the same. However, in the same grain zones 5, 6 in Fig. 7 and Fig. 8, the ratio of Ca/Si compounds is lower, for mixture №1 - 1.04-0.88, for mixture №2 - 0.77-0.76. This may indicate a greater amount of low basic calcium hydrosilicates.

The microstructure of the sections differs significantly in the images. For sample №2 in Fig. 8, it is more developed and compacted. The reason may be that the modified samples are characterised by a higher content of hydration products. It seems that the hydration of clinker minerals during concrete hardening produces a number of chemically active substances, primarily calcium oxide hydrate and calcium silicate hydrate. Probably, metakaolin and microsilica in the concrete mixture create conditions for the transformation of unstable and soluble calcium hydroxide into strong crystalline calcium silicate hydrate (CSH). Thus, the compacted structure of the concrete gives an increase in the strength index for sample №2.

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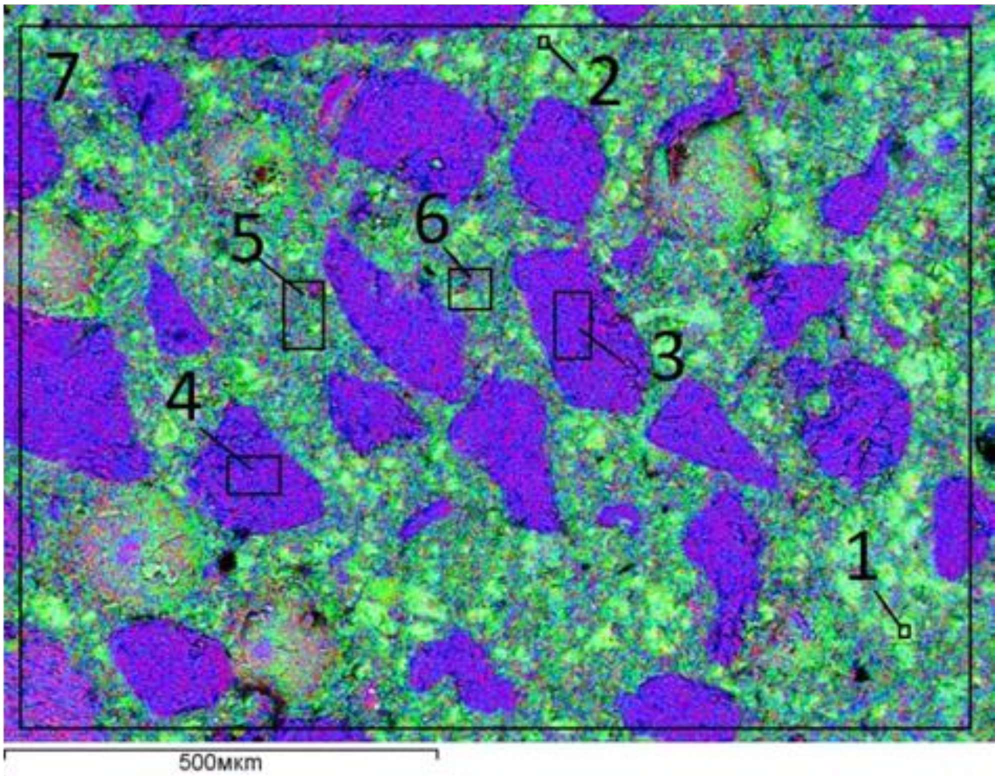

Fig. 20. Fragments of images of the macro- and microstructure of surface sections of the cement matrix of mixture №1

Table 7

Spectral distribution of the main elements in the areas of cement matrix sections of composition №1 indicated by numbers (Fig. 20).

№ of area	C	O	Mg	Al	Si	K	Fe	Ca
	%							
1	2.52	40,30	0,57	1,78	13,38	0,49	1,74	39,23
2	6,54	36,56	0,59	0,43	12,34	-	-	43,54
3	20,32	42,05	-	-	37,18	-	-	0,45
4	18,40	40,61	-	-	40,19	-	0,34	0,46
5	21,33	37,56	0,70	1,8	17,81	0,8	1,30	18,69
6	21,66	38,90	0,71	2,15	18,44	0,92	1,01	16,20

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7	19,06	40,28	0,54	1,37	23,64	0,58	0,8	13,74

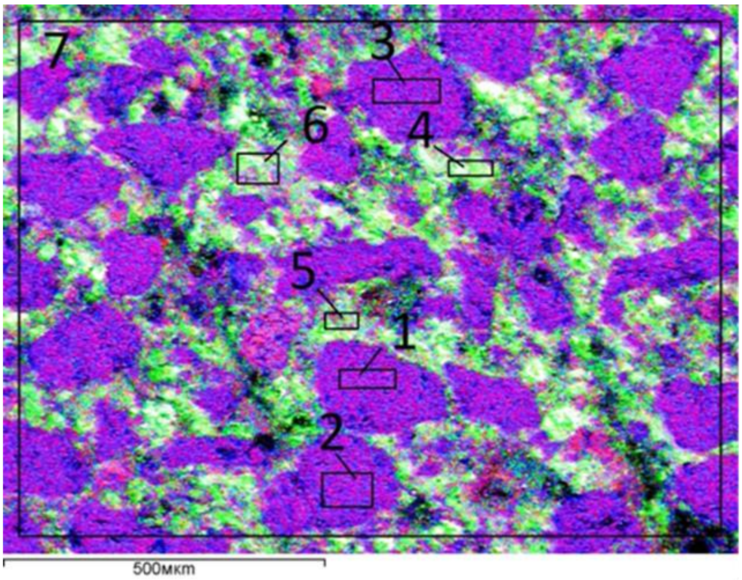

Fig. 21. Fragments of images of the macro- and microstructure of surface sections of the cement matrix of mixture №2

Table 8

Spectral distribution of the main elements in the areas of cement matrix sections of composition №2 indicated by numbers (Fig. 21).

№ of area	C	O	Mg	Al	Si	Fe	Ca
	%						
1	11,51	46,05	-	-	42,24	-	0,20
2	12,12	45,50	-	-	41,95	-	0,43
3	17,15	42,85	-	0,18	38,98	-	0,55
4	14,06	41,09	1,24	1,92	17,09	0,94	22,95
5	9,37	45,89	1,00	2,92	21,94	1,13	17,09
6	8,02	45,23	1,10	2,86	23,41	1,01	17,80
7	20,28	40,69	0,40	1,53	26,38	0,80	9,34

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Filling the pore structure with hydration products leads to a decrease in their volume, even a slight decrease in pore volume (by 1-2%) is a consequence of an increase in the structural strength of the composite.

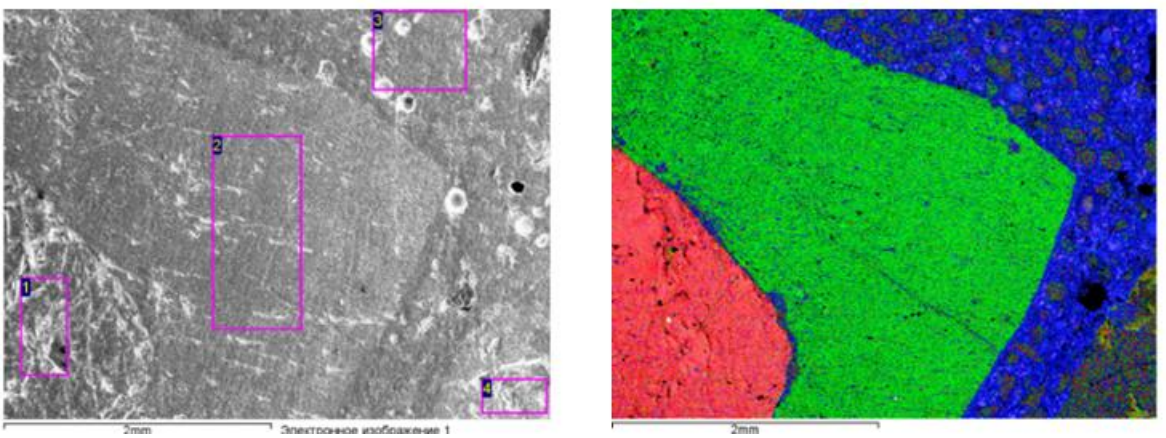

Fig.22. SEM image of the boundary between aggregate and binder of the mixture №1 (red - Fe, green - Si, blue - Ca)

The forces of interaction between the binder and aggregate are similar to those within the composite. However, there is a certain chemical bond between the cementitious system and the aggregate, which can enhance the adhesion of the contact surface in the areas of interaction with the aggregates (Fig. 22).

Table 9

Spectral distribution of the main elements in the areas of the cement matrix sections of composition №1 indicated by numbers (Fig. 22).

Spectrum	in static	C	O	Mg	Al	Si	K	Ca	Fe	in total
1	Yes	10,78	37.57	4.00	8.70	16.26		0,92	21.77	100,0
2	Yes	15.81	39.68		7.72	27.51	8.39	0,90		100,0
3	Yes	21.60	39.86	0,60	1.15	24.39	0,59	11.10	0,71	100,0
4	Yes	12.55	45.71		0,58	40,17	0,54	0,44		100,0

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Max		21.60	45.71	4.00	8.70	40,17	8.39	11.10	21.77	
Min		10,78	37.57	0,60	0,58	16.26	0,54	0,44	0,71	

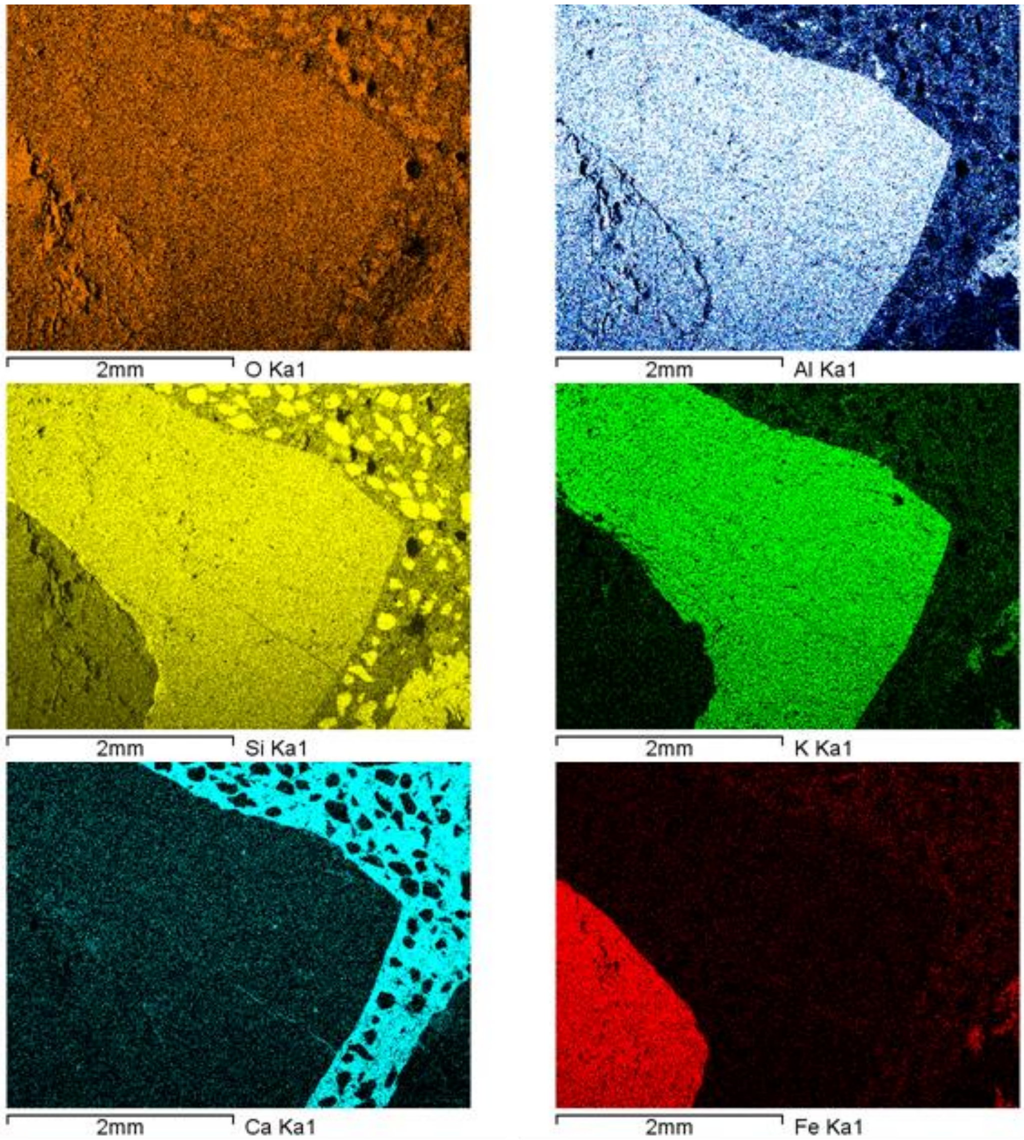

Fig. 23. Elemental distribution maps of compounds

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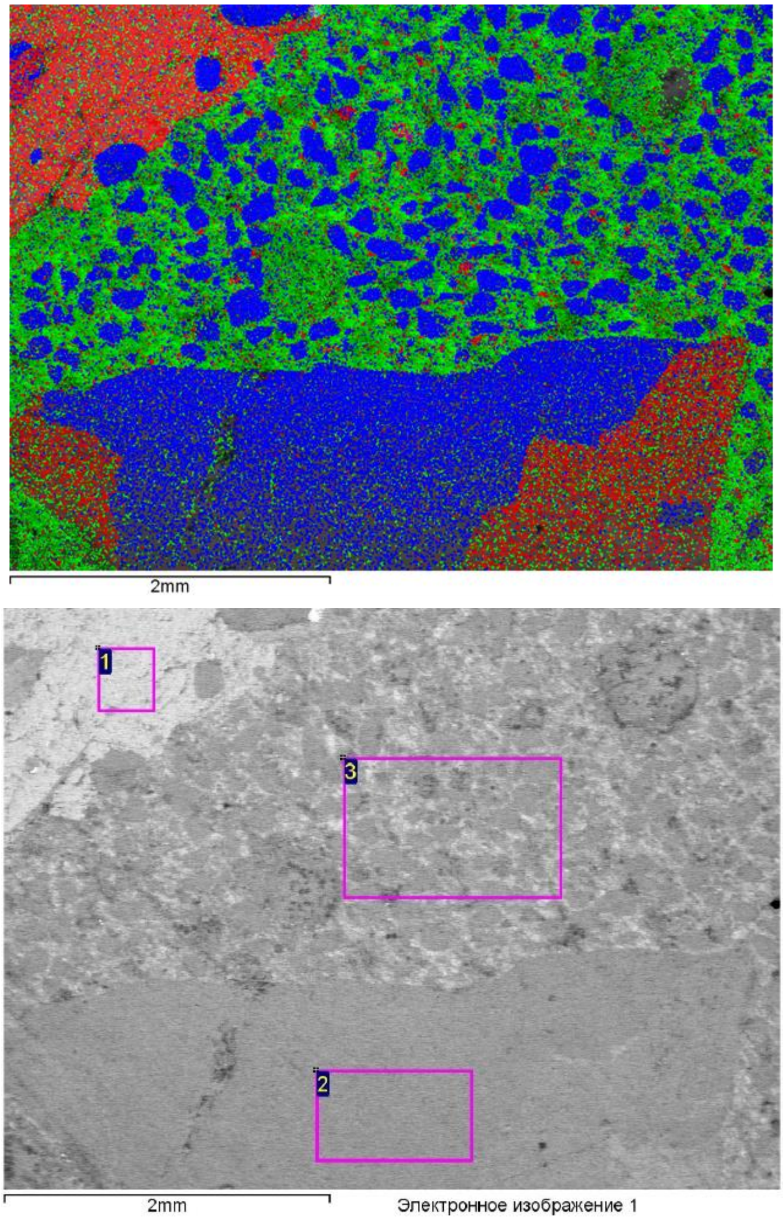

Fig.24. The image of the boundary between aggregate and binder of the mixture №2 (red - Fe, green - Si, blue - Ca)

Table 10

Spectral distribution of the main elements in the areas of the cement matrix sections of composition №2 indicated by numbers (Fig. 24).

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Spectrum	in static	C	O	Mg	Al	Si	K	Ca	Fe	in total
1	Yes	14,11	37,04	3,89	8,66	16,54		0,89	18,87	100,00
2	Yes	16,43	43,50			39,60		0,47		100,00
3	Yes	20,49	40,89	0,51	1,50	25,53	0,52	9,84	0,72	100,00
Max		20,49	43,50	3,89	8,66	39,60	0,52	9,84	18,87	
Min		14,11	37,04	0,51	1,50	16,54	0,52	0,47	0,72	

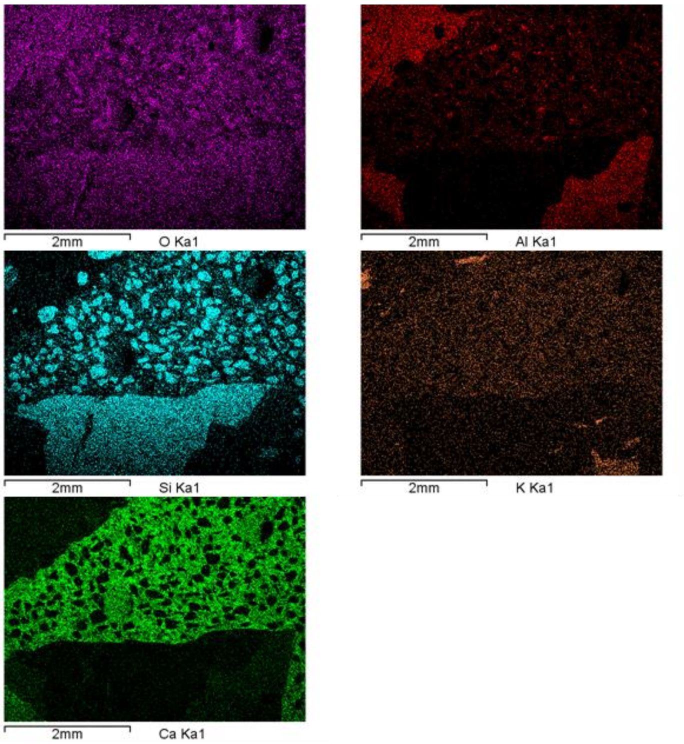

Fig. 25. Elemental distribution maps of compounds

6.2.2 X-ray studies

A high-resolution PANalytical Philips X'Pert PRO diffractometer was used for X-ray studies: a parabolic Hegel mirror placed behind the X-ray tube with CuKα1 radiation with wavelength λ=1.54056 Å, followed by a four-crystal Bartels monochromator (4×Ge220) and a spot detector with a triple analyser crystal (3×Ge220). The divergence of the primary beam and the

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angular acceptance of the analyser crystal used before the detector were Δαi,f≈1-2 angular seconds.

The X-ray and spectral analysis data show that in a series of samples with a strength of 120 MPa (mixture №2), a number of chemically active substances are formed during the hydration of clinker minerals during concrete hardening (Fig. 26). These are, first of all, calcium oxide hydrate, calcium silicate hydrate and such structural gel models as Genite and Tobermorite. The results of the identification of the formed phases are given in Table 11.

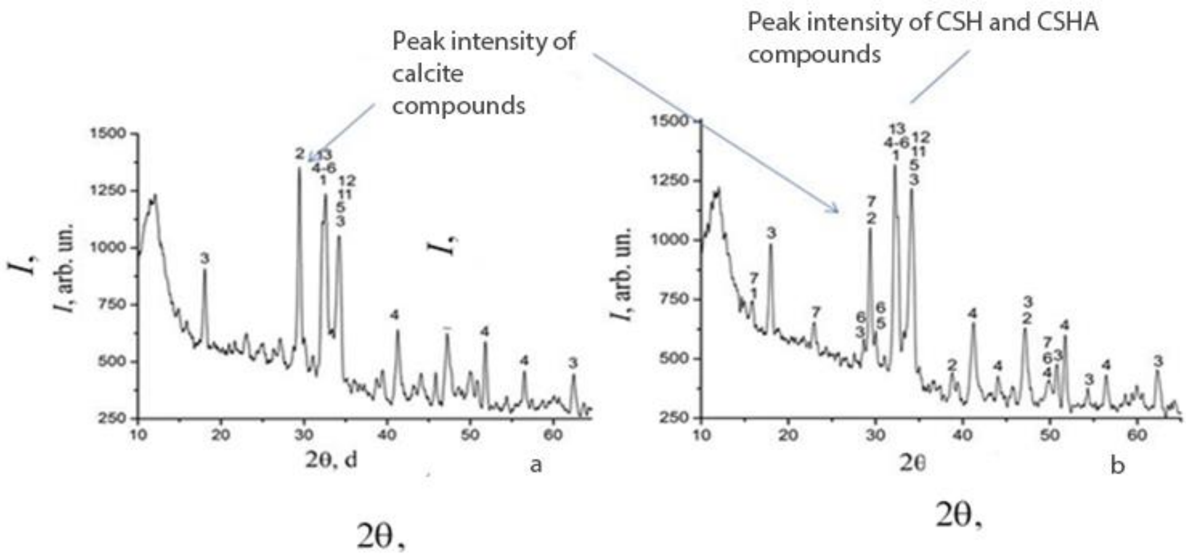

Fig. 26. Diffraction curves of cement hydration compounds: mixture №1 and hydration compounds of modified with microsilica and metakaolin cement (a); mixture № 2 (b)

The characteristic products of Portland cement hydration for sample №2 in the diffraction curve of Fig. 26 are numbered and correspond to next compounds: Ettringite (1 - Al2Ca6H66O49.68S3 - d/n=0,974; 0,563; 0,388; 0,278 nm); calcium hydrosilicates (4 - Ca3H2O7.5Si1.5 - d/n=0,278, 0,335, 0,181 nm); Genite (5 - Ca9H22O32Si6 - d/n=1,049; 0,262; 0,278 nm); Tobermorite (b - Ca2H3O11Si3 - layer thickness of 1.1 nm - 0,308; 0,297; 0,351 nm) (Fodchuk et al., 2020).

It is important that these maxima are located in the same angular positions as the intensity maxima for clinker minerals, in particular, for alite (C3S) and belite (C2S). This indicates their crucial role in the formation of the cement matrix.

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The analysis of the theoretically calculated diffraction curves (by the Rietveld method) for the main hydration compounds (calcite, portlandite, calcium hydroaluminate and calcium hydrosilicates of different basicity) confirms the presence of these compounds in the phase composition of the hydration products, since the geometry of the theoretically calculated diffractogram repeats the experimental one, on the main parameters of the diffraction maxima for mixture №1 (Fig. 27 a). However, in the composite of mixture №2, there are differences in the angular positions of calcite compounds and highly basic calcium hydrosilicates (Fig. 27 b). Such discrepancies are possibly due to the generation of a large number of different types of calcium hydrosilicates and hydroaluminates, which cannot be detected in the diffractograms in their unsynthesised form (Fodchuk et al., 2020).

The composition of the main hydration compounds of mixture №1 (Fig. 26) is similar to that of mixture №2. However, there are some differences. In particular, the intensity of the peaks (indicated by the number 2) from calcite is much higher (by ≈ 15%), which indicates their higher concentration in the hydration phases than in concrete composites with finely dispersed modifiers.

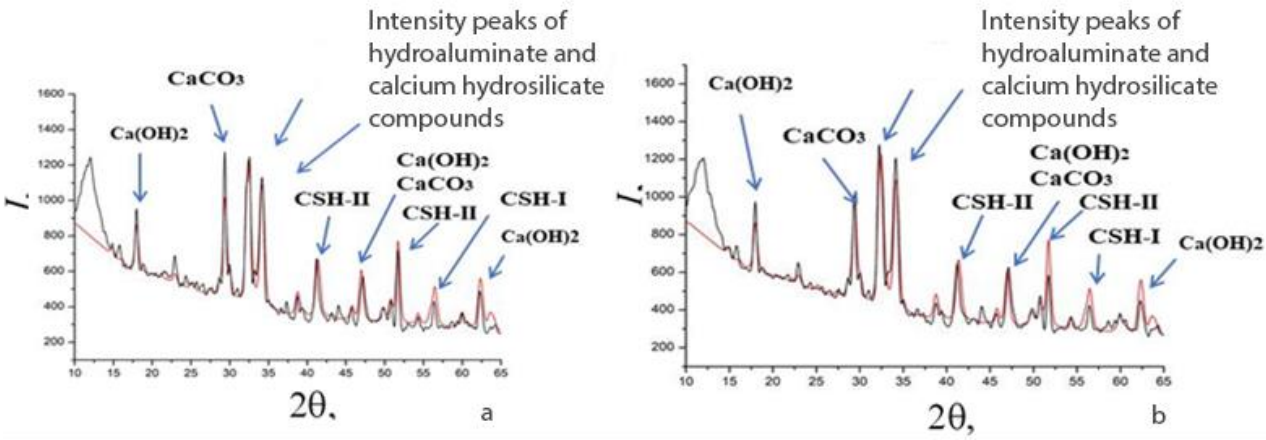

Fig. 27. Analysis of theoretical (according to Rietveld method) and experimental diffraction curves of hydration compounds of mixture №1 (a) and mixture №2 (b)

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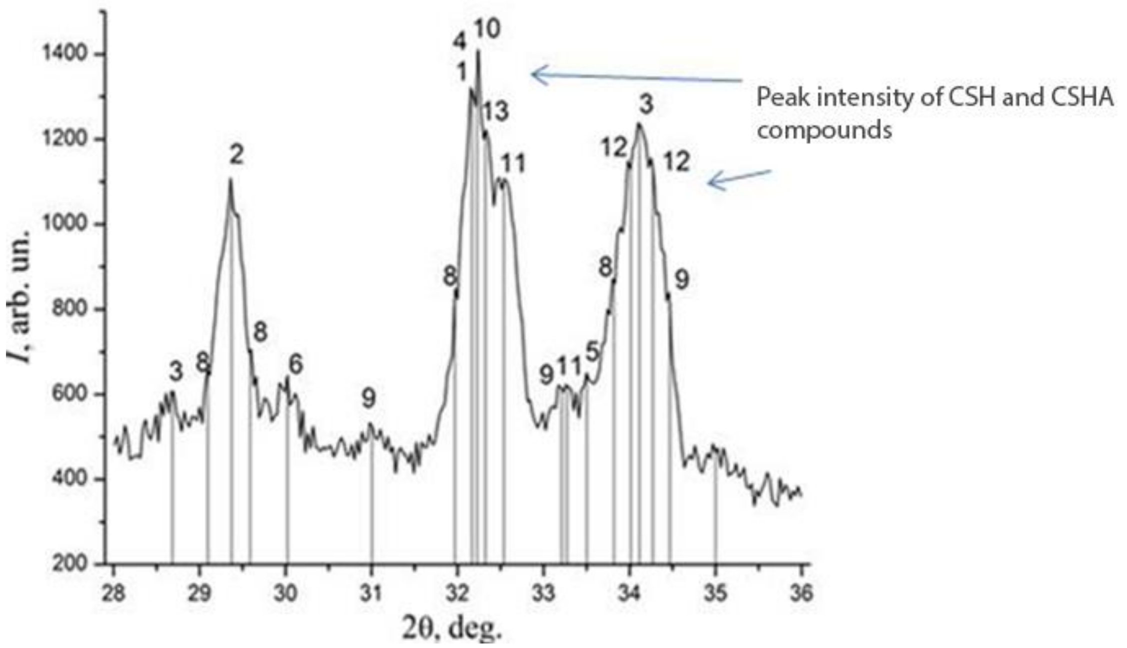

Fig. 28. Fragment of mixture №2 X-ray diffraction curve, shown in Fig. 26

Table 11

List of compounds of the phase composition of hydration products (Fig. 28).

№	Chemical formula	*d / n*	Compound name
1	$Al_2Ca_6H_{66}O_{49.68}S_3$	0,974, 0,563, 0,388	Ettringite
2	$CaCO_3$	0,278, 0,303, 0,191	Calcite
3	$Ca(OH)_2$	0,491, 0,262, 0,192	Portlandite
4	$Ca_3H_2O_{7.5}Si_{1.5}$	0,278, 0,335, 0,181	Hydrosilicate calcium
5	$Ca_9H_{22}O_{32}Si_6$	1,049, 0,262, 0,278	Genite
6	$Ca_2H_3O_{11}Si_3$	0,308, 0,297, 0,351	Tobermorite 1.1 nm
7	$Ca_{2.5}H_{11}O_{12.5}Si_3$	0,552, 0,310, 0,301	Tobermorite 1.4 nm
8	$Ca_5H_{10}O_{22}Si_6$	0,307, 0,301, 0,279	Clinotobermorite
9	$Ca_2H_2O_5Si$	0,287, 0,269, 0,260	Calcium silicate hydrate
10	$Ca_5H_2O_{10}Si_2$	0,303, 0,277, 0,256	Calcium silicate hydrate

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11	$Al_2CaH_{10}O_{21}Si_6$	0,305, 0,275, 0,268	Calcium silicate hydroaluminates
12	$Al_2CaH_8O_{10}Si_{12}$	0,263, 0,262	Calcium silicate hydroaluminates
13	$Al_{3,5}Ca_3H_{9,7}O_{12}$	0,276, 0,309	CAH

It is important that the use of cement with a low C3S content (less than 50%) makes it much more difficult to produce high-strength concrete, in particular when silica and metakaolin are used.

This is due to the fact that the effectiveness of the use of such additives implies the presence of excessive portlandite in the cementing system, while the system with a low C3S content is characterized by a reduced content of calcium hydroxide Ca(OH)2 (Sumariuk & Fodchuk, 2021). X-ray studies confirm the crucial role of controlling the chemical composition of cement, which has a decisive impact on the development of microstructure and phase transitions in complex and long-term hydration processes.

6.2.3 Spectral analysis of high-strength composites

The microstructure of the surface of fractures and their phase composition were investigated using scanning electron microscopy (Fig. 29) and energy dispersive X-ray spectroscopy (Fig. 30, Fig. 31) for a more complete picture of the formation of hydration phases in high-strength composites and the effect of ultrafine modifiers.

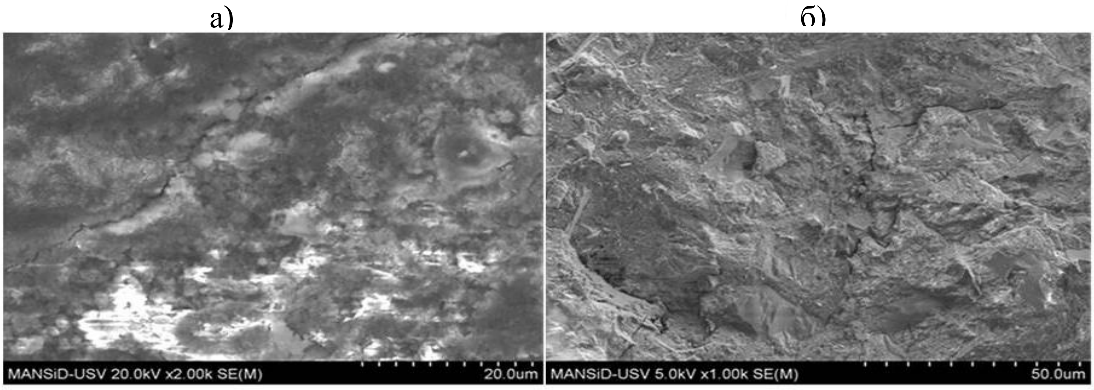

Fig. 29. SEM-images of the fracture surface of the cement matrix of mixture №1 (a) and mixture №2 (b)

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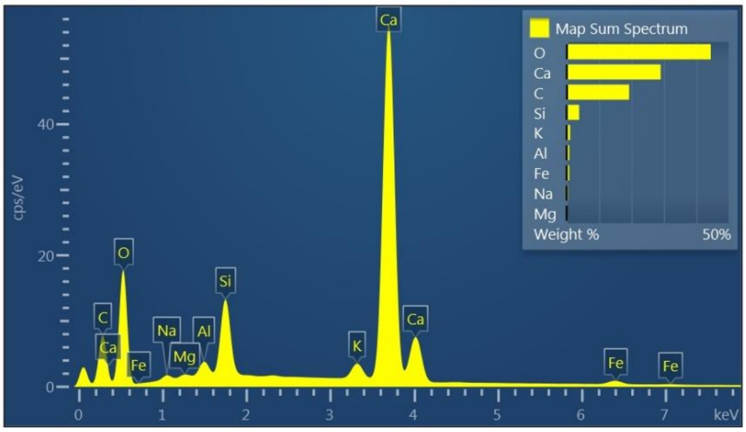

Fig. 30. Elemental composition of mixture №1 according to the results of energy dispersive X-ray analysis, in accordance with the images in Fig. 29, a

The list of elements in table 12 and their percentage content indicate the presence of the vast majority of calcite CaCO3 and Ca(OH)2 in the cement matrix of mixture №1.

Table 12

Quantitative correlations between the main components of the elemental composition of the fracture, of concrete composition №1 (Fig. 29, a).

Element	Apparent concentration	Concentration, %	Chemical compound
C	108,28	19,27	C
O	285,15	44,50	SiO_2
Na	5,13	0,45	*Albite*
Mg	2,27	0,21	MgO
Al	10,60	0,82	Al_2O_3
Si	55,79	3,86	SiO_2
K	19,90	1,07	KBr
Ca	495,17	29,03	*Wollastonite*
Fe	10,54	0,79	Fe

A layered structure is usually formed (Fig. 29, a) with low adhesion and cohesion to cement stone in case of the presence of moisture as a result of the reaction of calcium oxide with

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atmospheric carbon dioxide (Taha & Nounu, 2008). According to the data of energy dispersive X-ray analysis, the fracture of the concrete composite of mixture No. 1 mainly occurs in areas with high concentrations of calcite (Fodchuk et al., 2020). The higher the dispersion of the calcite phase components, the higher the concentration of aluminum atoms in them and the lower the concentration of silicon, which is the probable reason for the decrease in the strength of the composite at the micro level.

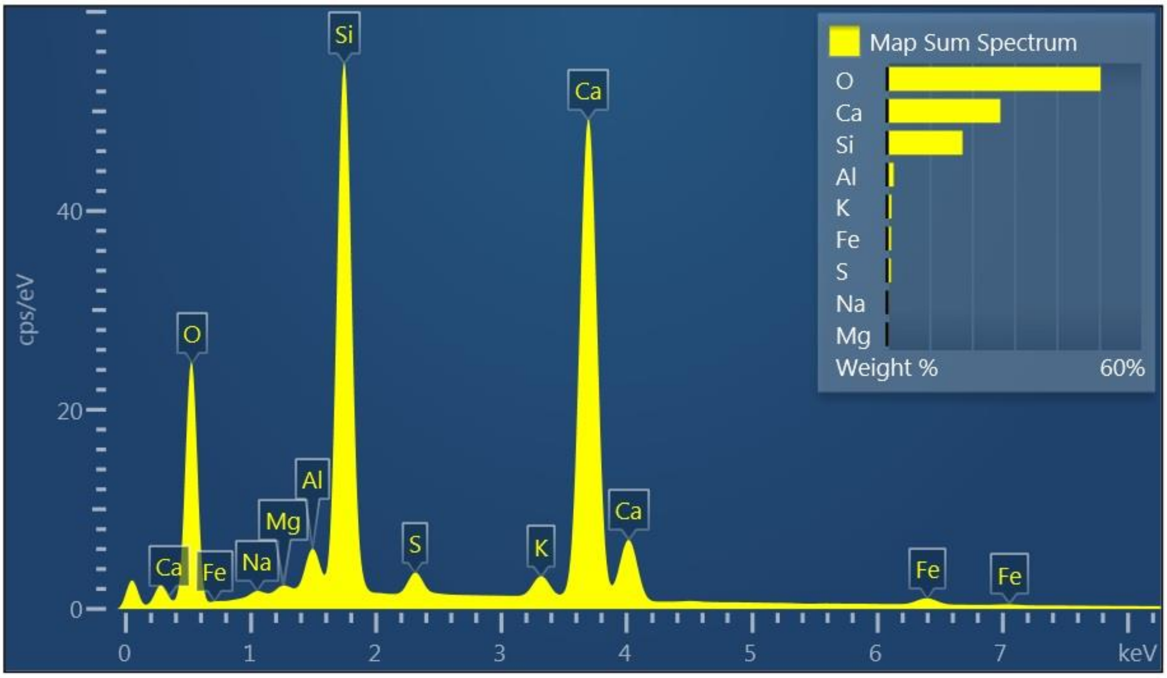

Fig. 32. Elemental composition of mixture №2 according to the results of energy dispersive X-ray analysis, in accordance with the images in Fig. 29, b

The structure of the composite of mixture №2 is distinguished by a large number of phases and their heterogeneity. The structure of the composite of mixture №2 is dominated by phases of low-basic CaO/SiO2 (≈1.8) and high-basic CaO/SiO2 (≈2.6) calcium hydrosilicates, as well as unreacted microsilica particles. Probably, the significantly higher compressive strength for mixture №2 is due to the more developed specific surface area of pozzolanic particles, which are able to react faster with Ca(OH)2, forming a dense microstructure with a

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predominant amount of calcium hydrosilicates and other hydration products that fill the pore structure, increasing the structural strength and density of the composite.

Table 13

Quantitative correlations between the main components of the elemental composition of the fracture of concrete composition №2 (Fig. 29, b).

Element	Apparent concentration	Concentration, %	Chemical compound
O	393,92	50,40	SiO_2
Na	3,87	0,34	*Albite*
Mg	3,43	0,31	MgO
Al	19,98	1,52	Al_2O_3
Si	257,48	17,81	SiO_2
S	12,53	0,90	FeS_2
K	17,78	1,03	KBr
Ca	439,97	26,75	*Wollastonite*
Fe	12,70	0,94	Fe

The fracture of concrete specimens of mixture №2 (under a pressure of 120 MPa) occurred along the fracture surfaces dominated by calcium hydrosilicate phases, which are denser and stronger than the structure of calcite and calcium hydroxide, which prevail on the fractures (Fig. 29, b) of specimens of mixture №1.

The microstructure of the surface regions of concrete differs from that of the composite volume, and is important in terms of its impact on the durability of the concrete. There are several reasons for the differences, including compaction and stresses that occur during the moulding of the specimens, which can affect the distribution of the aggregate. Also, moisture gradients are created when the surface is exposed to a dry atmosphere, slowing or even stopping the hydration of the surface layers, changing the pore structure and promoting carbonation.

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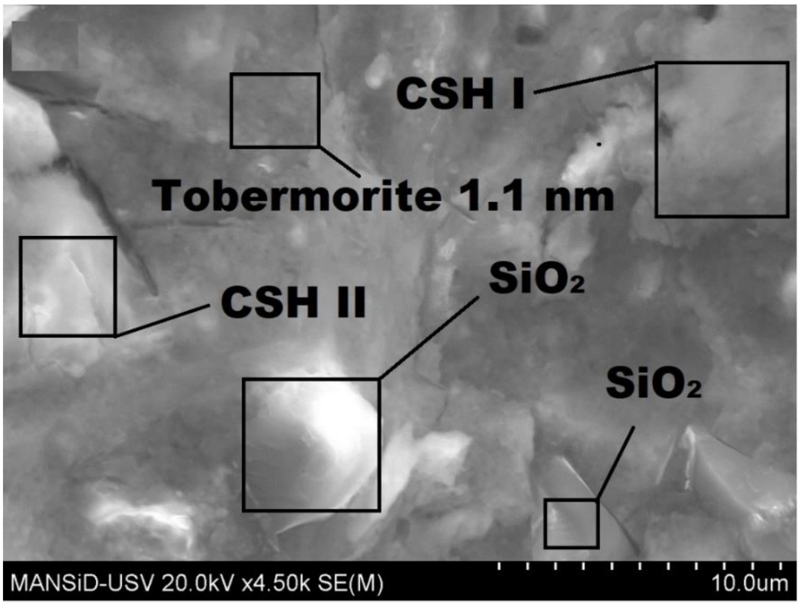

Fig. 32. SEM-image of the surface microstructure of the cement matrix of mixture №2

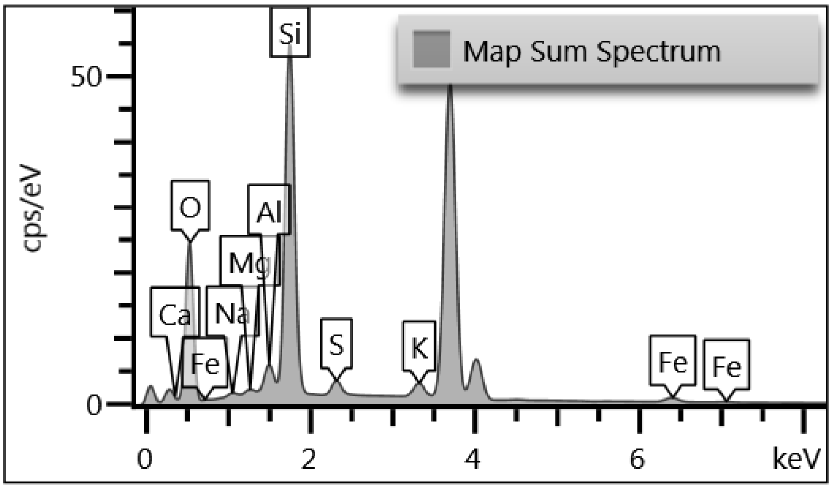

Fig. 33. The results of spectral analysis of the microstructure of the cement matrix surface section (Fig. 31) of mixture №2

Table 14

Quantitative correlations between the main components of the elemental composition of the concrete fracture of composition №2 (Fig. 31).

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Element	Apparent concentration	Concentration, %	Chemical compound
O	393,92	48,4	SiO_2
Na	3,87	0,34	*Albite*
Mg	3,43	0,31	MgO
Al	19,98	2,52	Al_2O_3
Si	257,48	19,81	SiO_2
S	12,53	0,9	FeS_2
K	17,78	1,03	KBr
Ca	439,97	25,75	*Wollastonite*
Fe	12,70	0,94	Fe
Total:		100,00	

Thus, the modification of the concrete composite with a complex of microsilica and metakaolin creates conditions for the transformation of unstable and soluble calcium hydroxide into a strong crystalline calcium silicate hydrate (Fig. 31). Consequently, the structure of concrete gives a significant increase in strength. In addition, a silicon oxide gel is formed when microsilica is introduced into the liquid phase of the cement batter, which subsequently adsorbs free Ca2+ and OH- ions and contributes to the formation of crystallised low-base calcium silicate hydrates. Under limited conditions, low-base calcium silicate hydrates lead to an increase in the number of gel pores and a decrease in open porosity. Such closed pores prevent the propagation of cracks into the depths of the solid, as the stress drops very quickly from high values at the pore surface to low values in its interior, i.e., small closed pores prevent the material from fracturing.

6.3 High-strength concrete with complex modifiers of new generation

The durability of concrete can be considered as a function that determines the retention of concrete's performance properties over time. Lifetime of a structure depends on the strength and durability of concrete. The use of mineral admixtures in concrete plays an important role in achieving the specified strength and durability characteristics. Nowadays,

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nanotechnology is used in concrete to reduce the permeability of concrete and to extend the lifetime of structures. Nanomaterials have an extremely small size, which, when used in cementitious systems, improves their strength and reduces porosity at the micro level. This section describes the characteristics of the phase composition of the hydration products of concrete composites based on microsilica and metakaolin modifiers. The use of finely dispersed modifiers generates the formation of complex complexes of various types of cluster formations in the cement matrix of a high-strength composite. These reactions continue over a long period of time and affect the processes of structural relaxation of the material.

With proper design and control over the quality chemical composition of materials, concrete composites can have physical and mechanical properties that will allow structures to be used for more than 100 years. The durability of concrete depends on the development of the phase composition of hydration products and the pore structure of the material. In aggressive environments, concrete is potentially vulnerable to chemical attacks, but due to the use of finely dispersed pozzolanic materials, the phase composition of hydration products is formed from a predominant number of strong and resistant structures.

In recent years, the use of fine modifiers has gained significant development in the manufacture of concrete (Zhang, 2007; Marsh, 1984; Poole et al., 2007; Carsana et al., 2014; Mirzahosseini & Riding, 2014; Taha & Nounu, 2008; Gartner & Hirao, 2015). They are more reactive and effective, filling the pores of concrete, producing compact and denser hydration products, reducing the penetration of any liquids (Fodchuk et al., 2020; Idir et al., 2011; Sumariuk & Fodchuk, 2021).

One of the important factors that determine the quality characteristics of concrete composites is durability. Durability is the ability of a building material, product or structure to retain its properties (specified physical and chemical parameters) at standard operating values (Table 15).

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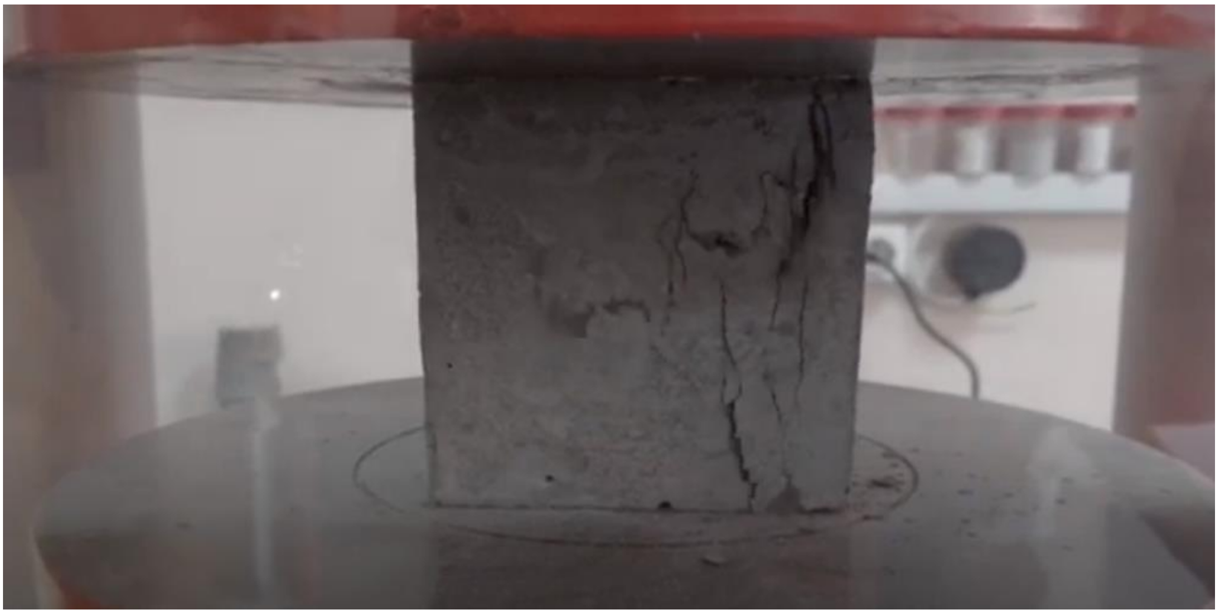

Fig. 34. Strength tests performed on day 365 of hydration

Strength tests (Table 16) conducted at 365 days of hydration show that the degree of strength improvement increases with age for concrete composites modified with microsilica and metakaolin additives. The 36% increase in strength is explained by the optimal use of free calcium hydroxide and amorphous silica, which additionally fill the pore space and significantly increase the strength, since pores are stress concentrators in the composite.

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Table 15

The service life of buildings and engineering structures

Type	Approximate value of the estimated service life, years
Buildings:	
residential and public buildings	100
manufacturing and auxiliary buildings	60
warehouse buildings	60
agricultural buildings	50
movable prefabricated buildings (including industrial, residential and other)	20
movable container buildings	15
Engineering structures:	
bridges, depending on the type	80-100
dams	120
tunnels	120
water tanks	80
tanks for oil and oil products	40
tanks for chemical industry	30
capacitive structures for bulk materials	20-30
towers and masts, depending on the purpose	20-40
chimneys	30
greenhouses	30

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Table 16

Determination of concrete compressive strength at 365 days in accordance with to DSTU B V.2.7-214:2009, EN 12390-1:2000 "Concrete, methods for determining strength by control samples"

№ of sample	Compressive strength, kN	Average value
1	1647	**1650** kN
2	1638	
3	1675	
4	1640	

These tests prove that the use of fine modifiers based on microsilica and metakaolin for critical concrete structures can be one of the most common ways to increase the service life of structures.

It is also important that reactive modifiers affect the compaction of the pore structure of the composite, which leads to higher strength and lower permeability (Table 17). Thus, high-strength composites containing fine modifiers are characterised by an improved pore structure, which also changes over time - by reducing the average pore size, the number of macropores and increased pore size uniformity with the provision of a fine pore structure. All of these physical and chemical tests confirm the causal physical and chemical structural processes that were identified and described in the previous sections using X-ray methods.

The concept of durability of concrete structures is becoming increasingly recognised, in which case failure can be defined as the deterioration of structural relaxation to an unacceptable level at an age less than the design life.

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Table 17

Determination of water absorption of concrete for 365 days in accordance with DSTU B V.2.7-170:2008, DIN EN 206-1, DIN 1045 "Methods for determination of average density, moisture content, water absorption, porosity, water resistance"

№ of sample	Water absorption by weight on day 28 of hydration	Water absorption by weight on day 365 of hydration
1	1,8 %	1,3 %
2	1,9 %	1,5 %
3	1,7 %	1,4 %
4	1,8 %	1,4 %

- In order to develop concrete composites with a certain minimum durability, it is necessary to understand the processes at the micro and nanostructural level that cause deterioration, including the rates at which these processes occur under the conditions in which the concrete will be exposed. A wide range of climatic, chemical, and physical factors need to be considered to account for all factors, and that is the subject of further research (Sumaryuk, O. V., 2021)
- Modification of the cement matrix with a complex of finely dispersed silica and aluminosilicate compounds, at a certain ratio, leads mainly to the formation of low-base calcium hydrosilicates and the following structural models C-S-H, such as Genite (*d/n*, nm: 1,049; 0,262; 0,278) and Tobermorite (*d/n*, nm: 0,552; 0,310; 0,301; 0,308; 0,297; 0,351), which have a layered structure and are essentially nanomaterials. These phases are formed from Ca(OH)2 and active silica components with a Ca/Si ratio of 1.1-1.2.
- The introduction of metakaolin promotes the formation of stable calcium silicate hydroaluminates with maxima on the X-ray diffraction curve corresponding to $d/n \approx$ 0,305; 0,275; 0,268; 0,263; 0,262 (nm) and hydroaluminates $d/n \approx 0{,}276$; 0,309 (nm).
- It was found that in X-ray diffraction curves the main intensity maxima of hydration products are located in the same angular positions as the maximum intensity of

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clinker minerals, in particular, for alite (C3S) and belite (C2S). This indicates their crucial role in the formation of the cement matrix structure.

- The presence of compounds that include Al and Fe at the late stages of hydration (more than 1 year) is a sign of the formation of secondary phases of calcium hydroaluminates and hydroferrites. The 36% increase in strength is attributed to the optimal use of free calcium hydroxide and amorphous silicon dioxide, which is a sign of the progressive pozzolanic reaction in the cement matrix during one year of hydration.
- During the year of hydration, with the introduction of siliceous and aluminosilicate modifiers, a significant decrease in the content of Ca(OH)2 and highly basic calcium hydrosilicates CSH-II is observed, with a simultaneous increase in the content of genite and tobermorite, which were probably transformed from CSH, which is the reason for the increase in strength.

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Erasmus+ Programme Key Action 2 Cooperation Partnerships for Higher Education (KA220-HED)
Project No: 2023-1-RO01-KA220-HED-000155412
Project title: European Network for Additive Manufacturing in Industrial Design for Ukrainian Context – Acronym: AMAZE

MODULE 3
CAD/CAM/CAE design

Project Title	**European Network for Additive Manufacturing in Industrial Design for Ukrainian Context 2023-1-RO01-KA220-HED-000155412**
Output	**IO1 - AMAZE e-book for industrial design for complex parts**
Module	**Module 3 CAD/CAM/CAE design**
Date of Delivery	**March 2024**
Authors	**Igor FODCHUK, Mariana BORCHA, Yurii SOBKO, Volodymyr ROMANKEVYCH, Nataliia VATAMANIUK**
Version	**FINAL VARIANT, *date***

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Contents

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Summary: This module describes the process and structure of work in Autodesk Revit software, using the example of the reconstruction of an industrial building in Chernivtsi. The stages of project implementation using digital technologies are described, and a 3D model of the object under study is created and printed.

This module is devoted to the reconstruction of an industrial building, namely a brewery in Chernivtsi, which was carried out in Revit. In the process of developing the model, a partial reconstruction of the existing building was proposed with the additional construction of a new building nearby.

The reconstruction of such an industrial facility is a complex project that required solving a number of specific tasks. Among them:

- finding the best architectural and structural solution, taking into account the changed functionality of the building and design standards;
- replacement of technological and related engineering equipment with modern equipment and the use of existing holes and shafts for laying the building's utility lines;
- decisions on dismantling and replacing part of the building structures.

Brief historical background. The first joint-stock brewery in Chernivtsi was built in 1869-1871. The brewery is located north of the city centre, on the right bank of the Prut River, in close proximity to the railway and train station. It was founded by local entrepreneurs Heinrich Wagner, Markus Zucker, Isaac Rubinstein and architect Gregor. The association "Erste Bucowinaer Bierbrauerei - u.Spiritus-Industrie A.-G." had a statutory fund of 250 thousand florins. In the first year of exploitation, the brewery burned down. However, it was rebuilt and production resumed on 1 July 1877 (Fig. 1).

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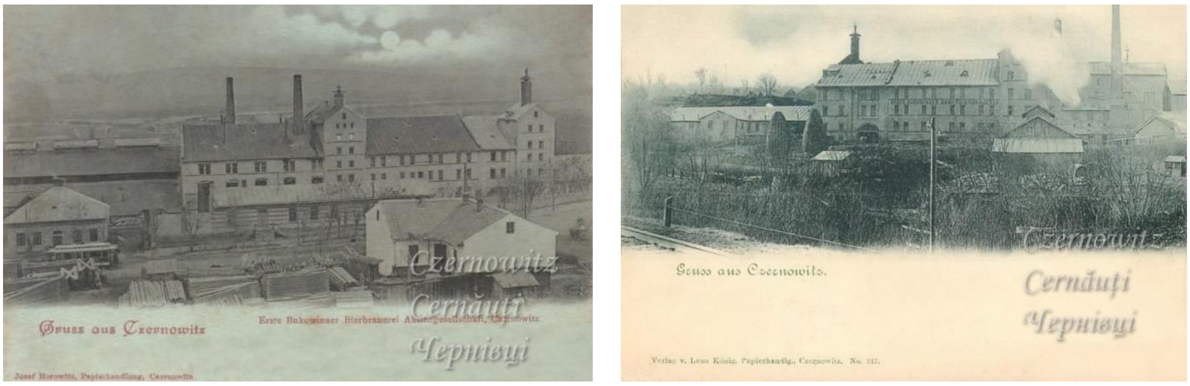

Fig. 1. Historical photographs of the brewery [12].

"Bavarian" beer was exported to Romania, Germany and Austria. Barley from Romania and Bessarabia, hops from the Czech Republic, and water from local artesian wells were used in its production. The development of the industry in western Ukraine is also evidenced by the fact that in 1911 Bukovyna and Lviv brewers united in the Galician-Bukovyna beer cartel. This meant a monopoly on the production and sale of beer in the region (Fig.2.).

Fig. 2. Beer brands produced in Chernivtsi (from the collection of S. Nezhurbida)

The brewery was largely developed during the period of its existence in the USSR. The brewery underwent a significant technical reconstruction. In 1994, the brewery was privatised by a leaseholder group and transformed into CJSC "Chernivtsi Brewery". In 1998, the project

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"Technical Reconstruction of the Chernivtsi Brewery" was implemented, during which equipment from Germany and the Czech Republic was installed at the factory [11].

The facade of the production building is designed in the classicist style and is decorated with characteristic pilasters. To the left of the main building are two buildings with a gate between them. The balcony fence of the building to the right of the gate contains pseudo-gothic elements. The arched windows of the building to the left of the gate refer to the Romanesque style.

Chronology of names: Erste Bucowinaer Bierbrauerei, Bürgerlichen Bräuhaus Czernowitz, Beresa Cernăuţi, Chernivtsi Brewery, Chernivtsi Soft Drinks Factory, Chernivtsi Brewery JSC, "Rosy Bukovyny" Brewery JV.

Nowadays, the factory is a closed and abandoned space (Fig. 3.). The decline of this industrial building due to a number of factors has turned it into a depressed and non-functional territory. However, this building has historical and cultural value for the region.

Fig. 3. The current condition of the brewery

The main problem of the territory is its lack of maintenance and the ruined, burnt-out former factory, which in 2009 was decided to be used as a warehouse.

The factory's territory is located at the intersection of all major transport routes - the main arteries of Chernivtsi, which connect the site with almost all districts of the city and border the historic part of the city (Fig. 4.).

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Vokzal'na Street (formerly Gagarina Street) (Fig. 5.), where the factory is located, has a large daily traffic of cars and public transport from/to the historic city centre. There is a railway station, a bus station and public transport stops close to the research area. This indicates accessibility to the future public facility.

According to the Chernivtsi City Zoning Scheme and the Chernivtsi City Master Plan (Fig. 6.), the site is located in a zone that allows for mixed multi-apartment residential and public buildings.

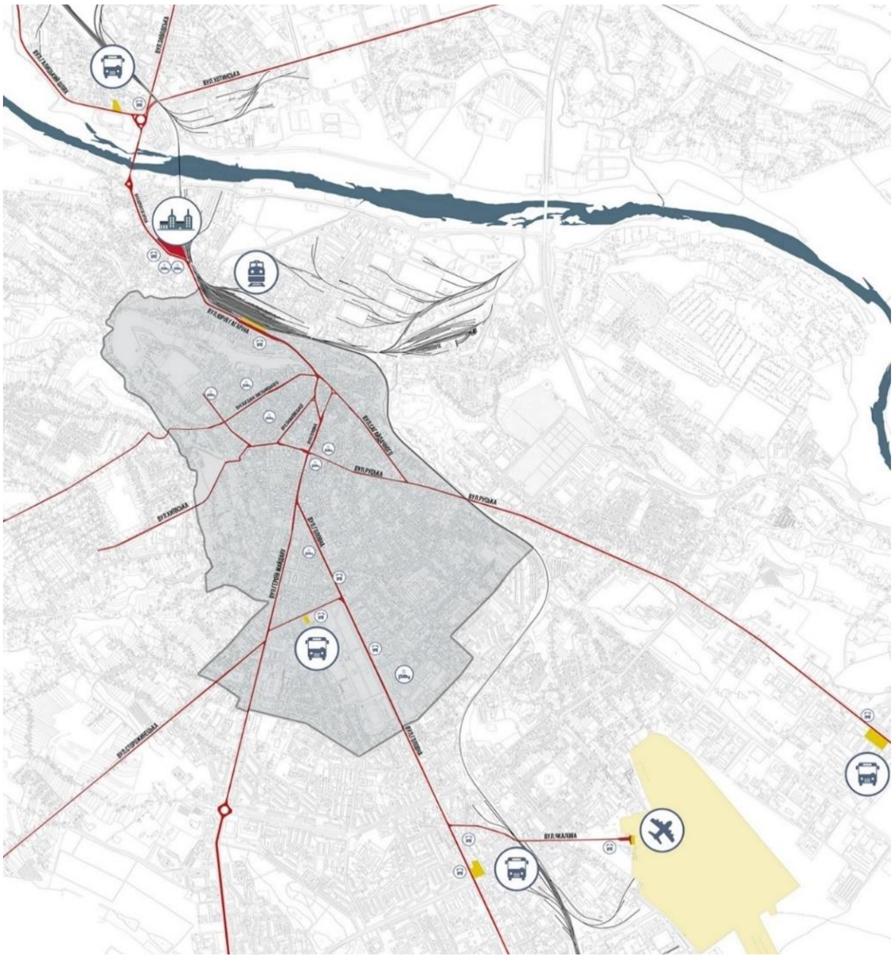

Fig. 4. Situation scheme. Location of the project site in Chernivtsi [13].

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Fig. 5. The project site. Top view (Google Earth)

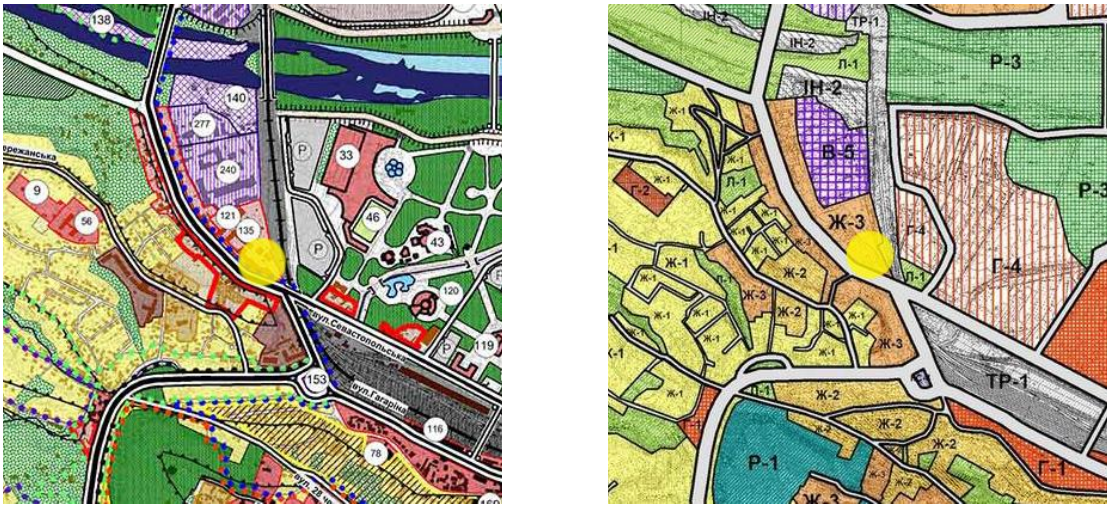

Fig. 6. Chernivtsi City Master Plana and Chernivtsi City Zoning Scheme

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1 *Reconstruction of buildings using BIM technologies*

In 2022, the Verkhovna Rada supported Bill №6383 on the introduction of BIM technologies in Ukrainian construction. The explanatory note to the document states that its purpose is to create legal conditions for the use of modern building information modelling technologies as one of the key tools for further reform, modernisation and digital transformation of the construction industry in Ukraine.

Such innovations will allow:

- make the most efficient use of material and labour resources in the construction of facilities;
- ensure the durability and safety of buildings;
- minimise the negative impact on the environment;
- accurately forecast and optimise costs at all stages of the facility's life cycle;
- efficiently plan reconstruction and overhaul works.

It is also a very relevant topic in the current realities of rebuilding Ukrainian cities. Reconstruction and restoration of buildings after military actions is becoming an important area of construction for residential buildings and large industrial structures.

The BIM concept is based not only on a 3D model of a building, but also on the information contained in each component and element of this model. A smart model, which is an intellectual basis for decision-making, allows you to analyse a building object to meet the needs of different users, for example, to analyse the condition of structures or their damage, energy modelling, etc [14].

The main difference between reconstruction and new construction projects is the initial data collection, which is not always of high quality and often limited due to lack of information. One of the biggest constraints that currently exists for the building reconstruction process is the collection and integration of information for further use.

The feature of buildings to be reconstructed and restored is that they have a complex structural scheme. Unlike new buildings, the components are not standardised. Moreover,

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new solutions, structural components and various modifications are added to the design model. There is twice as much information as in a new building.

A lot of problems also arise when reconstructing historic buildings, where it is important to preserve authenticity, recreate the facade and fit the building into the existing environment [15].

Automated BIM model creation for building and construction reconstruction means achieving optimisation that starts with data input (point clouds, images, videos) and ends with the finished BIM model, and in the intermediate processes, semi-automated or automated methods are applied to save effort and time, increasing efficiency. Photogrammetry and laser scanning have often been used together to survey complex or large buildings [16].

The general sequence of BIM for object reconstruction:

- data collection using various technologies;
- generation of a point cloud;
- importing and processing the point cloud for semi-automatic recognition in the BIM environment;
- semi-automatic generation of BIM elements;
- create models for other components;
- connecting all components to create a complete copy.

Also, one of the most important principles underlying the concept of integrated reconstruction of buildings and structures is the principles of resource conservation and energy efficiency. Therefore, integrated reconstruction projects should be energy efficient.

An energy-efficient project is a project aimed at reducing energy consumption, including the reconstruction of supply networks and systems, regulation and metering of water, gas, heat and electricity consumption, and modernisation of wall structures and production process technologies.

When creating a BIM model, the principles of energy efficiency can be followed in the process of creating a project, where:

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- an energy-efficient approach reduces the negative impact on the environment, which traditionally accounts for a significant percentage of the building industry;
- comfort and microclimatic conditions of the buildings are improved, and hazardous factors are eliminated, which has a positive impact on health and quality of life;
- the method of environmental and economic assessment of the life cycle of materials and structures is applied, which can significantly reduce the amount of waste and negative environmental impact at the stages of materials production, construction of buildings and reconstruction itself;
- creating an attractive aesthetics of green building that can improve the social and emotional state of the population, and draw attention to environmental pollution problems and demonstrate ways to solve them;
- the use of energy-efficient buildings will reduce dependence on imported energy and contribute to national security in general.

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2 Purpose and functions of Autodesk Revit

Autodesk Revit [1] is a software package that implements the principle of Building Information Modeling (BIM) to create visualisations and drawings of plans, sections, details, and other tools for building design. It is designed for architectural design, design of load-bearing structures and utility networks, and supports sustainable design methods, conflict detection, construction and production planning.

The building information model contains information about the construction of the project, its dimensions, stages, and quantitative characteristics of the elements [2]. Drawings created with Revit are not a collection of 2D lines and shapes. Any view, whether two- or three-dimensional, detail, or specification is part of the same information model.

The software includes easy-to-use conceptual design tools. It also allows you to visualise the model. Additionally, Autodesk Revit offers such functions necessary for architectural and design work as energy consumption calculation and structural analysis with the ability to perform static calculations in the cloud, especially important is the creation of a two-way connection between the model and various analyses and automatic updating of the model based on the results [3].

Building Information Model – BIM technology:

- model is the simplest representation, a 2D or 3D model that is entered by the user into the design space.
- information means that models in the design space are endowed with certain properties, in Revit these properties are called parameters. The difference between BIM programs and CAD programs is that the user can edit these parameters, as well as enter their own parameters for objects and change them during the design process. For example, the physical parameters of an object are width, length, height, material, etc., and the user can also enter parameters such as manufacturer, price, etc [4].

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- building - the final result of the design process, which is a building - a set of various objects with their own properties that create a complete structure. As opposed to a conventional 3D editor, in a BIM program, each object is defined by the program or the user as a specific object with a specific function, rather than as a collection of polygons and planes.

When you create a project in Revit, stage is important. Assigning elements to certain stages can be used to filter the visibility of these elements; stage is also reflected in the specifications. Stages are the stages of a project and reflect the creation and life cycle of the entire building and/or its elements. The breakdown into stages depends on the user - you can define stages by stage numbers or stage names ("Construction", "Existing building", "Demolition", etc.). They are linked to certain stages and, using stage filters, you can make parts of the project visible, invisible, or marked accordingly at different stages of the project.

In general, the sequence of actions for creating a project in Revit is similar to other CAD software, with adjustments for Revit features. After setting up the workspace and creating basic elements (e.g. levels, etc.), as well as creating a construction site (may include a site drawing, topographic surface of the construction site, orientation to the cardinal points, etc. The next stage is the preparation of project documentation [28, 29].

Building a model can be started in one of two ways: by creating a conceptual model and then converting its parts into building elements (walls, roofs, etc.), or by creating a model from standard elements. In both cases, further work on refining the model will include the addition of typical elements - walls, partitions, roofs, windows, doors, etc. Also, work on the model will include adding and configuring new model views (facades, sections, details). In addition, in most cases, it will be necessary to use additional elements such as zones, stairs, and components such as furniture and equipment.

When creating a model, you should take into account the need for several specialists to work simultaneously, as Revit is a BIM system designed for collaborative work [27].

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During the creation of a physical model of a building, its analytical model is also created - a simplified three-dimensional representation of the engineering and design description of the physical model of the load-bearing structures. The analytical model contains load-bearing elements, geometry, material properties and loads that form the building system. This data can be used to link the design with analysis and calculation programs for structural design. With the Advance Steel Extension for Revit, BIM data can be exchanged between Autodesk Revit and Autodesk Advance Steel, including elements such as steel beams, plates, timber and reinforced concrete elements, grids, and connection elements.

Autodesk Revit provides tools for designing engineering systems for DOE buildings, such as air duct systems with mechanical air circulation, heating, cooling, electrical systems, and pipelines. It can be used in conjunction with other Autodesk products to create more coordinated models.

A feature of Revit, in comparison with its closest competitors, such as Graphisoft Nemetschek Group, Nemetschek Allplan, Bentley Microstation, is a new concept of element structure and the use of a hierarchical project structure. At the very least, it does not have the usual means of distributing geometry - Layers - but instead has a whole hierarchy of Categories, Families, Types and Elements, as well as several methods for managing them [5].

Category is the systematic division of Autodesk Revit data by purpose (Wall, Window, Equipment, etc.). There are categories depending on the use: Models, Views, and Design. They have an individual set of properties and parameters, as well as behaviour and interaction conditions (Fig. 7.). Categories cannot be created and edited by users.

Model categories include, as a rule, three-dimensional elements and are conventionally divided into Basic (Walls, Ceilings, Roofs, Stairs, Fences, etc.) and Components (Doors, Windows, Profiles, Equipment, etc.).

The design categories usually include two-dimensional elements and are divided into Breakdowns (Levels, Axes, Reference planes, Reference lines, etc.) and Symbols (Dimensions, Text, Labels, Detailing, Lines, etc.).

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View categories include data display elements (Plans, Facades, Sections, Nodes, Tables) at the required scale, display type, graphics, etc.

Family is a "project" within a project or a "smart 3D model". A family is a group of elements that is characterised by a common set of properties (parameters) and their associated graphical representation. For different elements of the family, the values of the parameters may differ, but the set of parameters (their names and purpose) remain the same.

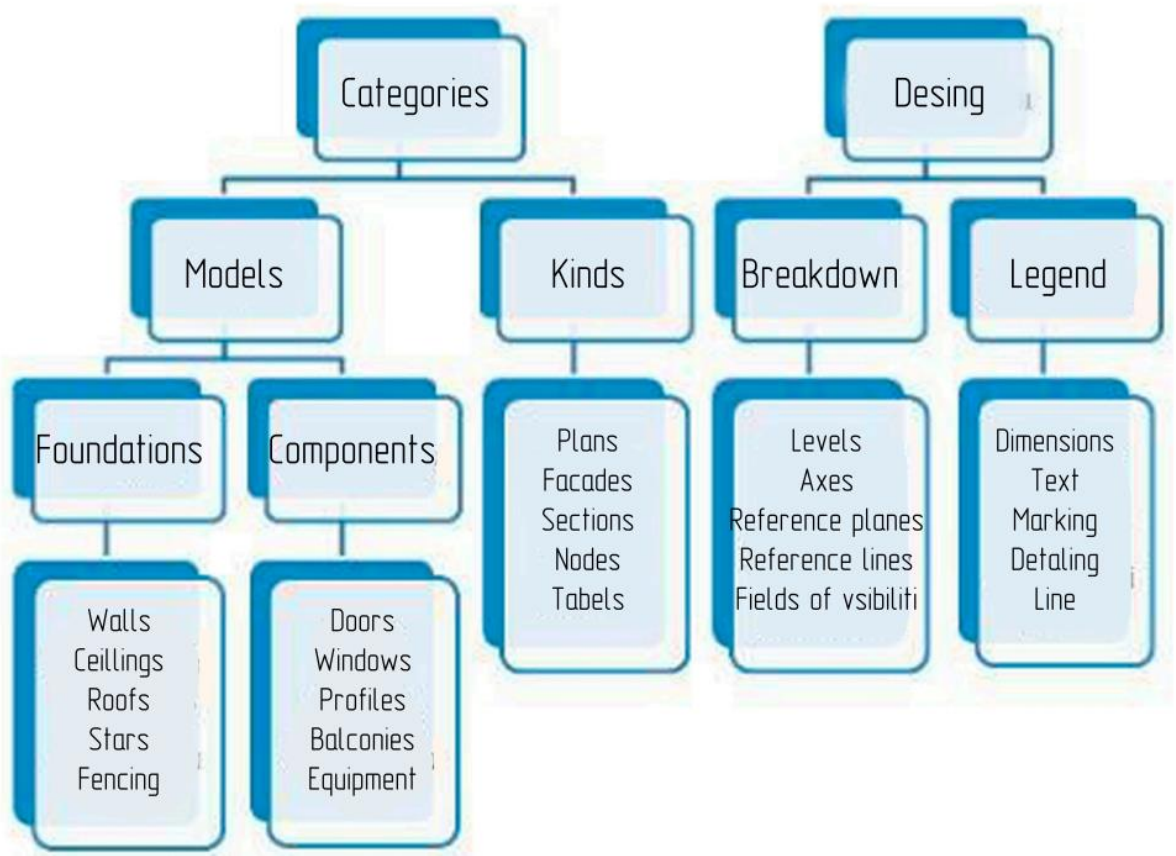

Fig. 7. Categories

Families can be windows, doors, cabinets, lamps, columns, facade elements, tiles, etc. There can be families within families. For example, window profile families are pulled into

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window families. You can program families that will behave differently in certain situations. For example, if you look at a socket in a plan view, it has its own designation, in a section it has a different designation, and in 3D view it will be a three-dimensional model. Families are the "heart" of Revit, and it is families that allow you to make a project that is very flexible to adjust.

There are three types of families in Revit:

- system families;
- families of standard components (component families);
- context families.

System families are used to create the main building elements, such as walls, roofs, ceilings, floors and other elements that are assembled on the construction site. System parameters that affect the project environment and include standard sizes for levels, grids, drawing sheets, and view screens are also system families.

Standard component families are used to create both building components and some annotation elements. Typically, standard component families are used to create those building components that can be added separately, delivered and installed in or around a building, such as windows, doors, cabinets, appliances, furniture and landscaping components. These families may also include those annotation elements for which a standard adaptation procedure is provided, such as symbols and basic captions.

Context families are unique and are used to create unique components designed for a specific project. Based on contextual families, you can create geometric objects that have references to geometric objects in another project and, when changes are made to them, are adjusted accordingly in size and other parameters.

All content in a Revit project has parameters, which are simply information or data about something. Parameters can affect different aspects of an object, such as visibility, size, shape, and material.

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To understand the fundamental concept of parameters, it should be noted that there are two types of parameters: type and instance. Type parameters manage information about each element of the same type. For example, if the material of a piece of furniture is designated as a type parameter, changing it will change the material for all furniture of that type. Instance parameters control only those cases that are selected. So, if the material of the selected furniture is an instance parameter, only the selected items will be edited. Instance parameters can be permanently displayed in the property's palette. When you select something, the instance parameters are displayed first. In (Fig. 8.), the wall instance parameters are shown, which control the relative height, constraints, and structural use [7].

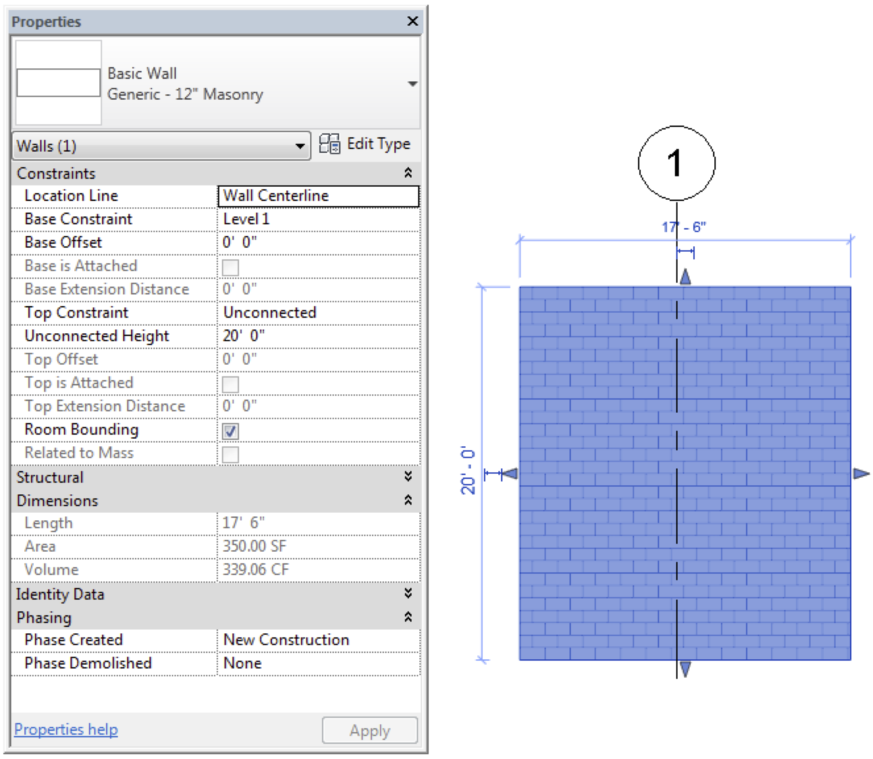

Fig. 8. Parameters of the wall instance

Clicking the Edit Type button opens the type parameters (Fig. 9.). These parameters include the structure, graphics, and assembly code.

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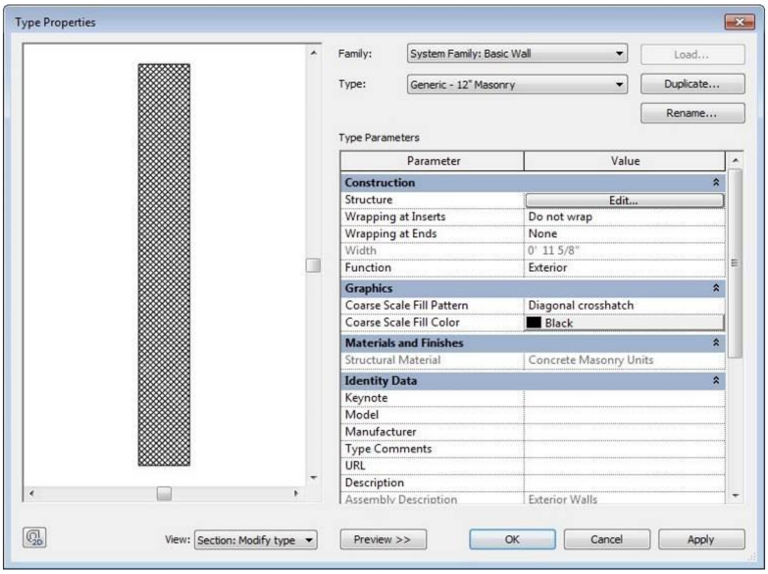

Fig. 9. Parameters of the wall type

The element type provides an additional classification in the family categories and determines the behaviour of the family in the model.

Elements are divided into three main types:

- model elements;
- basic elements;
- type-specific elements.

In this case, elements belong to families that define the main characteristics of all instances of these elements.

Model elements include the actual parts of the virtual building - walls, roofs, columns, etc. These elements define the geometry of the building.

Basic elements include parts of the virtual building's imaginary division that are used to describe the project, such as levels, grids, reference planes, etc.

Type-specific elements, those parts of the project that are tied to certain types, such as dimensions, labels, are used to describe and document the project. They are displayed only on the views to which they are linked.

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These types of elements are further subdivided into components: model elements, for example, are divided into main components and model components. The main components include walls, roofs, ceilings and floors - something that is created directly on the construction site. Model components include both load-bearing and non-load-bearing elements of building models, as well as elements such as beams, columns, braces, windows, doors, furniture, boilers, pipes, etc.

View elements are also divided into annotation and information elements. The former includes 2D elements for documenting and scaling for printing - dimensions, grades; the latter include 2D elements for detailing and describing the model - detail lines, colour areas, 2D detail drawings.

The behaviour of the elements will depend on the context, their creation, and whether they are set automatically or manually (Fig. 10.).

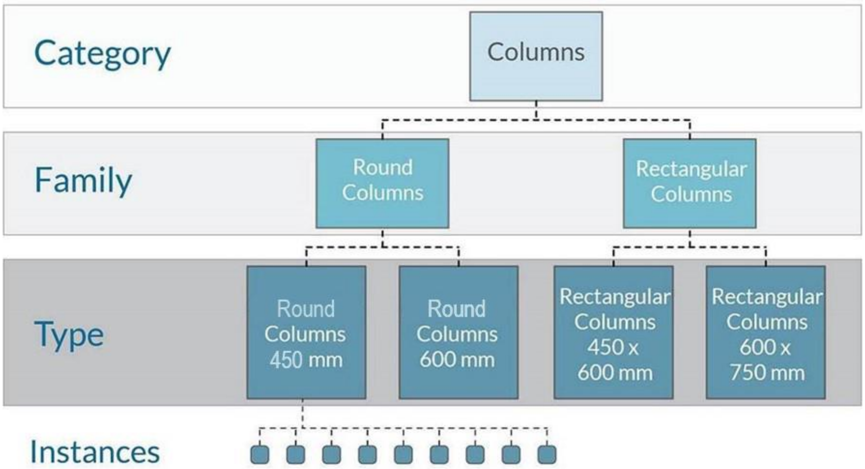

Fig. 10. The "column" element in the Revit structure

Rendering. After you create a building, model, or any other object in Revit, you can use the Revit rendering engine to create a more realistic representation. This is achieved using a specific set of tools and materials. Revit comes with a variety of predefined materials, each of which can be modified as the user wishes. It is possible to start with a "General" material and

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set the angle, size, brightness and intensity of textures, glossy maps (also known as shinemaps), transparency maps, reflective, shear and other maps, or simply use sliders for any of the above texture features (Fig. 11.).

Fig. 11. An example of a rendering in Revit [13].

2.1 *Revit software interface*

From the Revit home page, you can do the following:

- use the arrow at the top of the bar on the left to switch to the ribbon and the Revit user interface.
- open a Revit model in the cloud if you have the appropriate access.
- open or create a model or family.

In the "Recent Files" section, open the created model or family.

In the "Training" section, access interactive learning resources.

The "File" tab provides access to file operations such as "Create", "Open", and "Save". It also allows you to manage files with advanced tools such as "Export" and "Publish".

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The "Quick Access" panel contains a set of tools that are used by default. You can customise this panel to display the most frequently used tools.

The "Info Centre" provides a set of tools for accessing various sources of information about the program.

The "Project Manager" displays a logical hierarchy of all types, specifications, sheets, groups, and other project elements. By expanding categories, users can access their nested items.

The status bar displays tips and tricks for the operations being performed. When an element or component is selected, the status bar displays its family name and size [9].

The options panel below the ribbon displays conditional tools that depend on the currently selected tool or element (Fig. 12.).

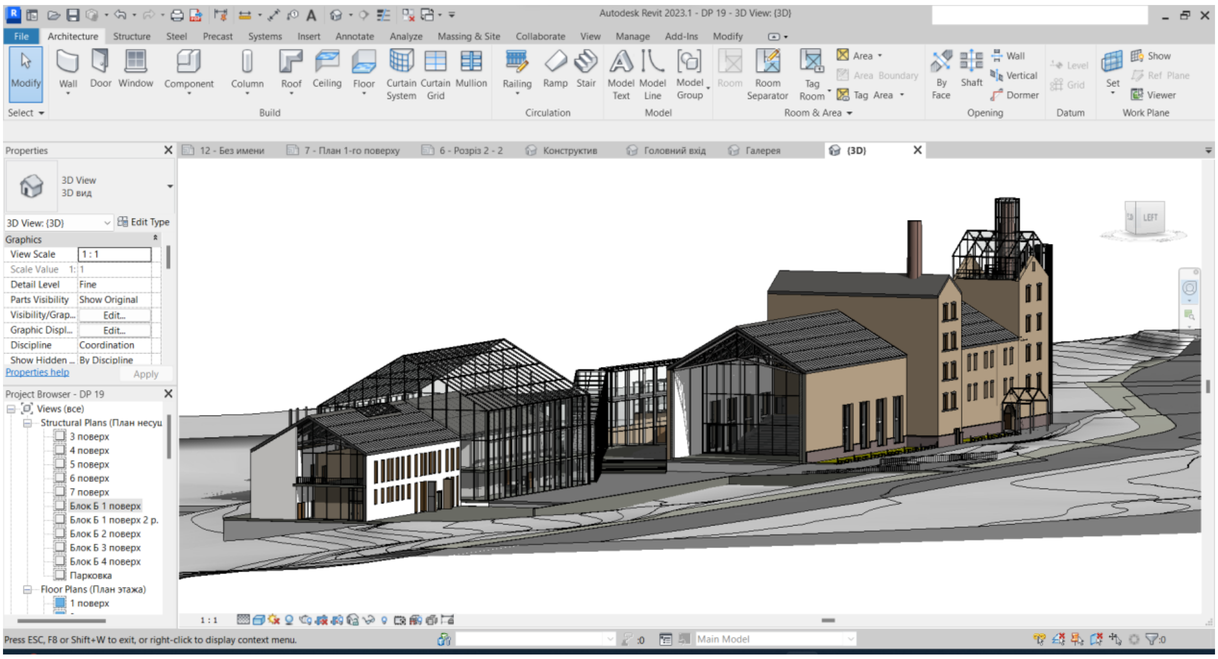

Fig. 12. Elements of the Revit interface [13].

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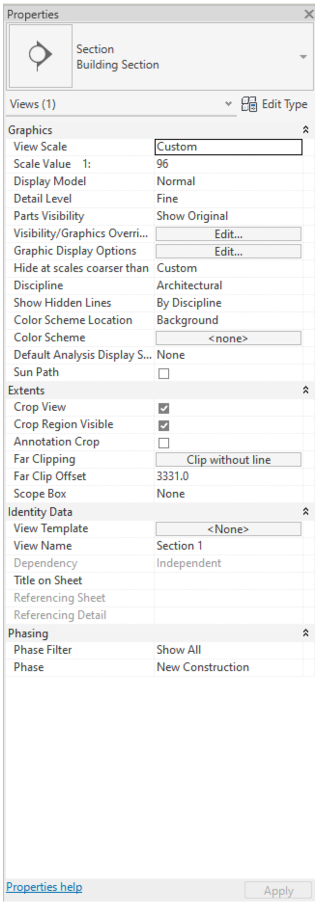

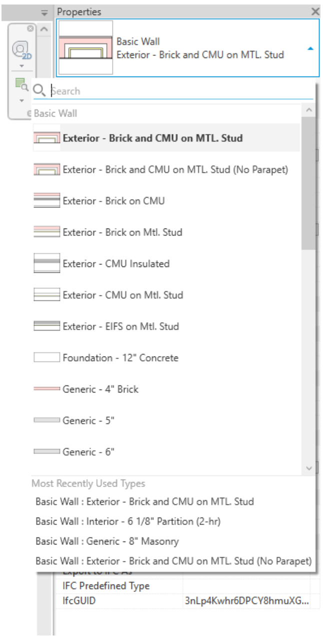

Fig. 13. Project Manager   Fig. 14. Properties palette   Fig. 15. List of standard sizes

The "Type selection" list displays the currently selected family size, and you can select another size in it (Fig. 13-15).

The "Properties palette" is a dialogue box where you can view and change the parameters that define the properties of the elements.

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The drawing area displays the views (as well as sheets and specifications) of the model. When you open a view in the model, the view is displayed in this area.

When selecting an element near it, or directly on it, various control handles and shapes appear. Using the control handles, the shape and size of the elements can be changed.

The toolbar contains all the most important tools you need to work with this application. The toolkit is divided into thematic categories. In particular, the toolbar contains the Architecture, Structures, Systems, Insertion, and Annotations sections. Tabs can be divided into two categories: contextual and static. Static tabs are fixed at their location and cannot be changed. Contextual tabs, on the other hand, are dynamic. They can be seen only when working with certain tools. These tabs include operations that are specific to the selected tools and elements. They close when you're done editing or using the tools.

File formats. Revit supports a wide range of industry standards and file formats, including

- Revit's own formats: RVT, RFA, RTE, RFT;
- CAD formats: DGN, DWF, DWG, DXF, IFC, SAT and SKP;
- image formats: BMP, PNG, JPG, JPEG and TIF;
- other formats: ODBC, HTML, TXT and gbXML.

Data can be imported into Revit from other CAD systems. The following CAD formats are supported: AutoCAD (DWG and DXF), MicroStation (DGN), SketchUp (SKP and DWG), SAT, and 3DM (Rhinoceros) [9].

2.2 Import and export files

Import CAD files into a Revit model using the Import CAD tool, which imports vector data from other CAD programs. It is also possible to import CAD files using i-drop technology. Revit supports importing files using drop points (Autodesk i-drop technology). Download point technology allows objects to be imported from web pages.

Importing ACIS objects. ACIS objects describe bodies or bounded surfaces. Revit lets users import ACIS objects from DWG, DXF, DGN, and SAT files.

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Import SketchUp files. You can include a TrimbleSketchUp project in a Revit project as a starting point for a building model. In Revit, the data imported from TrimbleSketchUp is treated as a large block of geometry that cannot be managed. However, to improve the results, it is possible to change the layer settings from TrimbleSketchUp.

Import 3D shapes. 3D geometry can be imported from supported file formats and applications. When importing a file containing 3D objects, its format may support different geometry quality. These variations are caused by the file type, the export settings for the original application, and the Revit import settings [6].

In Revit models, information from IFC (Industry Foundation Classes) files can be used.

Revit supports *export* to several computer-aided design (CAD) formats [8].

The DWG drawing format is the format of AutoCAD, as well as other CAD applications.

The DXF data transfer format is an open format supported by many CAD applications. A DXF file is a text file that describes a 2D drawing. The text in such files is not compressed, so DXF files are usually large. When using the DXF format to export 3D drawings, cleaning may be required to ensure that the drawings display correctly.

DGN is a file format supported by MicroStation software from Bentley Systems, Inc.

SAT is an ACIS (solid state modelling technology) format supported by many CAD applications.

When using the export tools while working with a 3D view, Revit exports the current 3D model, not its 2D representation.

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3 Physical and architectural models of reconstruction of an industrial building in Chernivtsi

The task in organising the reconstruction of this area was to create an environment that would combine and revive the surrounding existing buildings and be perceived as a single whole. The main idea was to fit the new building into the silhouette of the old industrial neighbourhood, the chimney and the factory facade, which are present on the site. Respect for the history of the building is not only about reconstructing and preserving its remains after the fire, but also about trying to continue the story, ultimately bringing the building back to life [13].

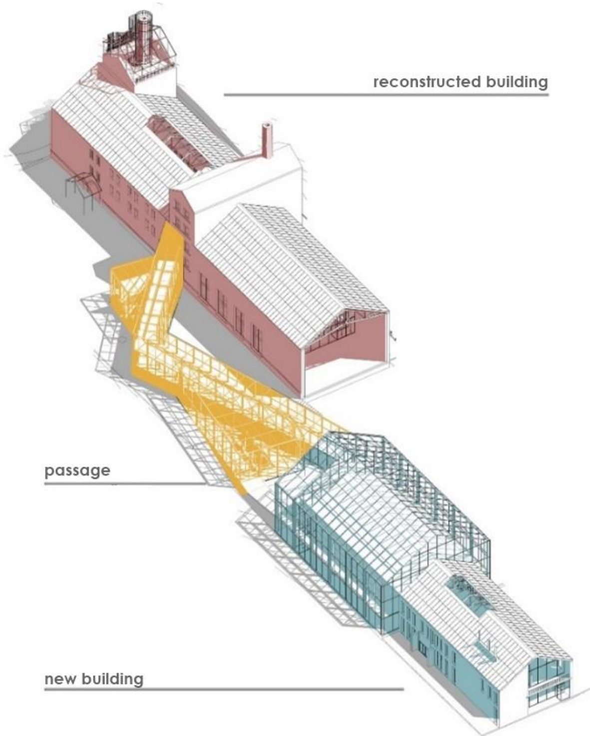

Fig. 16. Reconstruction project [13].

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The complex itself consists of two blocks, one historical and one modern, which contain two halls, united by a pavilion, which is a system of ramps (Fig. 16.). The ramp runs from the reconstructed building to the projected building and from the projected building leads to the winter garden. The projected complex can be used multifunctionally. For example, for large-scale conferences, presentations, and exhibitions, it is also a place for walking, with open areas with landscaping. There is also a brewery museum, which stretches over 5-floors and leads to an observation deck where visitors can enjoy the views of the city of Chernivtsi [13].

Taking into account the current situation in Ukraine, such a project could have the following functions: housing for IDPs (Fig. 17.) [30], commercial or humanitarian hub [31] (Fig. 18.); employment centre with production and coworking (Fig. 19.), or have cultural and educational function (Fig. 20.) [25, 32].

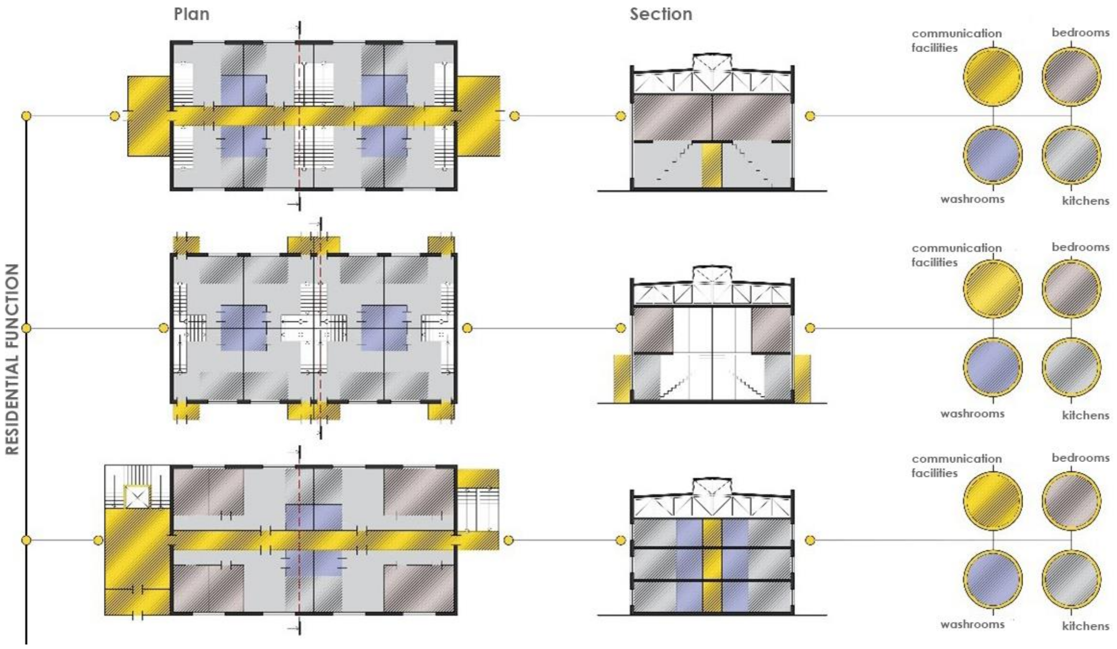

Fig. 17. Housing for IDPs [13].

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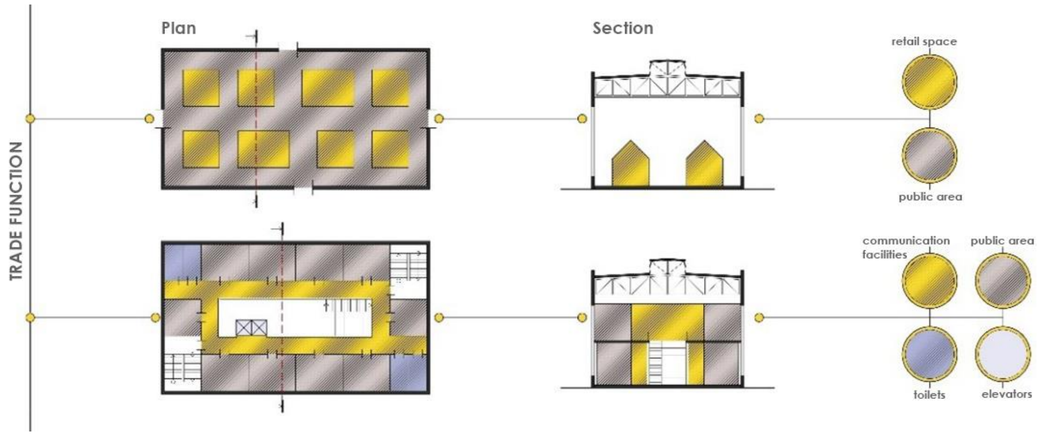

Fig. 18. Commercial or humanitarian hub [13].

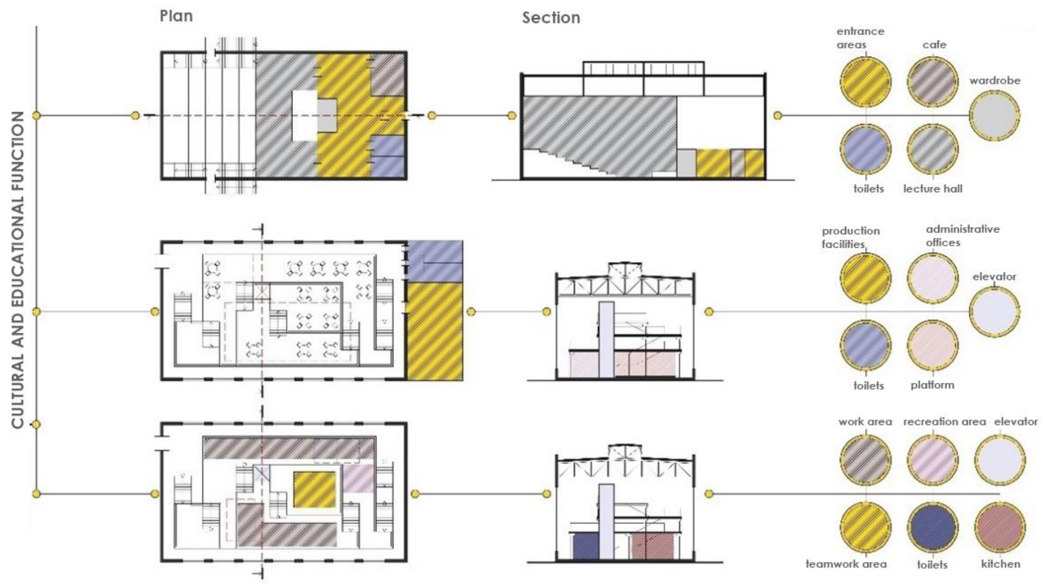

Fig. 19. Cultural and educational function [13].

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In general, the reconstruction of a brewery (Fig. 20.) is a more environmentally friendly option for redeveloping territories than demolition and construction.

It helps to reduce the cost of reconstructing an industrial building, create the status of a cultural monument, attract additional investment in the project due to the "historical" object included in the complex, and preserve urban planning dominants [32].

Currently, this industrial area, which has a good location near the city centre, should be allocated for commercial facilities, office centres, residential real estate and the development of the necessary infrastructure.

Fig. 20. Final rendering [13].

3.1 Concept for the reconstruction of an industrial building using Autodesk Revit

The architect has the ability to change the structure of any element using the extensive material database that is included in Revit, as well as create their own materials if necessary (Fig. 21.).

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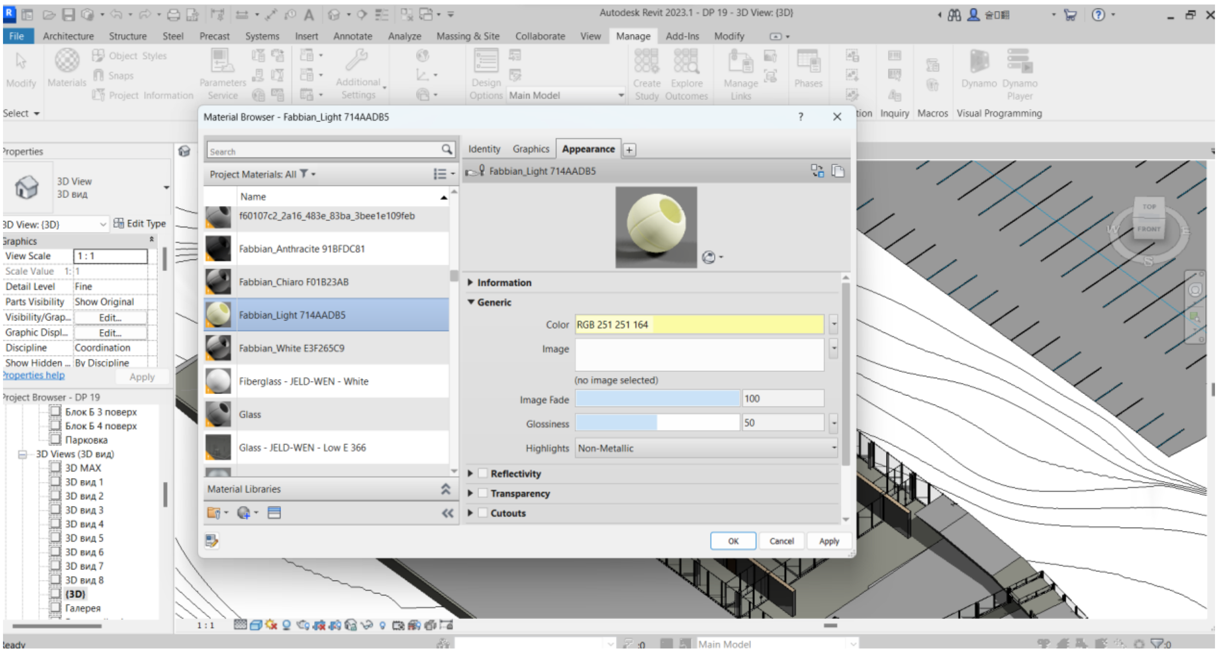

Fig. 21. Selection of construction materials

Revit is characterised by great flexibility and advanced features for architects using this design and modelling software. The unique ability to change the structure of any element is one of the key advantages of Revit. Another undoubted advantage is the ability of architects to create their own materials independently of design engineers in accordance with the unique requirements of the project [10].

The architectural section (Fig. 22.) of a plan in three dimensions in Revit is a tool for detailed study and visualisation of a project. With this feature, users can easily create sections of a building plan and see their 3D model from different perspectives [21]. This not only helps to identify architectural details and connections, but also realistically reproduces the appearance and structure of the building. With 3D sections in Revit, it is possible to study project elements in three dimensions, thoroughly analyse spatial interactions, and influence design and functionality. This feature becomes an integral part of the design process, allowing you to accurately define concepts and solve architectural problems at the planning stage [33].

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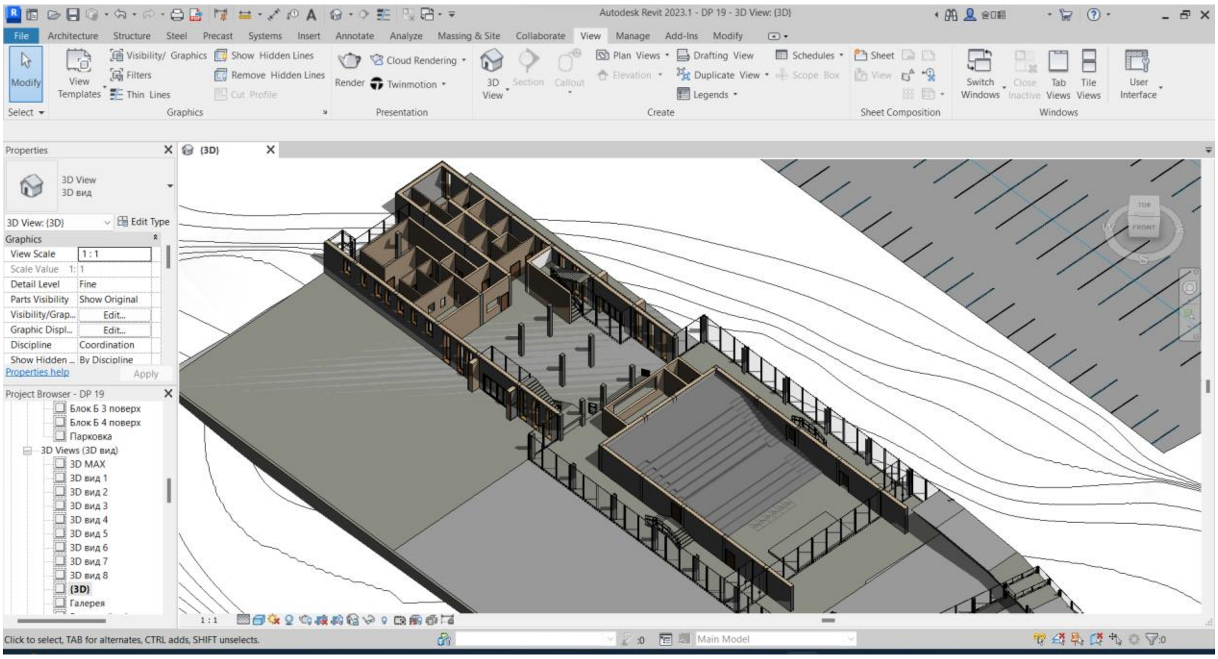

Fig. 22. 3D section in Revit [13].

Revit provides users with a unique opportunity to effectively manage architectural elements in their projects, simplifying the design process and providing a high level of detail. Specifically, users can upload or create their own architectural elements such as doors, windows, furniture, and more, integrating them easily and accurately into their project [17].

This functionality is distinguished not only by a wide library of built-in objects, but also by the ability of users to make changes to existing elements or create their own. This is done in a user-friendly interface that allows you to adjust the parameters, dimensions, and appearance of the selected object in detail. This approach makes Revit an ideal tool for architects seeking maximum customisation and accurate translation of their concepts into virtual space [18].

Revit has advanced structural element management capabilities, providing engineers and architects with intuitive tools for modelling and optimising building structures [26]. The software allows users to choose from a variety of standard structural elements such as walls,

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columns, beams, foundations, etc., or create custom designs to precisely meet the requirements of a particular project.

One of the key advantages is the ability to record the physical and structural properties of building elements, providing a high degree of detail. Engineers can analyse the behaviour of structures under different loads and conditions, which allows them to optimise their efficiency and reliability. In addition, Revit integrates with other engineering tools, enabling convenient data exchange between design teams and simplifying collaboration during the design of building structures (Fig. 23.).

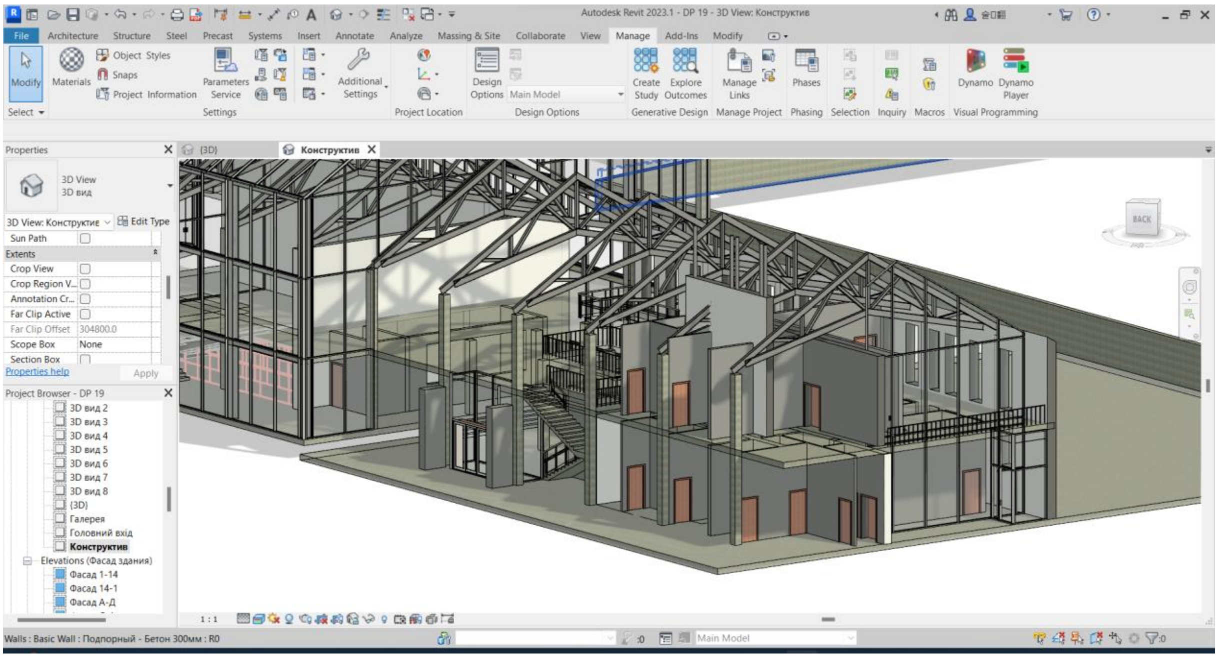

Fig. 23. Design of structural elements [13].

Revit impresses with its integration and ability to allow structural engineers to actively interact and edit various structural elements, giving them a high degree of control over the project [19]. The design engineer can change the type and materials of structures independently of the architect to meet the technical and engineering requirements of the project (Fig. 24.).

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A particularly important feature is the ability to reinforce reinforced concrete structures, where the design engineer can perform calculations and configure reinforcing elements directly in the programme [20]. This simplifies and streamlines the design process, allowing for accurate material consumption specifications for each structural element to be generated automatically.

This approach ensures high efficiency and accuracy of design, allowing design engineers to effectively manage and optimise material consumption to achieve high quality and efficiency in construction [22].

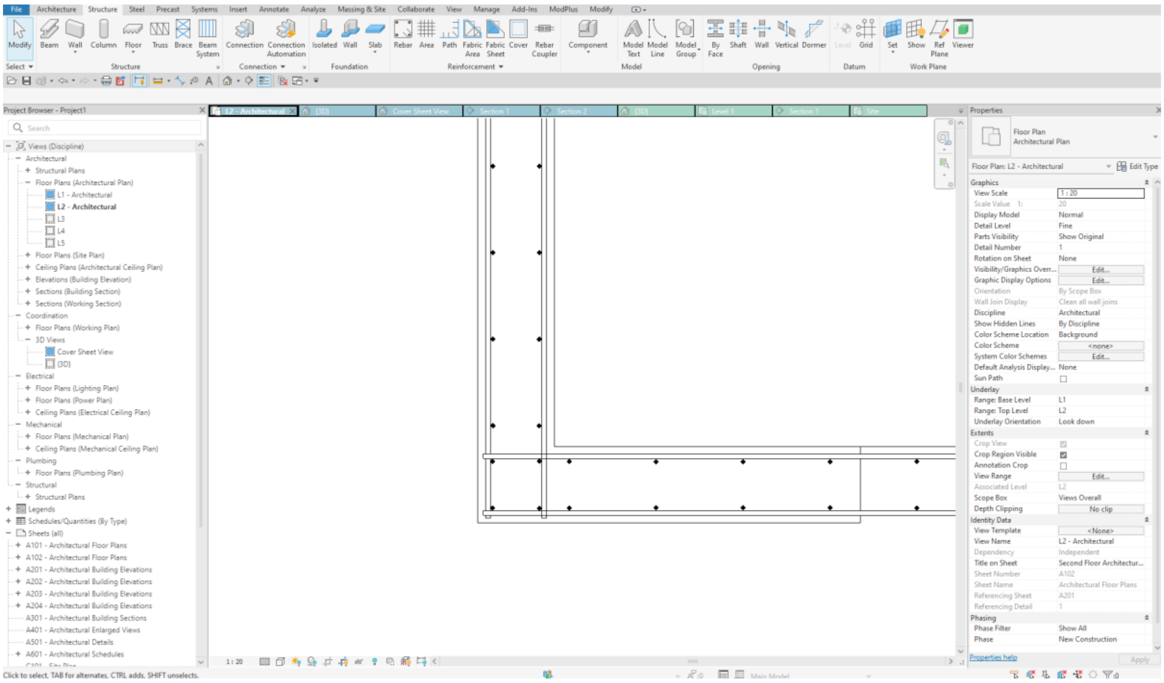

Fig. 24. Wall reinforcement

3.2 Description of the project implementation

By default, when you start Revit, the Recent Files window opens (Fig. 25.). Resources area is on the right side. The upper area refers to projects, and the lower area refers to families.

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Both areas display links to the four projects and four families that were opened most recently. Each area on the left side contains buttons for opening and creating projects and families [23].

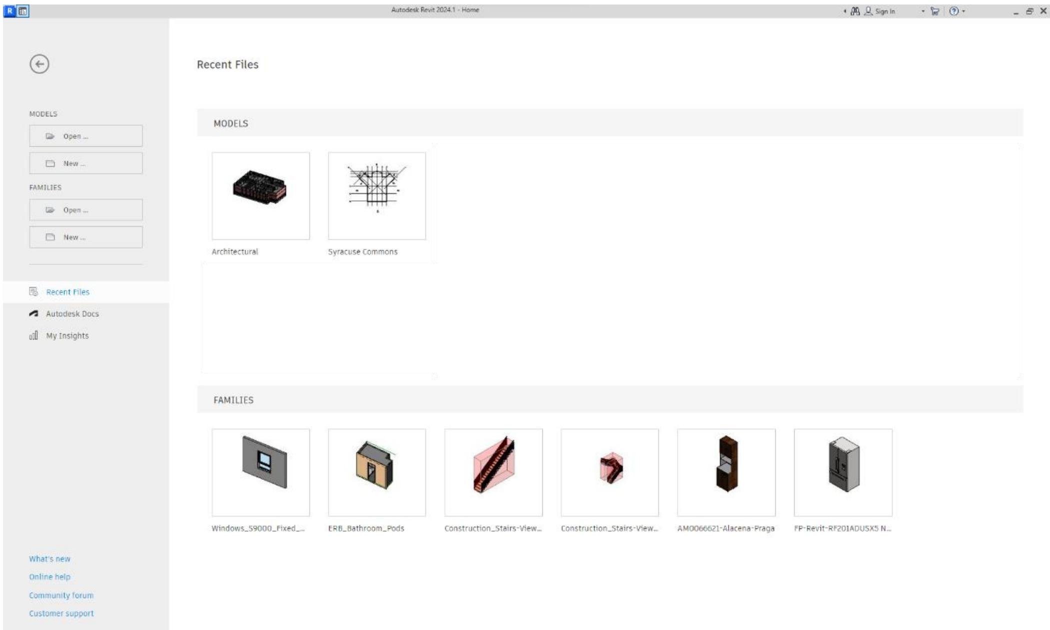

Fig. 25. Revit initial window

To create a new project, you need to execute the command Create → Project from the application menu.

Double-click the left mouse button in the Project Manager to switch to the Site plan (Fig. 26.). The first thing to do is to draw the axes. To draw the axes, select the Architecture, Datum, Grid command (Fig. 27.). In the Modify | Place Grid tab, select the most convenient way to draw axes for a particular project (Fig. 28.).

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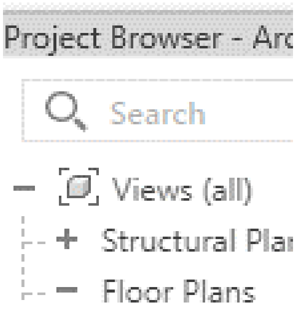

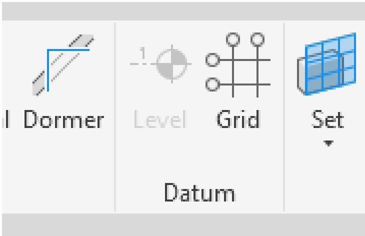

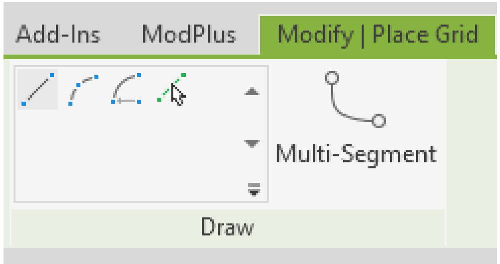

Fig. 26. Project Manager

Fig. 27. Axis command

Fig. 28. Edit tab | Grid coordinates

To change the axis labelling, select the desired axis, then click on the label and change it. By default, the numbers are in numerical order and the letters are in alphabetical order [24] (Fig. 29.).

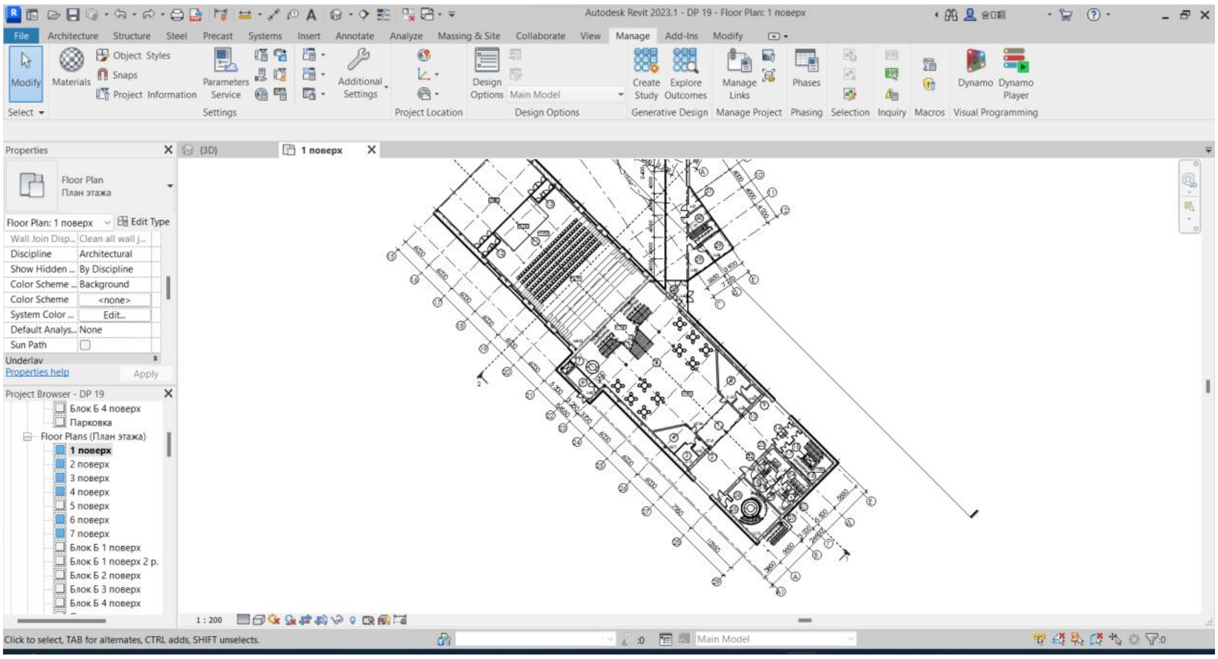

Fig. 29. Axes, columns and dimensions on the plan [13].

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Select the command Annotate → Dimension → Aligned dimension to set the dimensions. By clicking on the axes in succession and making the last click in any free space, a dimensional chain can be added. To lock the resulting dimensions, click on the open padlock icon (appears when you select an axis).

Next, it is necessary to calculate how high the floor will be and to mark the selected height, go to the Project browser - Project tab on the left panel and select any facade by clicking on Facades. By dragging the levels, it is possible to change the height, and by clicking on the level name, it can be edited (Fig. 30.) Also, levels can be added by the command Architecture → Datum → Level.

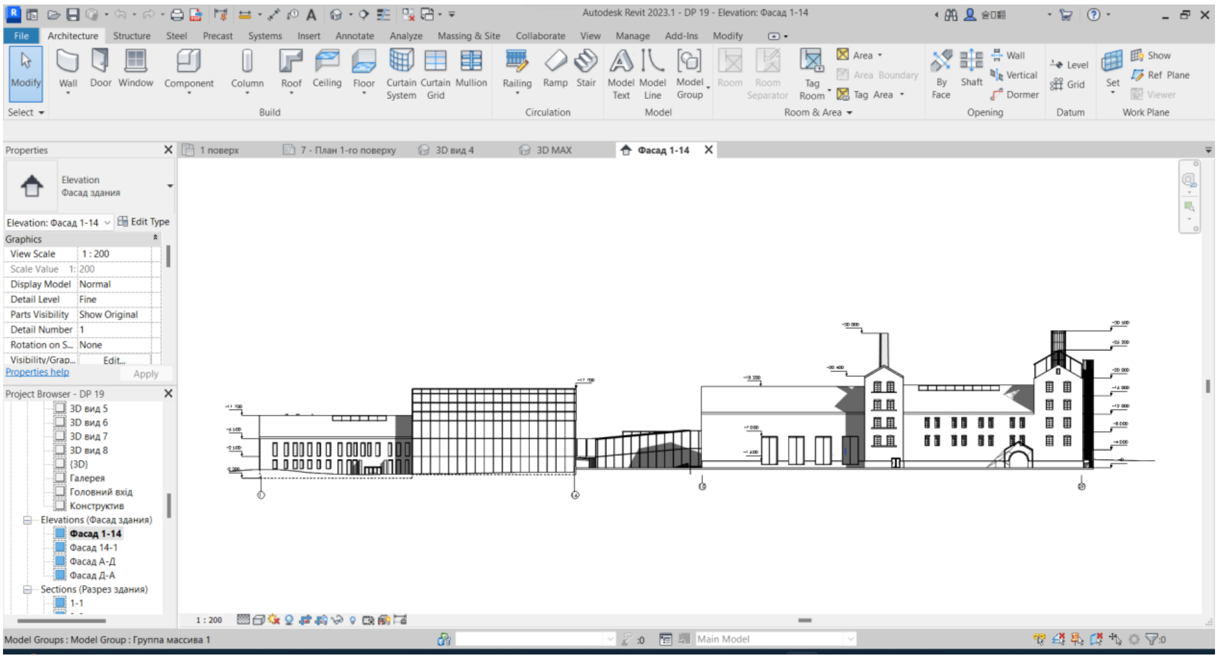

Fig. 30. Levels on the Facades tab [13].

The axes are already there, but the bearing elements are missing. As is commonly known, it is more convenient to place columns on the plan, so in the Project browser - Project tab, select the level at which you want to place them. To place columns, go to the Architecture → Build tab and select the Column element. This element has two sub-elements: Structural

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Column and Column: Architectural, which can be seen by clicking on the arrow next to the element.

The difference between the elements is obvious, but by selecting any of these elements and clicking on the Properties tab → Edit Type, you can edit the parameters, rename and load other columns (Fig. 31.).

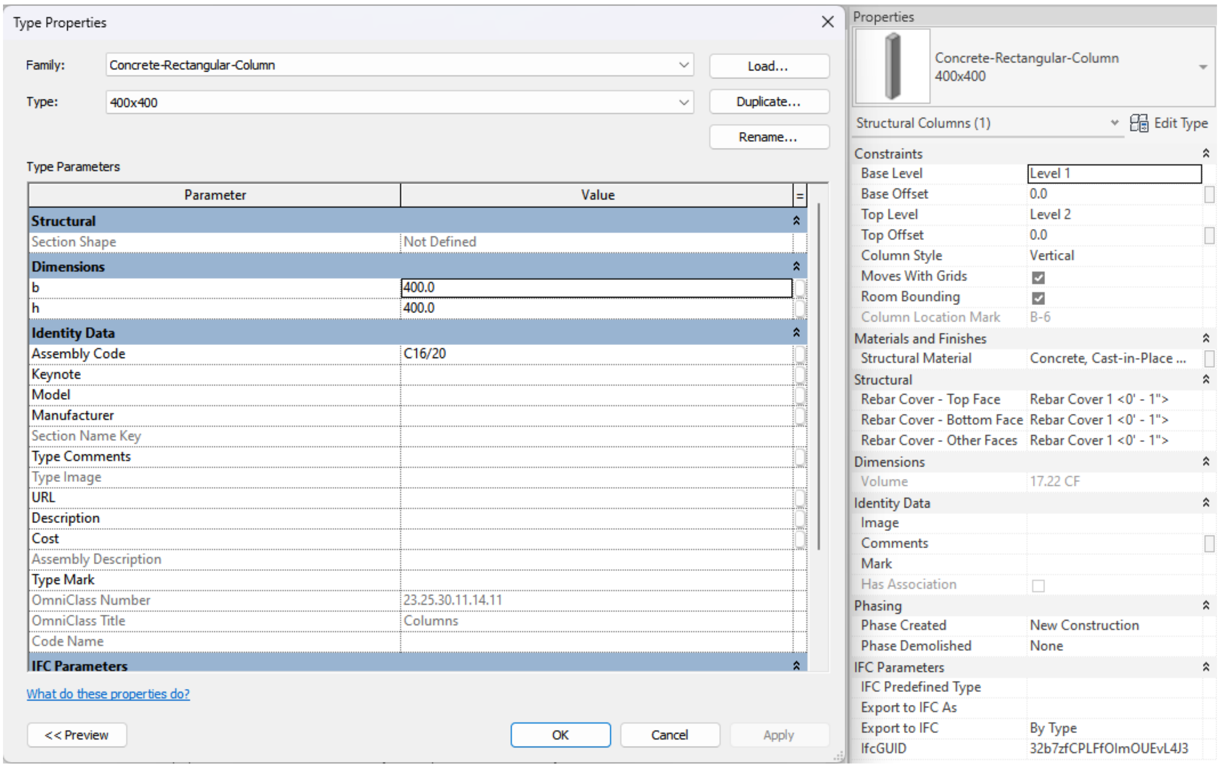

Fig. 31. Properties of the "Column" element

To draw walls, activate the Architecture → Build → Wall tool. In the left property panel, by clicking on the wall, select the one that suits most, or change the wall parameters in Properties → Edit Type (Fig. 32.).

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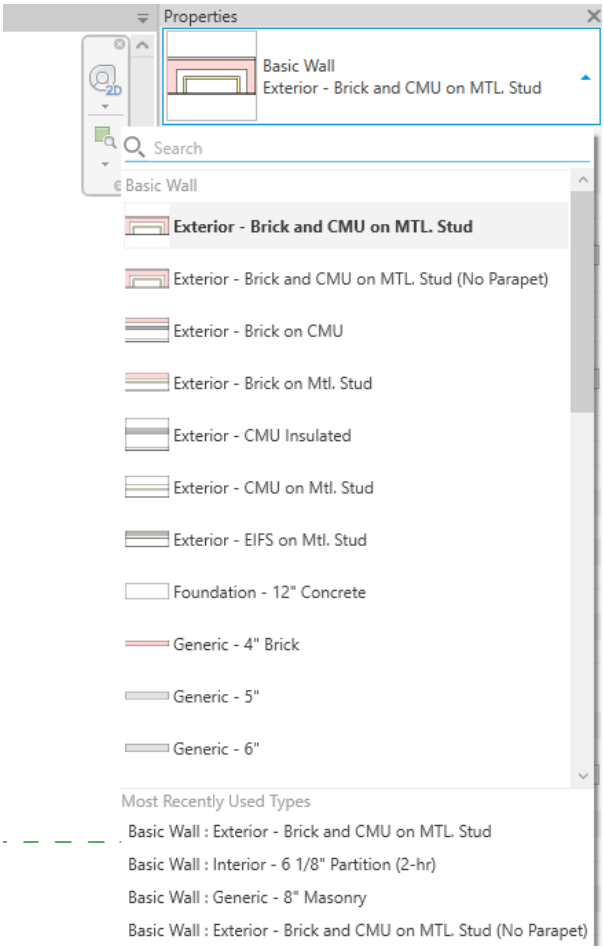

Fig. 32. Types of "Wall" elements

Windows and doors are added from the Architecture → Build → Window / Door tabs, respectively. In the properties, it is possible to select a door or window from the proposed ones, add it from the library, and change the parameters. Select the desired element, place the cursor on the wall and drag it to the appropriate location.

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To add a staircase, select Circulation → Stair from the same Architecture tab. Among the proposed components, select Stair by Component. This opens a contextual tab where it is possible to create a staircase using the necessary elements (Fig. 33.).

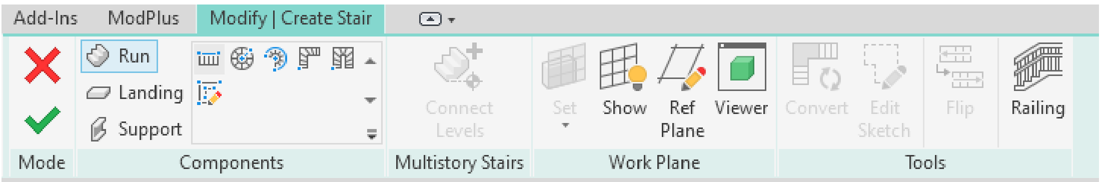
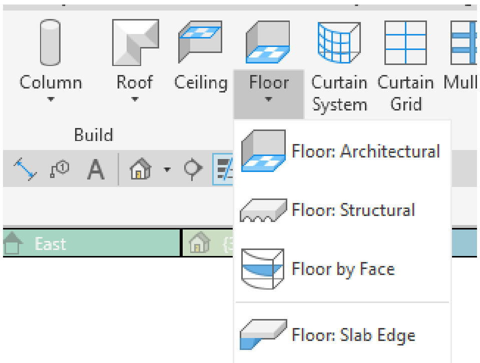


Fig. 33. Context tab for editing a stairs

Similarly, it is possible to create walls and place windows and doors on other floors by moving between them using the left pane of the Project browser - Project.

In order to create a floor between stories, select the Architecture → Floor tab and select the desired floor (Fig. 34.). A contextual tab will open, where it is possible to choose a more convenient tool for setting the floor (Fig. 35.).



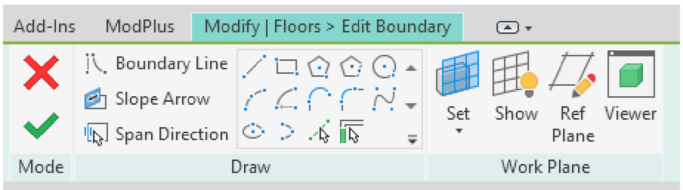


Fig. 34. The "Floor" command

Fig.35. Contextual tab for editing

To make an explication of all rooms, select the Room command on the Room and Area tab. The contextual tab opens, where the tools that can be used to create rooms are available (Fig. 36.). The name and number of the room can be edited by clicking on them.

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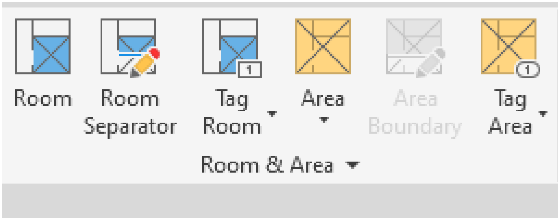
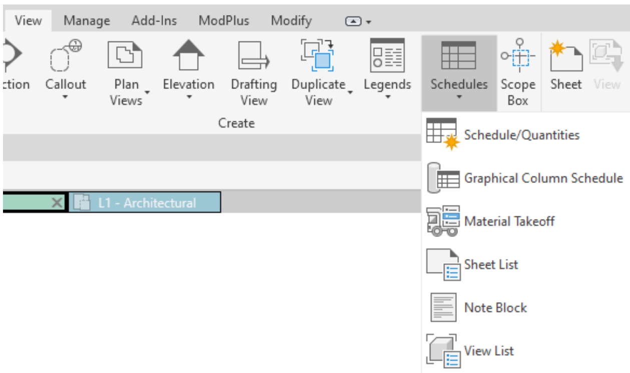


Fig. 36. Room

Next, go to the View → Create tab and select the Schedules/Quantities command (Fig. 37.). A window opens where in the Category section (Fig. 38.) select Rooms.



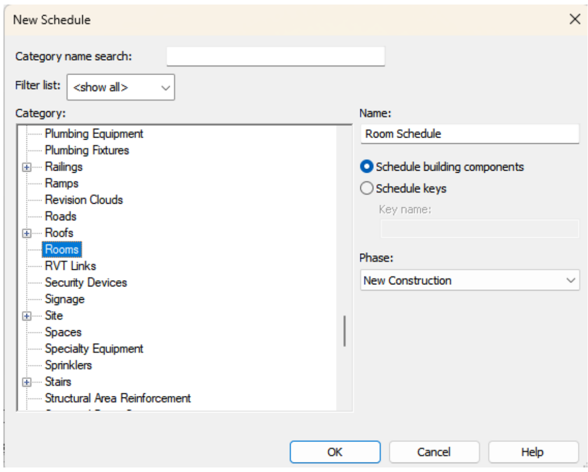


Fig. 37. Schedules/Quantities

Fig.38. Specification properties

From the Available fields to the Scheduled fields, drag the parameters necessary for displaying in the specification (Fig. 39.), it can be edited in the Properties tab on the left panel (Fig. 40-41.).

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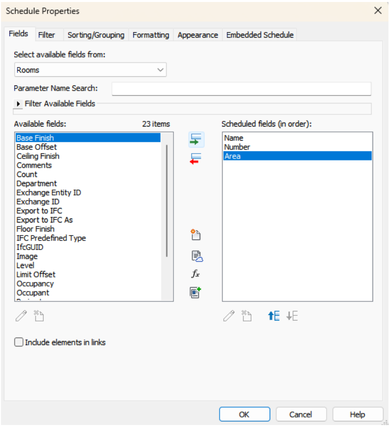

Fig. 39. Specification properties

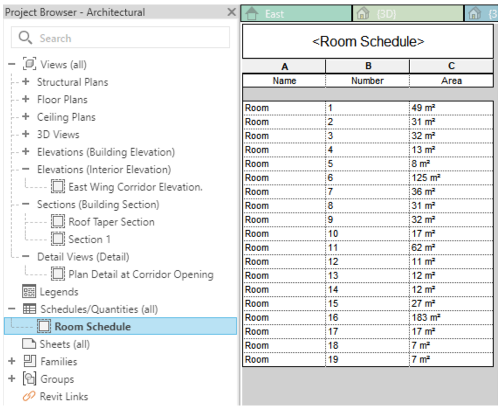

Fig.40. Specification of rooms

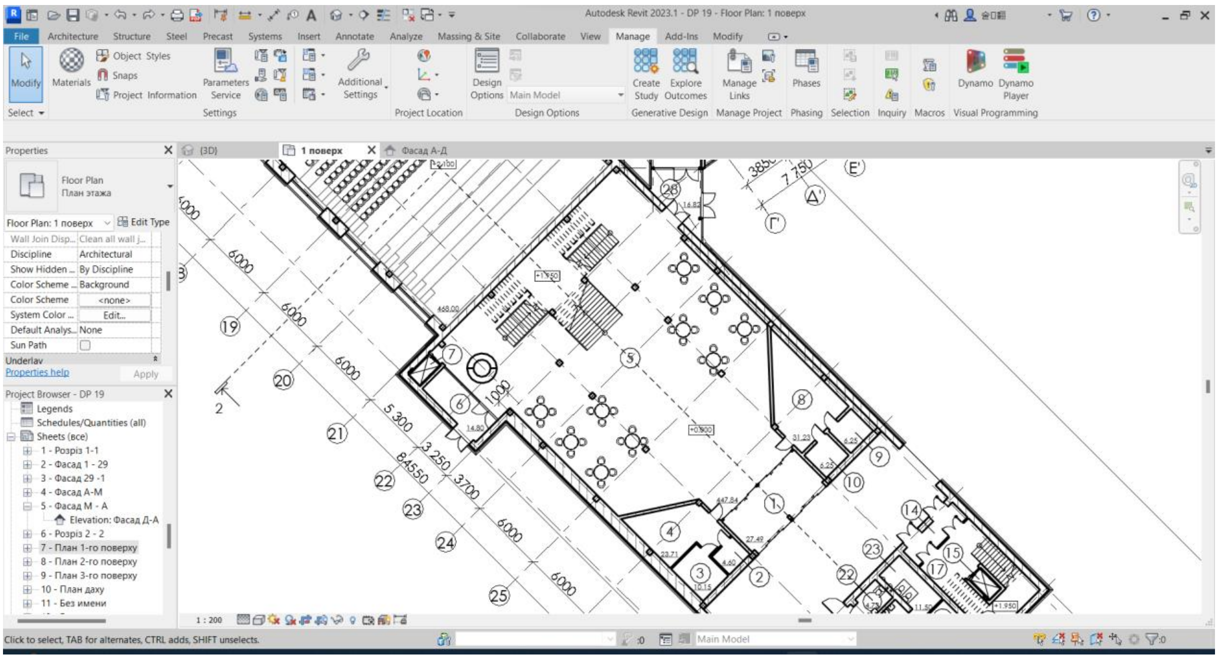

Fig. 41. Part of the ground floor plan with specification [13].

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The axonometric view of the building can be shown by clicking on the 3D tab on the left tab of the Projectbrowser - Project (Fig. 42.).

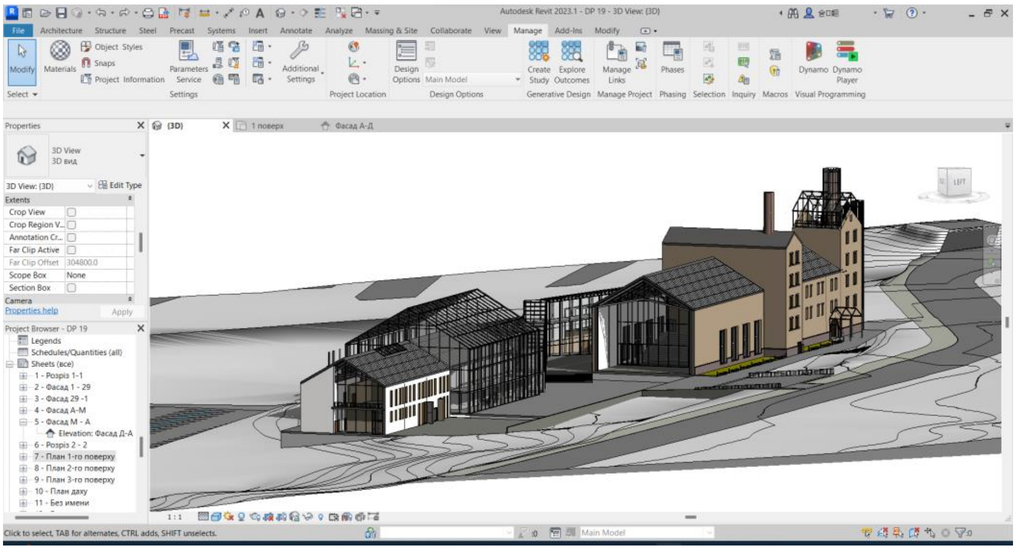

Fig. 42. 3D view [13].

The styles of displaying a 3D model can be changed in the Visual Style panel (Fig. 42-44).

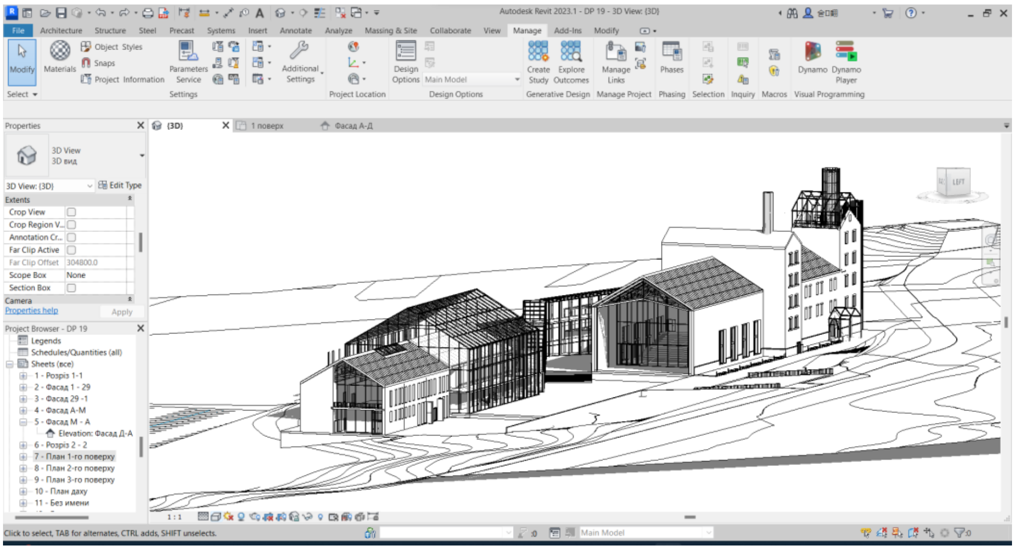

Fig. 43. Hidden line style [13].

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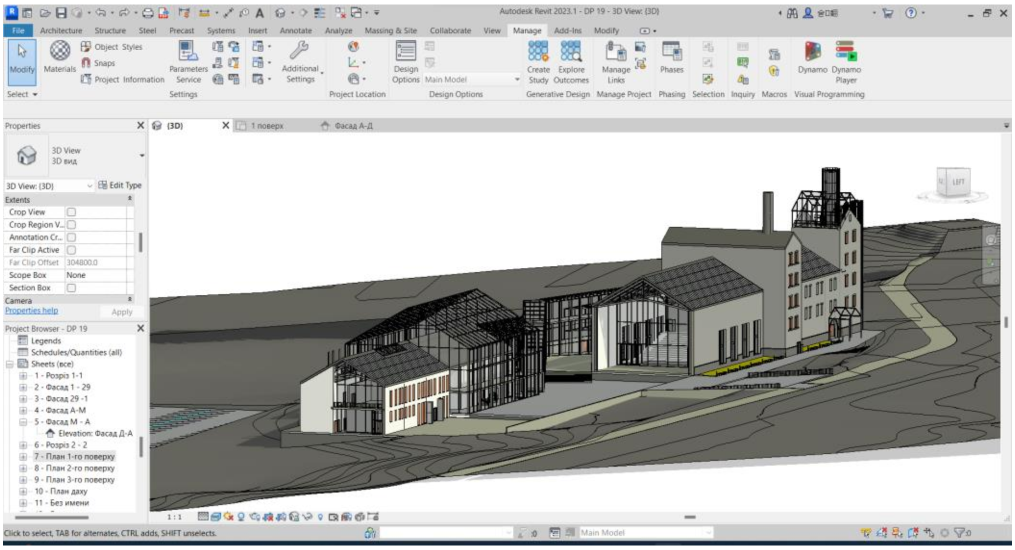

Fig. 44. Realistic style [13].

You can also create a custom style. To do this, select Graphic Display Options in the bottom Visual Style panel.

If changing the materials is necessary, choose Manage → Settings → Materials. A window opens where the materials of the model can be configured (Fig. 45.).

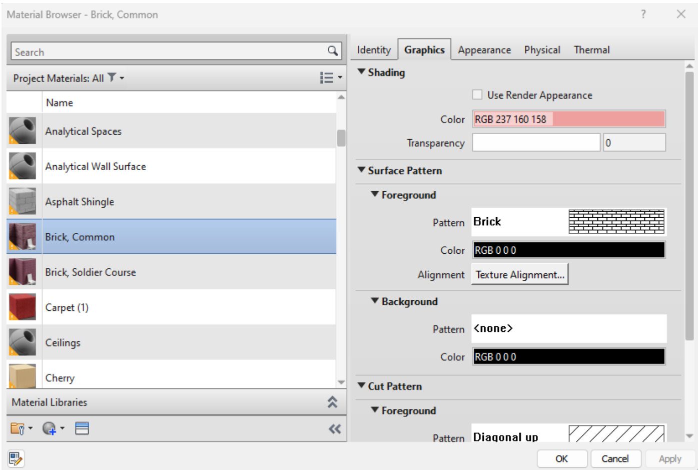

Fig. 45. Materials configuration window

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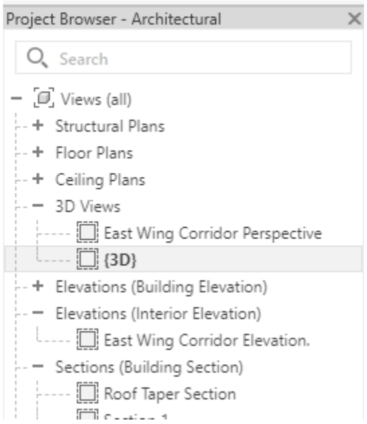
In order to make a render, create a camera. Go to the View → Create tab and select 3D View → Camera (Fig. 46.). Place the camera in the desired location on the plan (Fig. 47.).



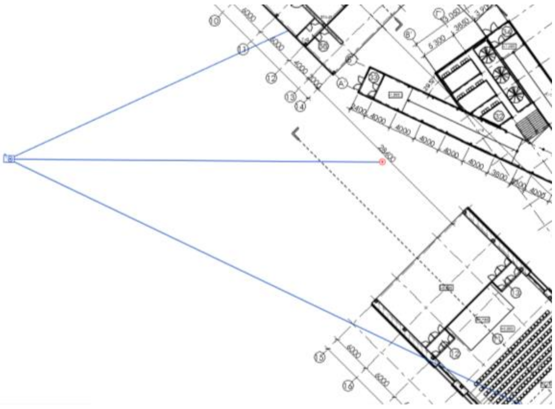


Fig. 46. 3D views in the project manager Fig.47. Installing a camera on a floor plan

Next, in the left pane of the Projectbrowser - Project, in the 3D Views tab, select the newly created view (Fig. 48.).

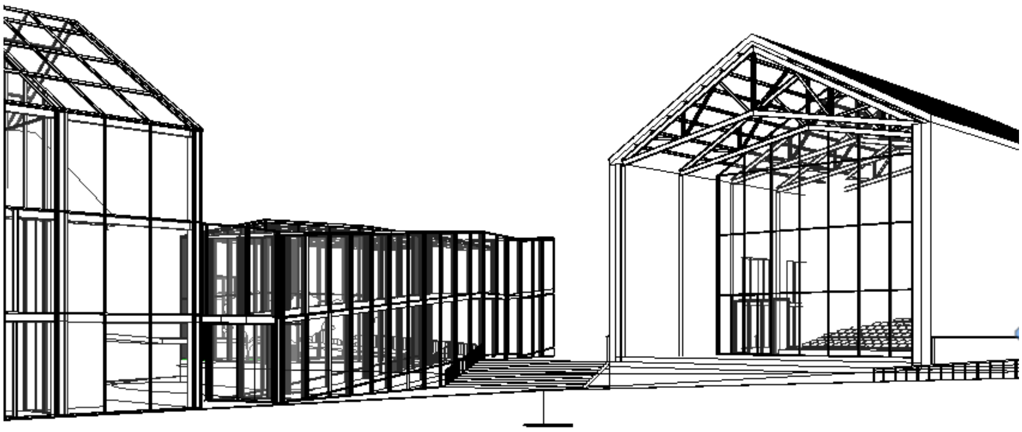


Fig. 48. View from the camera.

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If more than one camera is created, the corresponding views will appear in this tab. After switching to one of the views, the view from the corresponding camera is displayed. The viewport boundaries can be changed by dragging them to any side. When the view is selected, click the Show Rendering Dialog command in the lower panel (Fig. 49.).

Fig. 49. Visualisation dialogue box

A window with rendering settings opens. Here it is possible to change the quality, resolution, lighting, and background. To start rendering, click the Render command on the panel (Fig. 50.).

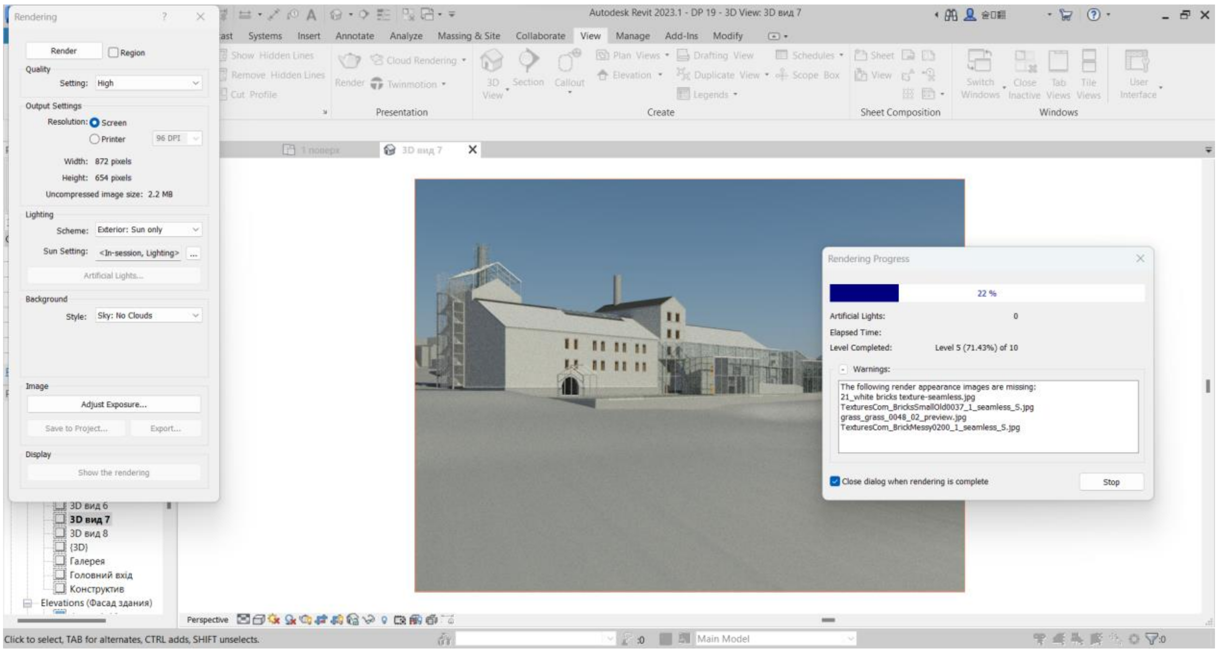

Fig. 50. The rendering process in Autodesk Revit [13].

When the rendering is complete, it can be exported to a computer or saved in the project. To transfer the materials created to a sheet, in the left pane of the Project browser - Project,

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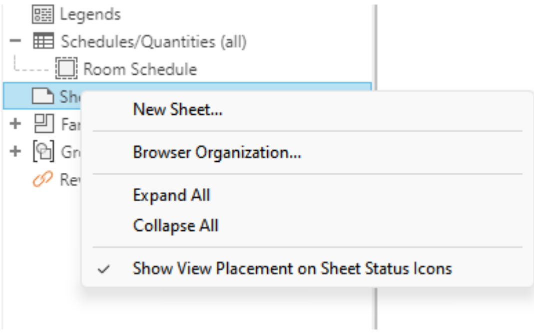
right-click on the Sheets tab and select New Sheet (Fig. 51.). A window opens where it is possible to select the desired sheet size or upload sheet (Fig. 52.).



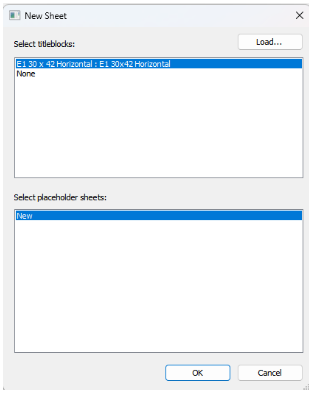


Fig. 51. Sheets tab Fig.52. The window for creating a new sheet

The selected sheet should open in the workspace (Fig. 53.).

Fig. 53. A blank sheet

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To add plans, facades, and perspectives to a sheet, drag the corresponding elements from the Project browser - Project panel onto the sheet. Arrange the materials on the sheet. To edit any element, double-click on it with the left mouse button (Fig. 54.).

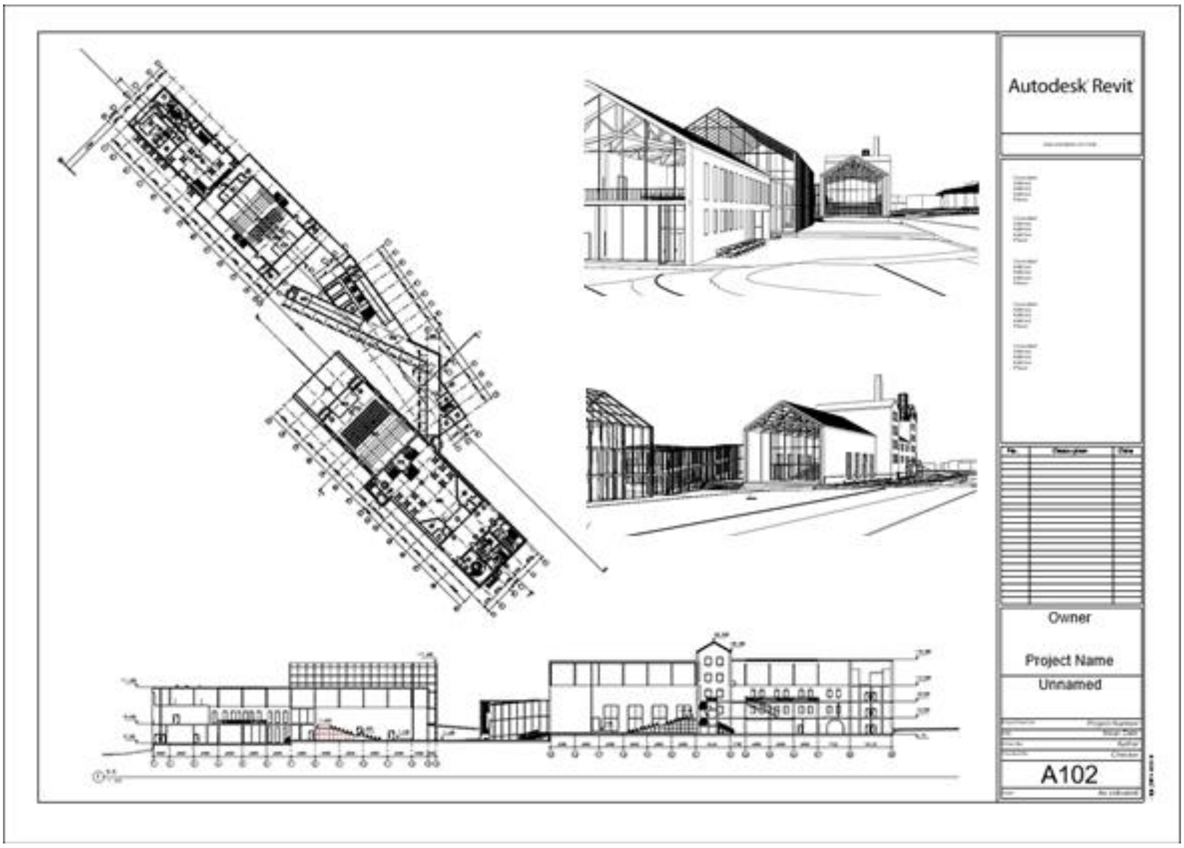

Fig. 54. Completed architecture sheet [13].

In accordance with this module, a model of the reconstructed object was printed on a 3D printer at a scale of M 1:500 (Figs. 55-56.).

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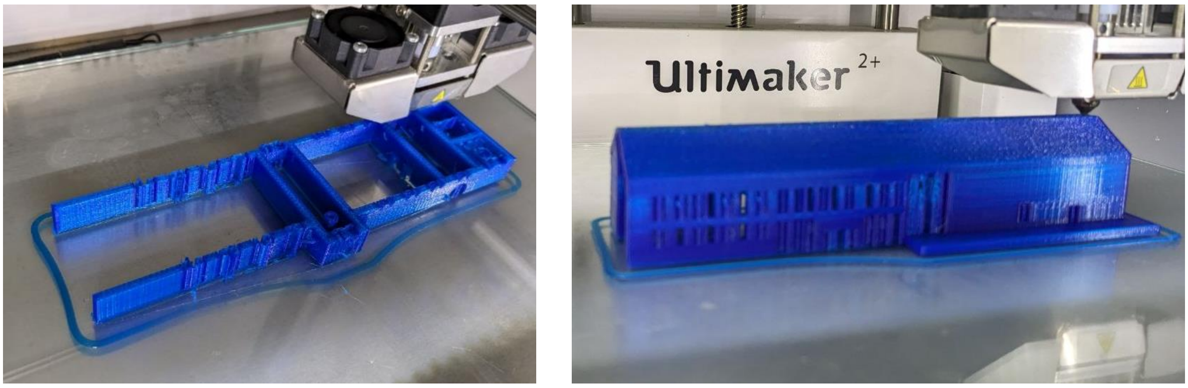

Fig. 55. The process of creating a 3D model

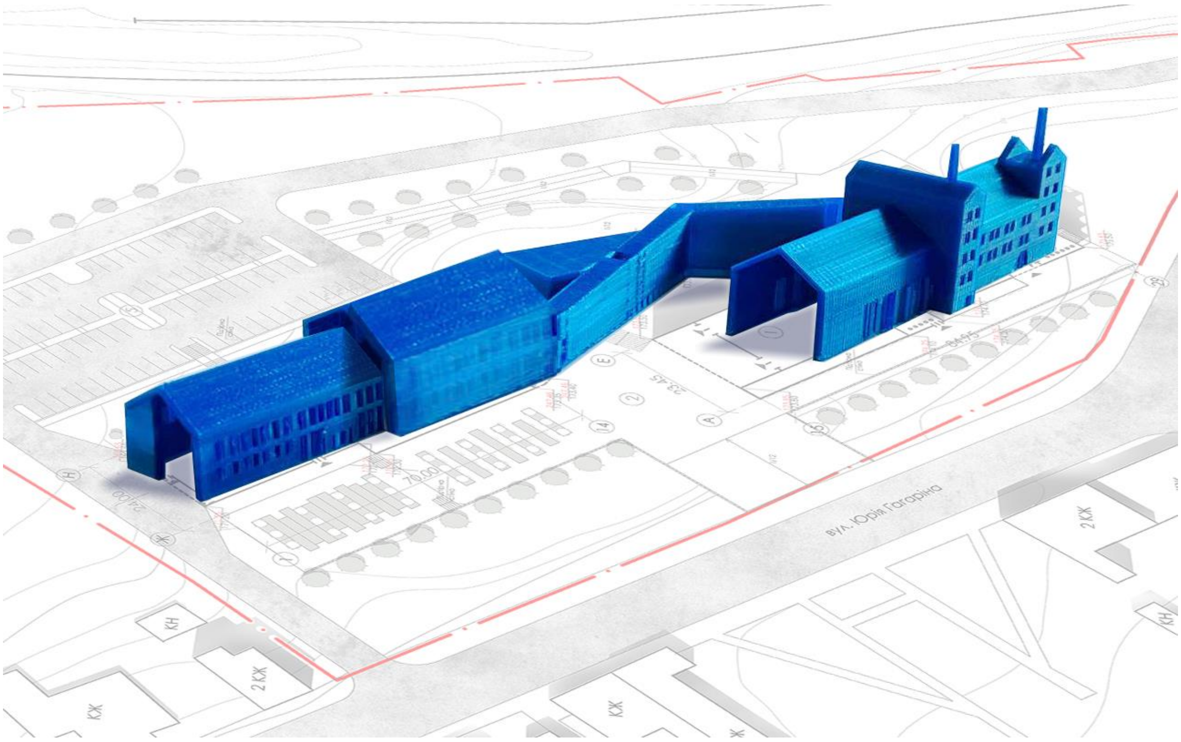

Fig. 56. Finished 3D model

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4 Conclusions

The following key advantages of Revit and BIM technology can be noted in the reconstruction of a brewery in Chernivtsi:

- the information and architectural 3D model of the building makes it possible to compare the original object with the reconstruction project, to demonstrate architectural and engineering solutions;
- collisions of a complex and voluminous engineering project, typical for industrial buildings, can be identified and corrected before it is transferred to the stage of actual reconstruction;
- the adaptive properties of the information model allow all related sections of the project to be automatically updated when corrections are made to any of them;
- Revit allows automatic generation of specifications for demolished objects, taking into account the types of structures, and thus calculates with great accuracy the volumes of building structures to be dismantled.

Therefore, the reconstruction of the brewery's industrial building, and the factory's territory as a whole, in Chernivtsi, which was previously closed, is becoming a new place of attraction for the city's residents and opens up new opportunities for the reorganisation of the urban historical environment near the railway station.

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AMAZE

Erasmus+ Programme Key Action 2 Cooperation Partnerships for Higher Education (KA220-HED)
Project No: 2023-1-RO01-KA220-HED-000155412
Project title: European Network for Additive Manufacturing in Industrial Design for Ukrainian Context – Acronym: AMAZE

MODULE 4
Reverse Engineering

Project Title	**European Network for Additive Manufacturing in Industrial Design for Ukrainian Context 2023-1-RO01-KA220-HED-000155412**
Output	**IO1 - AMAZE e-book for industrial design for complex parts**
Module	**Module 4 Reverse Engineering**
Date of Delivery	**March 2024**
Authors	**Remigiusz Łabudzki, Natalia Wierzbicka, Adam Patalas, Paweł Zawadzki**
Version	**FINAL VARIANT, 29.02.2024**

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1 *Introduction*

In today's intensely competitive global market, product enterprises are constantly seeking new ways to shorten lead times for new product developments that meet all customer expectations. In general, product enterprise has invested in CAD/CAM, rapid prototyping, and a range of new technologies that provide business benefits. Reverse engineering (RE) is now considered one of the technologies that provide business benefits in shortening the product development cycle. Figure 1.1 below depicts how RE allows the possibilities of closing the loop between what is "as designed" and what is "actually manufactured".

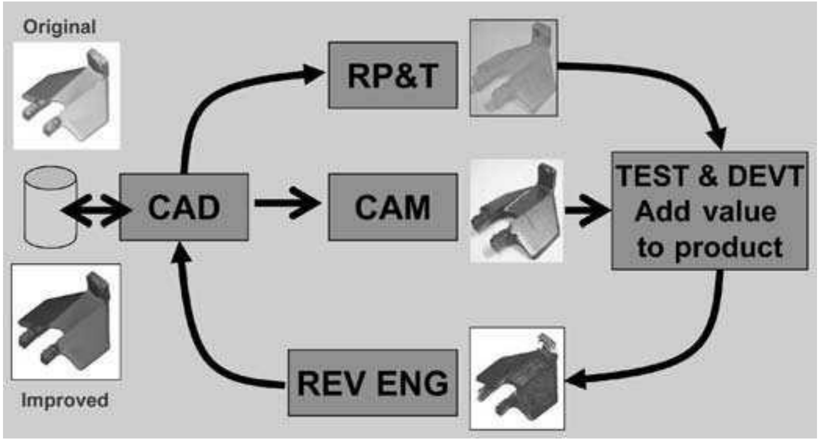

Figure 1.1 Product development cycle

1.1 *What Is Reverse Engineering?*

Engineering is the process of designing, manufacturing, assembling, and maintaining products and systems. There are two types of engineering, forward engineering (FE) and reverse engineering (RE) – figure 1.2. Forward engineering (FE) is the traditional process of moving from high-level abstractions and logical designs to the physical implementation of a system. In some situations, there may be a physical part/product without any technical details, such as drawings, bills-of-material, Or without engineering data. The process of duplicating an

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existing part, subassembly, or product, without drawings, documentation, or a computer model is known as reverse engineering (FE). Reverse engineering is also defined as the process of obtaining a geometric CAD model from 3-D points acquired by scanning/digitizing existing parts/products. The process of digitally capturing the physical entities of a component, referred to as reverse engineering (RE), is often defined by researchers with respect to their specific task [1].

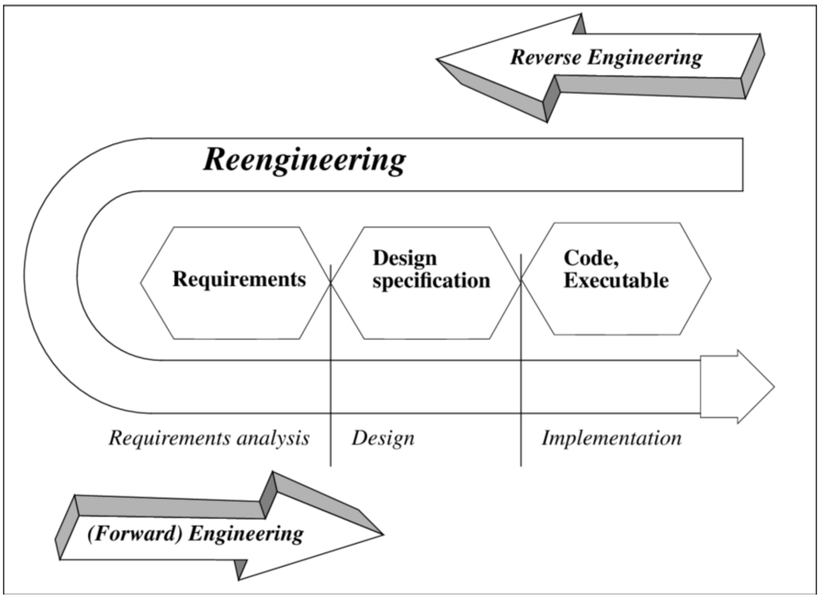

Figure 1.2 Forward Engineering (FE) vs Reverse Engineering (RE)

Abella [2] described RE as, “the basic concept of producing a part based on an original or physical model without the use of an engineering drawing”. Yau [3] define RE, as the “process of retrieving new geometry from a manufactured part by digitizing and modifying an existing CAD model”.

Reverse engineering is now widely used in numerous applications, such as manufacturing, industrial design, and jewellery design and reproduction For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn

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how it was built and how it works. In software engineering, good source code is often a variation of other good Skurce code. In some situations, such as automotive styling, designers give shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to manufacture the part. As products become more organic in shape, designing in CAD becomes more challenging and there is no guarantee that the CAD representation will replicate the sculpted model exactly.

Reverse engineering provides a solution to this problem because the physical model is the source of information for the CAD model. This is also referred to as the physical-to-digital process depicted in Figure 1.3. Another reason for reverse engineering is to compress product development cycle times. In the intensely competitive global market, manufacturers are constantly seeking new ways to shorten lead times to market a new product. Rapid product development (RPD) refers to recently developed technologies and techniques that assist manufacturers and designers in meeting the demands of shortened product development time. For example, injection-molding companies need to shorten tool and die development time drastically. By using reverse engineering, a three-dimensional physical product or clay mock-up can be quickly captured in the digital form, remodeled, and exported for rapid prototyping/tooling or rapid manufacturing using multi-axis CNC machining techniques.

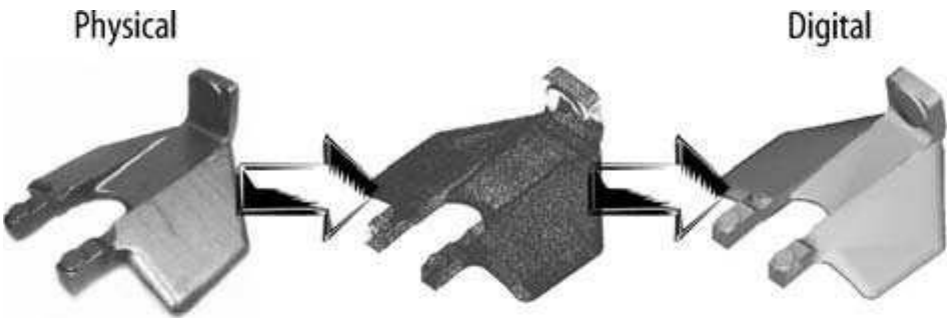

Figure 1.3 Physical-to-digital process

1.2 *Why Use Reverse Engineering?*

Following are some of the reasons for using reverse engineering:

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• The original manufacturer no longer exists, but a customer needs the product, e.g., aircraft spares required typically after an aircraft has been in servicefor several years.

• The original manufacturer of a product no longer produces the product, e.g., the original product has become obsolete.

• The original product design documentation has been lost or never existed.

• Creating data to refurbish or manufacture a part for which there are no CAD data, or for which the data have become obsolete or lost.

• Inspection and/or Quality Control–Comparing a fabricated part to its CAD description or to a standard item.

• Some bad features of a product need to be eliminated e.g., excessive wear might indicate where a product should be improved.

• Strengthening the good features of a product based on long-term usage.

• Analyzing the good and bad features of competitors' products.

• Exploring new avenues to improve product performance and features.

• Creating 3-D data from a model or sculpture for animation in games and movies.

• Creating 3-D data from an individual, model or sculpture to create, scale, or reproduce artwork.

• Architectural and construction documentation and measurement.

• Fitting clothing or footwear to individuals and determining the antropometry of a population.

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• Generating data to create dental or surgical prosthetics, tissue engineered body parts, or for surgical planning.

• Documentation and reproduction of crime scenes.

The above list is not exhaustive and there are many more reasons for using reverse engineering, than documented above.

1.3 *Reverse Engineering–The Generic Process*

The generic process of reverse engineering is a three-phase process as depicted in Figure 1.4. The three phases are scanning, point processing, and application specific geometric model development. Reverse engineering strategy must consider the following:

• Reason for reverse engineering a part

• Number of parts to be scanned–single or multiple

• Part size–large or small

• Part complexity–simple or complex

• Part material–hard or soft

• Part finish–shiny or dull

• Part geometry–organic or prismatic and internal or external

• Accuracy required–linear or volumetric

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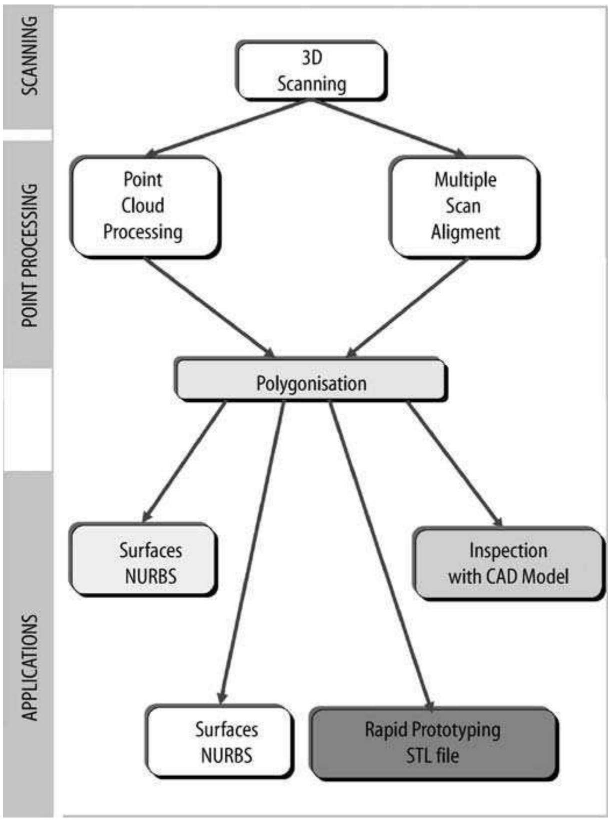

Figure 1.4 Reverse engineering – the generic process

1.4 *Phase 1–Scanning*

This phase is involved with the scanning strategy–selecting the correct Canning technique, preparing the part to be scanned, and performing the actual Canning to capture information that describes all geometric features of the part such as steps, slots, pockets, and holes. Three-dimensional scanners are employed to scan the part geometry, producing clouds of points, which define the surface geometry. These scanning devices are available as dedicated tools or as add-onsto the existing computer numerically controlled (CNC) machine tools. There are two distinct types of scanners, contact and noncontact.

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1.4.1 Contact Scanners

These devices employ contact probes that automatically follow the contours of a physical surface (Fig. 1.5). In the current marketplace, contact probe scanning devices are based on CMM technologies, with a tolerance range of +0.01 to 0.02 mm. However, depending on the size of the part scanned, contact methods can be slow because each point is generated sequentially at the tip of the probe. Tactile device probes must deflect to register a point; hence, a degree of contact pressure is maintained during the scanning process. This contact pressure limits the use of contact devices because soft, tactile materials such as rubber cannot be easily or accurately scanned.

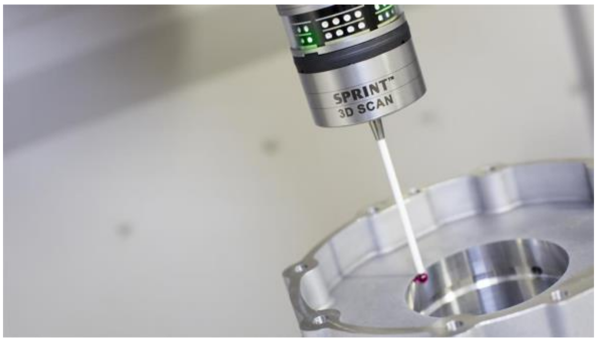

Figure 1.5 Contact scanning touch probe.

1.4.2 Noncontact Scanners

A variety of noncontact scanning technologies available on the market capture data with no physical part contact. Noncontact devices use lasers, optics, and charge-coupled device (CCD) sensors to capture point data, as shown in Figure 1.6. Although these devices capture large amounts of data in a relatively short space of time, there are a number of issues related to this scanning technology.

- The typical tolerance of noncontact scanning is within ±0.025 to 0.2 mm.

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• Some noncontact systems have problems generating data describing surfaces, which are parallel to the axis of the laser (Figure 1.7).

• Noncontact devices employ light within the data capture process. This creates problems when the light impinges on shiny surfaces, and hence some surfaces must be prepared with a temporary coating of fine powder before scanning.

These issues restrict the use of remote sensing devices to areas in engineering, where the accuracy of the information generated is secondary to the speed of data capture. However, as research and laser development in optical technology continue, the accuracy of the commercially available noncontact scanning device is beginning to improve.

The output of the scanning phase is point cloud data sets in the most convenient format. Typically, the RE software provides a variety of output formats such as raw (X, Y, Z values separated by space or commas).

Figure 1.6. Optical scanning device.

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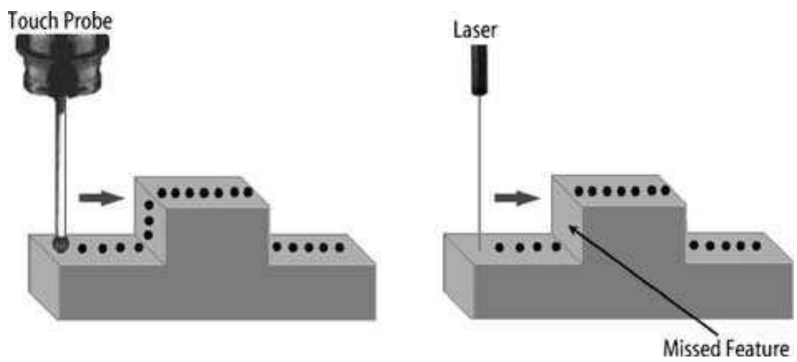

Figure 1.7. Vertical faces–touch probe versus a laser [4]

1.5 *Phase 2–Point Processing*

This phase involves importing the point cloud data, reducing the noise in the data collected, and reducing the number of points. These tasks are performer using a range of predefined filters. It is extremely important that the users have very good understanding of the filter algorithms so that they know which filter is the most appropriate for each task (Fig 1.8). This phase also allows us to merge multiple scan data sets (Fig. 1.9). Sometimes, it is necessary to take multiple scans of the part to ensure that all required features have been scanned. This involves rotating the part; hence each scan datum becomes very crucial. Multiple scan planning has direct impact on the point processing phase. Good datum planning for multiple scanning will reduce the effort required in the point processing phase and also avoid introduction of errors from merging multiple scan data. A wide range of commercial software is available for point processing.

The output of the point processing phase is a clean , merged, point cloud data set in the most convenient format. This phase also supports most of the proprietary formats mentioned above in the scanning phase.

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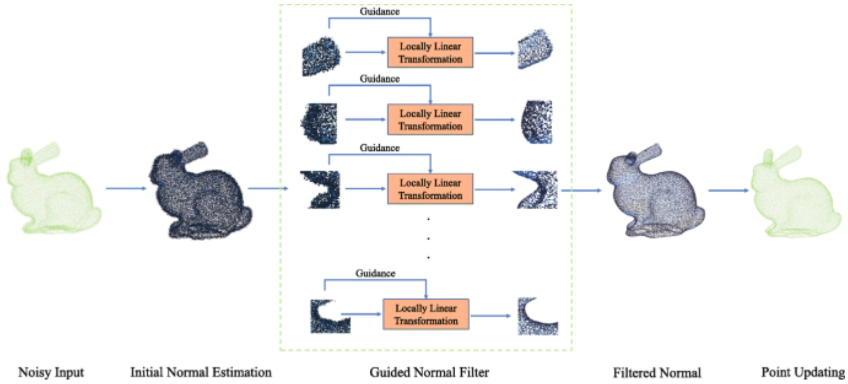

Figure 1.8 Filtering point cloud in RE

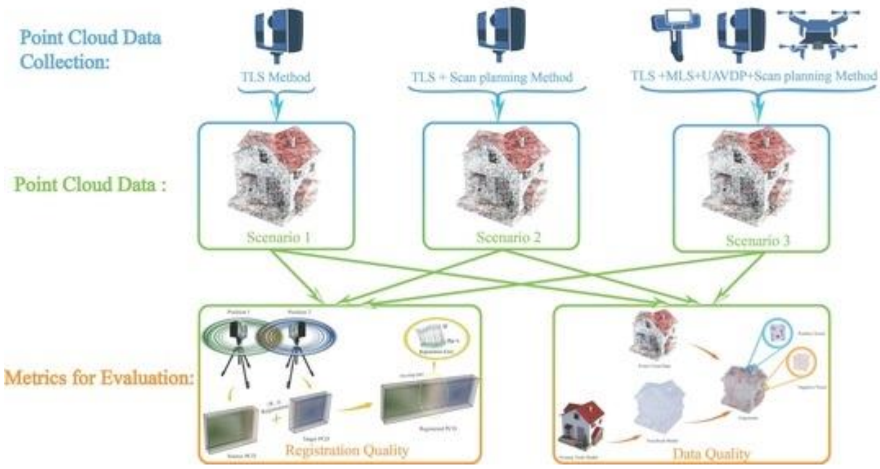

Figure. 1.9 Multiple scan planning in architecture

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1.6 *Phase 3–Application Geometric Model Development*

In the same way that developments in rapid prototyping and tooling Technologies are helping to shorten dramatically the time taken to generate physical representations from CAD models, current RE technologies are helping to reduce the time to create electronic CAD models from existing physical representations. The need to generate CAD information from physical components will are frequently throughout any product introduction process (Fig. 1.10).

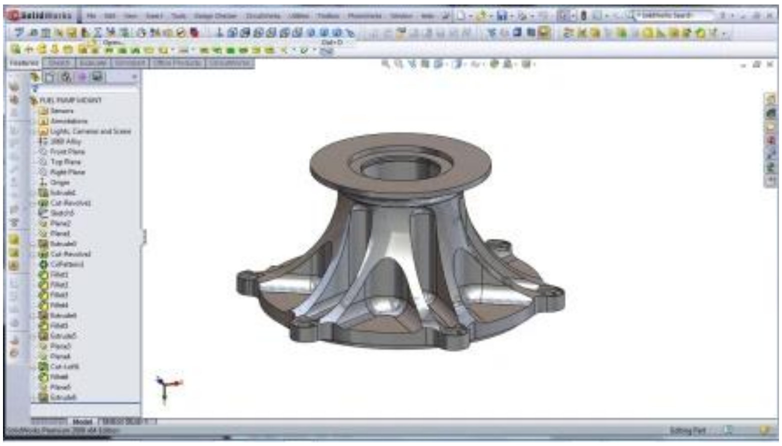

Figure 1.10 Sample of CAD model

The generation of CAD models from point data is probably the most complex activity within RE because potent surface fitting algorithms are required to generate surfaces that accurately represent the three-dimensional information described within the point cloud data sets. Most CAD systems are not designer to display and process large amounts of point data; as a result new RE module or discrete software packages are generally needed for point processing. Generating surface data from point cloud data sets is still a very subjective process, although feature-based algorithms are beginning to emerge that will enable engineers to interact with the point cloud data to produce complete solid models for current CAD environments.

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The applications of RE for generating CAD data are equally as important as the technology which supports it. A manager's decision to employ RE Technologies should be based on specific business needs.

This phase depends very much on the real purpose for reverse engineering. For example, if we scanned a broken injection molding tool to produce a new tool, we would be interested in the geometric model and also in the ISO G code data that can be used to produce a replacement tool in the shortest possible time using a multi-axis CNC machine. One can also use reverse engineering to analyze "as designed" to "as manufactured". This involves importing the as designer CAD model and superimposing the scanned point cloud data set of the manufactured part. The RE software allows the user to compare the two data sets (as designed to as manufactured). This process is also used for inspecting manufactured parts. Reverse engineering can also be used to scan existing hip joints and to design new artificial hips joint around patient- specific pelvic data. This creates the opportunity for customized artificial joints for each patient.

The output of this phase is geometric model in one of the proprietary formats such as IGES, VDA, STL, DXF, OBJ, VRML, ISO G Code, etc. This chapter defined the term "reverse engineering" followed by reasons for using reverse engineering. It also introduced the reverse engineering strategy, the three phases of the reverse engineering generic process, contact and noncontact scanning, point processing, and application geometric model development.

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2 Methodologies and Techniques for Reverse Engineering

2.1 Computer-aided Reverse Engineering

Each discipline of engineering has a different definition for RE. Computer engineers and computer scientists, for example, refer to RE when they speak of determining the algorithmic functionality of a software package when they have no prior knowledge of the original software design. Engineers and programmers attempt to develop functional block diagrams of the software through interaction with the interface and to develop high-level code descriptions from Raw machine code. This software definition is not the scope of our RE discussion. Another example of RE that might be familiar–but also outside the scope of this chapter–concerns revealing the inner workings of a machine to figure out what makes it tick. This form of RE is also a systems level approach where an engineer disassembles the item of interest to develop an understanding of the functional relationship of components or to gain insight into the types of materials used to fabricate the components. As with software RE, the goal is to develop a highlevel description of a system without a priori knowledge. These two examples are common applications that use the term RE, but we wish to emphasize that our definition of RE is not related to these examples, but is instead related to the area of computer-aided engineering (CAE).

In the late 1970s and into the 1980s, computer-aided design (CAD)–a komponent of CAE–began to revolutionize engineering disciplines. The peak of this revolution occurred in 1990 with the design of the Boeing 777; the entire aircraft was designed and preassembled through a virtual CAD) simulation. According to Boeing, the first 777 to roll out of the production hangar in 1994 was just hundredths of an inch–about the thickness of a playing card–within alignment. This precision contrasts with the half-inch alignments common with most aircraft parts before that time–an improvement of several orders of magnitude. This revolution in technology has continued into the 1990s and today with the emergencje and growth of computer-aided manufacturing (CAM). CAM is the automation of the manufacturing process itself–beyond just the design process – where machines such as computerized numerically

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controlled (CNC) mills allow precise fabrication of objects directly from CAD descriptions. With CAM, a designer can rapidly move from a conceptual CAD description to a real-world tangible object. We might use the term forward engineering—in a tongue-incheek manner—to describe this type of design, and the term CAE to describe the automation of forward engineering through CAD and CAM technologies.

CAE through CAD and CAM technologies is the automation of engineering and fabrication, where a design formalizes ideas through computer modeling and then fabricates those models into real-world objects. CARE flows in the opposite direction. CARE creates a computer model of an object through measurements of the object, as it exists in the real world. In this context, we define CARE as the reversal of CAE or the ability to generate a CAD model from a real-world tangible object (Fig. 2.1).

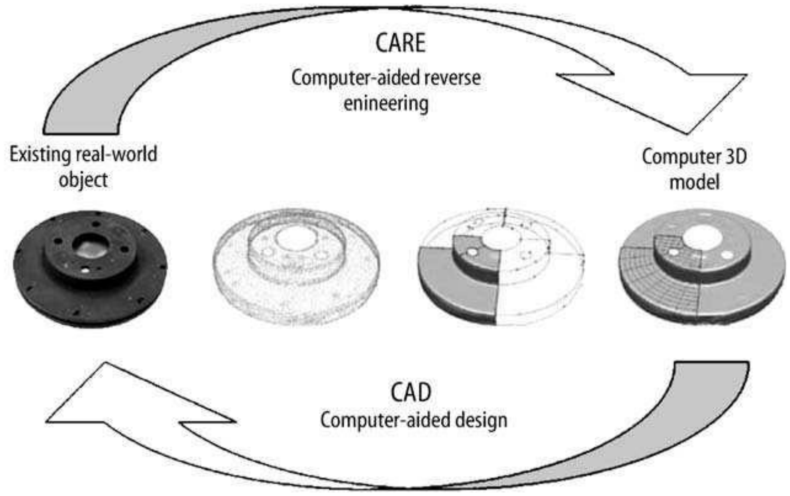

Figure 2.1 Computer-aided reverse engineering (CARE) process

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To understand the CARE steps, consider the stages shown in Figure 2.1 from left to right. The first step in the CARE process is to make measurements AT points along the surface of the brake. Each point has an x, y, and z coordinate locating the point in 3-D space. For a given object, a CARE system will measure hundreds or even thousands of such points depending on the nature of the object and the type of CARE system. The collection of these points is known as a point cloud; an example appears in the second picture from the left in Figure 2.1. In most applications, the point cloud is a sufficient description of the object. However, higher levels are possible as the remaining two pictures on the right show. The third picture from the left is a feature description of the object, in which the CARE system has detected surface edges and creases from the point cloud data. The final picture on the right is a full and complete CAD description of the object. For this description, the CARE system uses the point cloud and the detected features to fit surfaces for modeling the entire geometry of the object.

2.2 *Computer Vision and Reverse Engineering*

Computer vision bridges diverse fields from electrical engineering to computer science to cognitive psychology. Computer vision systems seek to develop computer models of the real world through processing of image data from sensors such as video cameras or–as in our case–3-D range scanners. Because computer vision is relatively new to RE, we begin this section by first investigating traditional (noncomputer vision) approaches to RE, and then use these methods as a backdrop for laser range scanners.

2.2.1 Coordinate Measuring Machines

Calipers are a common ad hoc approach to RE. These measurement devices allow engineers and machinists to determine accurate diameters, lengths, and other dimensions of objects. This approach to RE is a manual process that requires significant effort for complicated objects and surfaces. CMM technology is the first effort to automate the RE process. Before CMM and probably still popular for most simple tasks, engineers and machinists have used measurement calipers. For the disc brake, we could use calipers to measure the diameters of the various holes and cylinders that comprise the basic shape of the brake, as in Figure 2.2. Then, from these measurements, we could manually lay out a computer model of the brake

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using CAD primitives. For a simple object, this manual process of RE is straightforward, but as the complexity of the object shape increases, the basic CAD primitives such as planar and quadric surfaces are no longer suitable. A free-form surface, for example, that is nonplanar and nonquadratic [5] does not lend itself readily to characterization with just calipers. Free-form surfaces require special consideration and attention. Calipers are not practical for capturing their subtleties.

As an alternative, CMMs first appeared in the early 1960s and are a more practical means for characterizing and inspecting free-form surfaces. A CMM consists of a probe supported on three mutually perpendicular (x, y, and z) axes; each axis has a built-in reference standard. Figure 2.3 provides a conceptual view of a CMM. The probe allows accurate measurements along each axis relative to the standard. Thus, a CMM generates 3-D coordinate points as the probe moves across a surface. Operators may run a CMM in a manual mode where they maneuver the probe around an object and collect coordinate measurements, or they may program the probe to maneuver automatically on its own. This latter metod is more relevant to the CARE definition under discussion. Different CMM manufacturers offer different schemes to help operators plan the path that the probe will follow. The more advanced CMM systems allow operators to upload a CAD model of the object and then the CMM uses this model for the path planning strategy. The CMM will analyze the CAD model to identify critical points and regions such as discontinuity creases or tight spaces. Tight spaces are a point of emphasis because the probe must come in contact with or be close to the point on the surface where a measurement occurs. If the probe cannot reach the point due to extension constraints (i.e., the point is too far) or limited space (i.e., the probe is too large), then the system cannot measure at that location. The probe must touch or be near the measurement location. This constraint is the motivation for computer vision approaches to CARE because computer vision offers a more standoff measurement.

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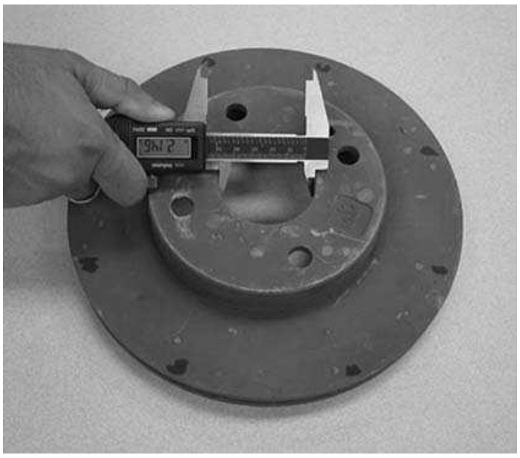

Figure 2.2 Measuring the disk brake using a calliper

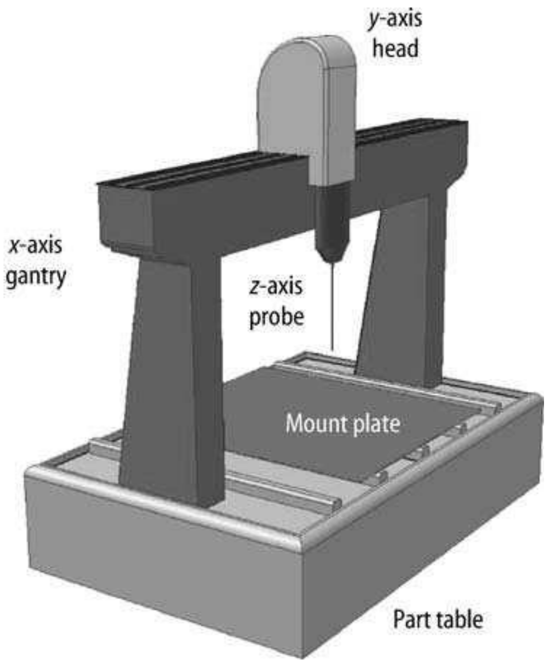

Figure 2.3 Conceptual view of a CMM that illustrates the major components of most systems

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2.2.2 Active Illumination 3-D Stereo

Computer vision attempts to develop solutions through sensors such as video cameras or other imaging-based systems [6, 7, 8]. To acquire 3-D information, the most well-known methodology that probably comes to mind is stereovision, in which two cameras operate in a manner similar to human eyes. Unfortunately, although stereo-based imaging has become useful in such applications as navigation planning and obstacle avoidance for Mars Rover missions, passive stereo does not offer the accuracy that industrial RE applications demand. The major drawback of stereovision is the need to establish correspondence between a point in one camera's image and the same point in the secondo camera's image. If we can establish this correspondence, we can construct an accurate stereo depth map, or range image, but correspondence is an elusive problem. The term passive stereo is important because it indicates that the camera in the system do not rely on active forms of illumination, except ambitne light. One way to overcome the correspondence problem is to control illuminati on in an intelligent manner and thus simplify the correspondence search. Such methods are known as active illumination stereo (or more simply active stereo) where we replace one of the stereo cameras with a well-defined light source. A laser is typically the light source of choice. Active stereo using laser-based illumination allows more accurate depth measurements than traditional passive illumination stereo. (We use the term depth measurement as an alternative to a 3-D point measurement from CMMs. At this point, the subtle nuance between these two terms is not important, but they are interchangeable because a depth measurement is a 3-D point measurement.) Although passive stereo is not viable for a CARE system, active stereo does offer potential. To understand active stereo, we should consider three popular approaches to illumination control. These major categories are (a) continuous wave modulation, (b) time-of-flight estimation, and (c) structured-light triangulation. Continuous wave systems measure depth by using a coherent light source, i.e., a laser, and measure phase differences of the light wave as it travels to and from the object. Figure 2.4 shows an example. The distance of an object from the camera is proportional to the phase difference between the transmitted wave and the returning wave.

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The accuracy of these systems correlates with the accuracy in measuring the phase differences and the wavelength of the laser. Time-of-flight methods operate similarly to radar where the system measures the time required for a laser pulse to travel to and return from an object. Figure 2.5 illustrates such a system. Highly accurate depth measurements require precision electronics to measure speed-oflight time increments. As a third option for active stereo, structured-light techniques compute depth through geometric triangulation. The camera, the object, and the light source form the triangulation geometry. See Figure 2.6. This configuration is similar to passive stereo geometry, except that we have replaced one of the cameras with a light source. The accuracy of these methods is a function of the camera resolution, geometric dimensions, and illumination precision, but the primary parameter for controlling and increasing accuracy is the camera resolution. System geometry and illumination are not as critical. Thus, structured-light systems offer a solution more practical than passive stereo in achieving the accuracy necessary for an RE system. In a later section, we will explore structured-light techniques more in depth, but first we seek to compare and contrast the benefits of active stereo to CMM.

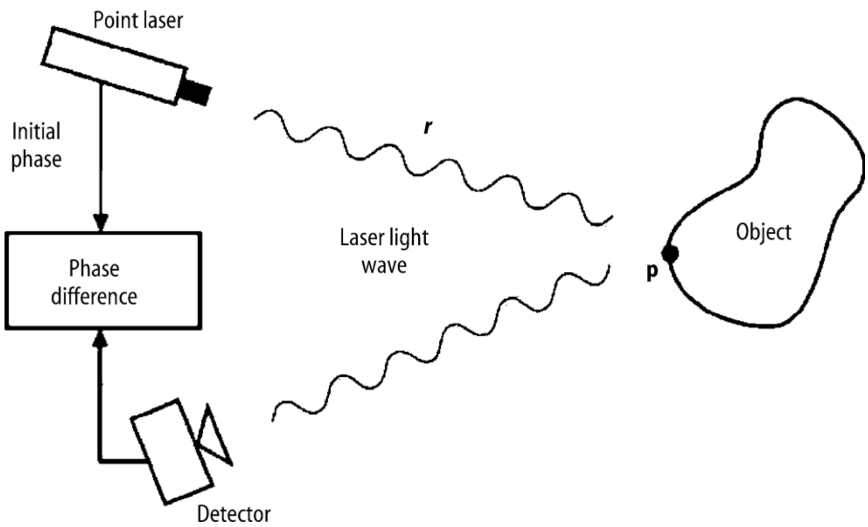

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Figure 2.4. Active stereo example of a continuous wave system. The laser travels as a light wave from the laser source to the object and back to the detector. As a wave, the laser light undergoes a phase change as it travels. The difference in phase reveals the object's distance.

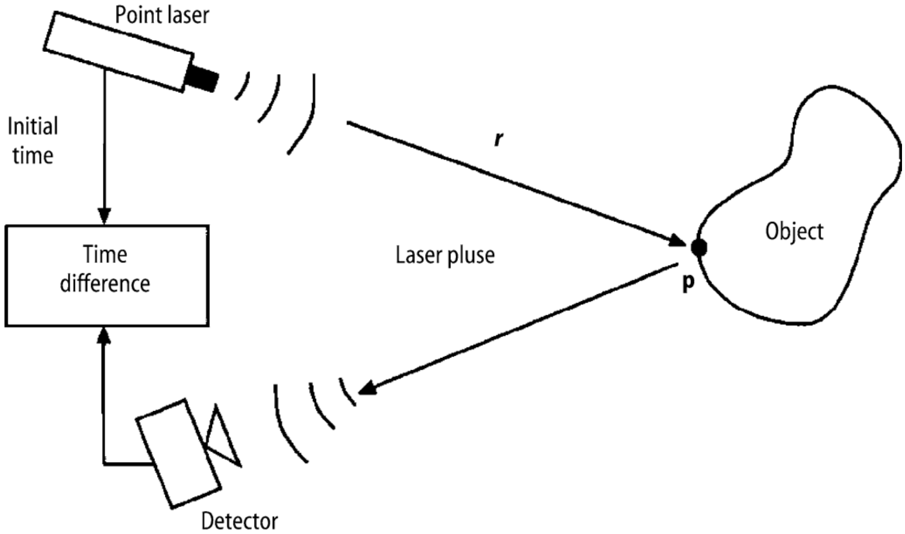

Figure 2.5. Active stereo example of a time-of-flight system. A point laser emits a pulse that is reflected from the object of interest. The difference between the initial time when the pulse was transmitted and the time that it returns to the detector correlates with the object's distance.

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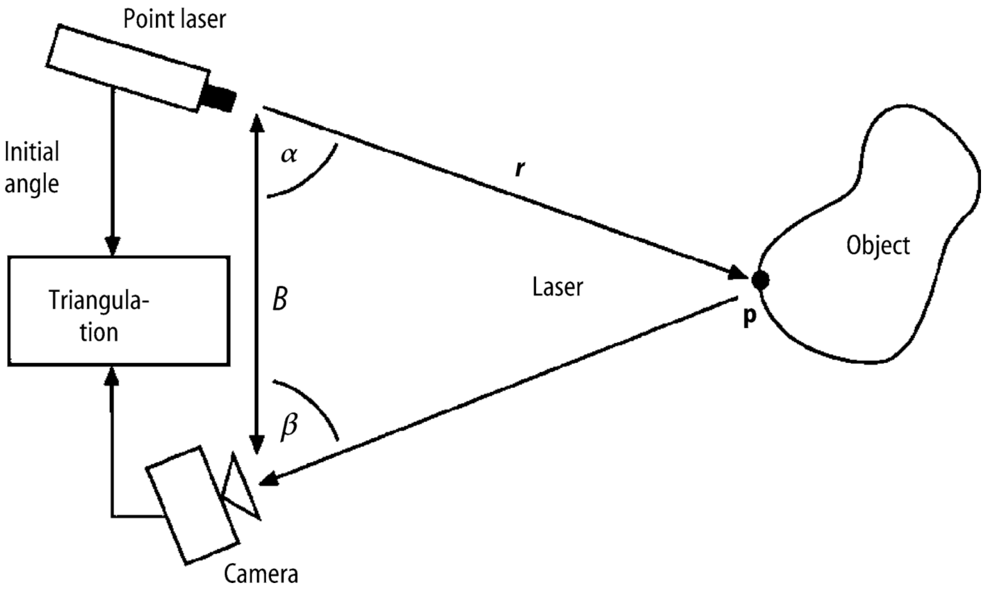

Figure 2.6. Active stereo example of a structured-light system. This example shows a triangulation-based approach where B, β, and α are typically known through system calibration.

2.2.3 Sheet-of-light Range Imaging

Sheet-of-light scanners offer the greatest speed advantage in collecting 3-D data compared to other laser scanners and thus are the most suitable for CARE applications. Their basic operation is such that the laser projects a line onto the object of interest, and triangulation among this line, the laser, and a camera field 3-D measurements. The photograph in Figure 2.7a is an example of a laser Line projecting onto a set of objects, and Figure 2.7b is an example of a system, the Ranger Scanner developed by Integrated Vision Products (IVP). In the figure, the objects are resting on a conveyor belt. This belt is one method for obtaining a full scan of an object. With the IVP Ranger, as with Rother sheet-of-light scanners, a single measurement results in a single line–a profile– of data. This profile is the 3-D data for points where the laser line falls on the object. A set of such profiles across the object

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is necessary to form a complete 3-D description of the object. Thus the conveyor belt moves the object under the laser line to scan the profiles over the entire object. If we stack the resulting profiles together, we have a 3-D model of the object. The conveyor generates profile slices of the object. Another approach is to not move the object but rather to move the scanner. Some sheet-of-light systems take this approach where usually the camera and laser are mounted on a wand. The user swipes this wand around the object of interest. With the conveyor, the spacing between the profiles is simply a function of the traveling speed of the conveyor and the acquisition rate of the scanner. With the wand, a more complicated tracking system is necessary to determine the interprofile relations. Commercial solutions range from magnetic position trackers to CMM probes.

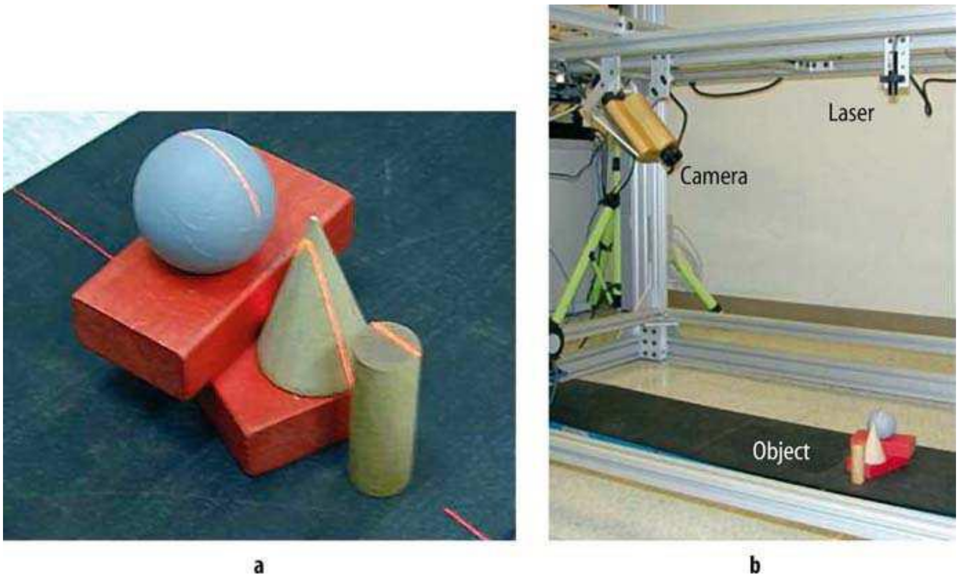

Figure 2.7 Examples of a sheet-of-light system. (a) The laser sheet casts a line on the objects under measurement. (b) This system is the IVP Ranger Scanner

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As for accuracy, the geometry defined in Figure 2.6 and the resolution of the camera govern the system. The most common arrangement is for the view angle α to be in the 30–60° range, and camera resolutions are of the order of 512 × 512 pixels or greater. These pixel resolutions correlate with more than nine bits of range resolution. As the view angle α increases toward 90° or decreases toward zero, the range accuracy decreases. At these extreme viewing angles, the camera has difficulty detecting the positional changes in the laser. First, let us consider a zero view angle. If the object surfaces are planar and perpendicular to the laser plane, the camera will not see the laser because of the oblique angle, but this angle yields the best projection for depth changes. Secondly, consider the 90° angle. With this view, the offset camera is almost looking straight down the laser plane. The camera detects the laser at the same position regardless of depth changes on the object's surface. This view offers the worst projection to the camera, but it gives the camera the best views of the laser reflection. Thus, the 30–60° range balances these two issues of no oblique viewing and projection resolution. This trade-off is also a function of the baseline distance B between the camera and the laser. As in traditional passive stereo, this distance should be of the order of the same magnitude as the range increments of interest.

The final problem we consider is occlusion, which is a common problem with computer vision systems. More specifically, the problem is known as self-occlusion where a part of an object occludes the viewing of another part of the same object. A sphere is a simple but not necessarily obvious example. When a camera views a sphere, the camera is able to image the front side, but it cannot image the reverse side. The front occludes the back. Shapes that are more complicated than a sphere have more intricate occlusions. Because the camera and the laser must view the object, a sheet-of-light range scanner has two possibilities for occlusions. As Figure 2.8 illustrates, the camera and laser cannot view the same surfaces of the object. The camera may image a surface that self-occlusion does not allow the laser to illuminate. Conversely, the laser may illuminati a surface that self-occlusion hides from the camera. A variety of strategies are possible to minimize occlusions, but we cannot eliminate the problem, as the simple sphere example demonstrates. In the next section, we discuss a pipeline for

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building CAD models using laser range scanners. We specifically discuss multiple views as a necessary solution to occlusion.

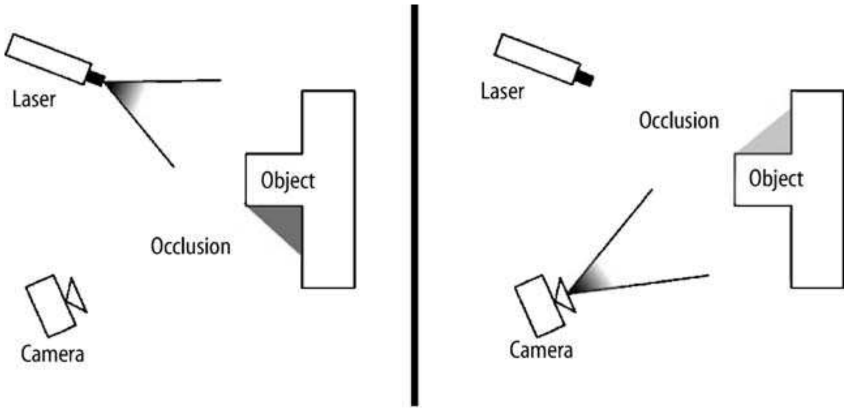

Figure 2.8. The occlusion problem with a sheet-of-light scanner. The object may occlude both the laser and the camera from viewing different surfaces on the object.

2.3 *Scan data processing*

2.3.1 Data Collection

The first step for a CARE scanner is data collection. Sheet-of-light systems are probably best suited for the CARE application. Figure 2.9. Block diagram of a CARE system based on a laser range scanner.

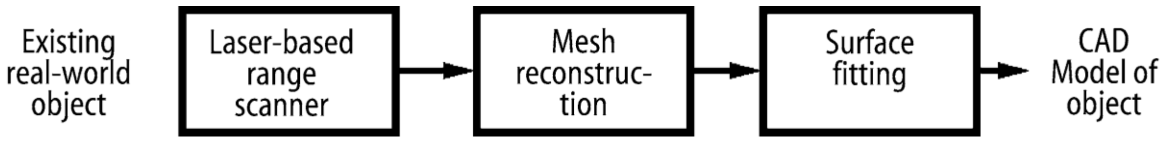

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Figure 2.9. Block diagram of a CARE system based on a laser range scanner

The first topic is calibration. Figure 2.10 demonstrates how calibration allows transforming a range image into a 3-D point cloud.

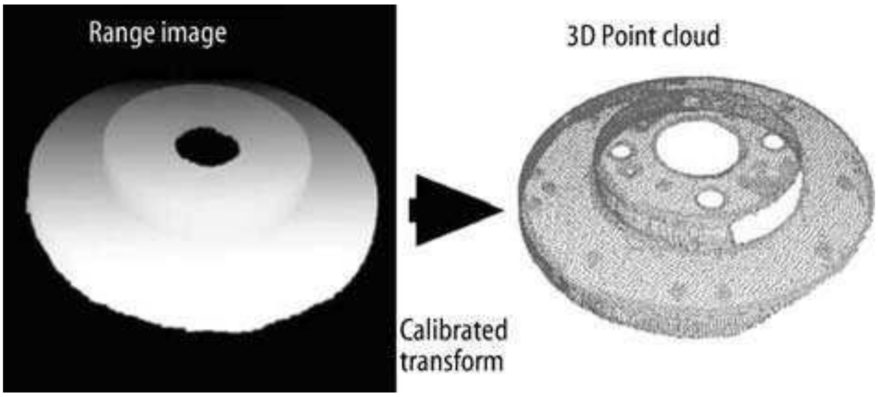

Figure 2.10. Example of a range image for the brake. The gray level of a pixel in the left image represents the distance between the brake and the sheet-of-light scanner. The darker pixels are farther away. If we calibrate the scanner, we can transform this range image into a 3-D point cloud, as shown on the right. The points (dots) exist in 3-D and each have x, y, and z coordinates.

After calibration, our next important topic is view registration. Figure 2.11 illustrates how at least two views are necessary to collect measurements of the en tire brake. If the scanner is on one side of the brake, small portions of the other side are occluded. The challenge with multiple views, however, is that we must now register the subsequent coordinate systems.

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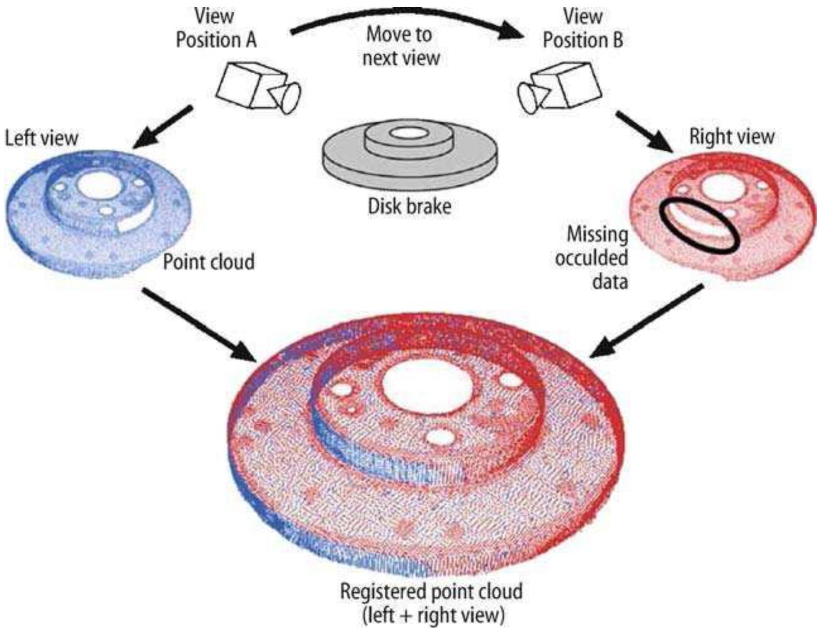

Figure 2.11. Multiple view scanning and registration overcome occlusions. Part of the brake is excluded in each of the views above. When these views are registered together, one view fills the occluded regions of the other view.

2.3.2 Mesh Reconstruction

Without much thought, most people initially consider mesh re construction trivial, and it probably is trivial for the human mind, but automatic re construction by a computer is not so easy. Hoppe et al. (1992) first addressed this topic for the general case of an unorganized point cloud. Since then, many researchers have presented their solutions, and a survey appeared in [5]. Figure 2.12 illustrates mesh reconstruction.

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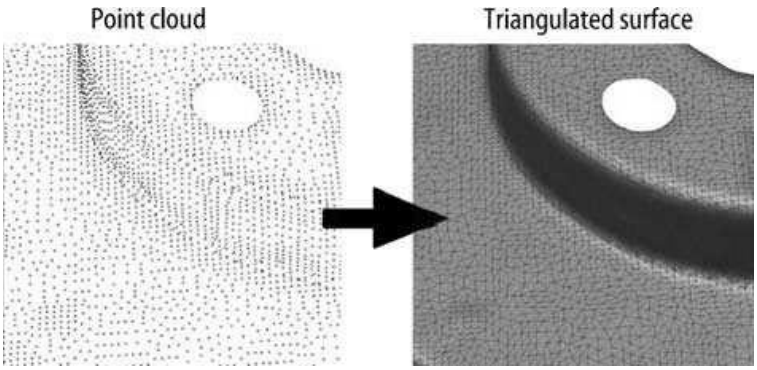

Figure 2.12. Reconstruction recovers the triangulated surface from the 3-D point cloud data

This figure is a zoom view of the disc brake to show the triangle mesh recovered from the point cloud. Triangles are a default standard as a surface primitive for a variety of reasons, but mainly they simplify computer visualizations because they have guaranteed convexity and thus are useful as a first-order approximation of an object.

For reconstruction, sampling defines the number of points in the point Cloud and their relative distance to each other (i.e., their density) on the object. Sampling is a trade-off between data set size and object coverage. A computer can more readily store and manipulate a smaller data set, but a larger set more accurately captures the fidelity of the object. Undersampling leads to incomplete and inaccurate models, but oversampling tends to overwhelm computing resources. Mesh reconstruction algorithms must define their sampling requirements, and users must tailor their CARE applications accordingly. Additionally, inherent in sampling is measurement error. Although this error is a data acquisition problem, most mesh reconstruction algorithms take this problem into account to minimize the effects of such terror.

A reconstruction algorithm requires a strategy to handle multiple views and their overlap. The third factor is missing data, which lead to holes in the mesh. These holes are not topological holes as with the doughnut but gaps in the mesh like cutouts on a sheet of paper.

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Generally, researchers have developed two categories of mesh reconstruction algorithms to deal with these factors of topology, overlap, and missing data. These categories are surface based such as presented by [9] and volumetric-based methods such as developed by [10].

2.3.3 Surface Fitting

Once we have a first-order approximation of the object from mesh reconstruction, the final stage of the pipeline is to generate higher order descriptions that are more appropriate for CAD applications. In some cases, a triangle mesh itself is sufficient as the final product of a CARE scanner. In other cases, parametric representations such as no uniform rational B-splines (NURBS) are necessary. Broadly label this final stage as surface fitting, but in practice, it takes many forms and is highly dependent on the CARE application. Eck and Hoppe [11] present a method for the recovery of splines from range scans, and their paper demonstrates the challenges that we outline.

For most complex objects, a single parameterized surface is not realizable and not practical for the entire object. Rather, we must divide the object into surface patches and then model each subsequent patch with its own parameterized surface. Thus, our first task is to segment the object into appropriate patches and then parameterize those patches individually. The major challenge is identifying appropriate patches, particularly, because parameterized surfaces assume a rectangular structure. Rectangles do not fit the arbitrary boundaries that often occur with patch selection. As a result, an additional step must trim the surface to these boundaries. Both direct and iterative optimization solutions are common. Figure 2.13, is a simple illustration of surface fitting for the now familiar brake. In this figure, we use feature detection of surface discontinuities to serve as the patch boundaries and then fit NURBS to the resulting patches. This figure concludes this chapter and finalizes the CARE procedure, originally shown in Figure 2.1.

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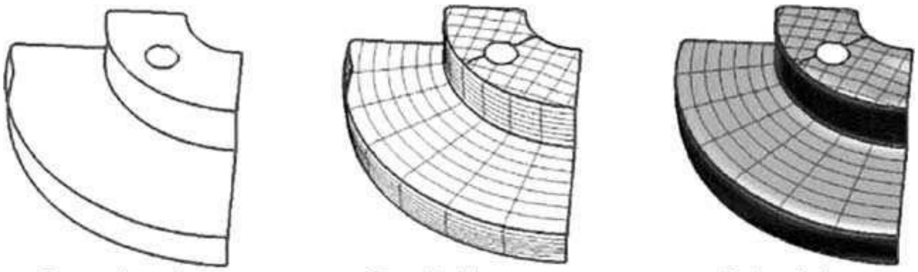

Figure 2.13. Typical surface fitting sequence.

The leftmost image shows the feature detection to establish potential surface discontinuities. The next image to the right shows the control grid to support the surface fitting process. Finally, the rightmost image shows the result of fitting a higher order surface to the measurement data.

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3 Reverse Engineering–Hardware

3.1 *Introduction*

Reverse engineering (RE) is generally defined as a process of analyzing an object or existing system (hardware and software) to identify its components and their interrelationships and to investigate how it works to redesign or produce a copy without access to the design from which it was originally produced (Wikipedia, 2005). In areas related to 3-D graphics and modeling, RE technology is used for reconstructing 3-D models of an object in different geometric formats. RE hardware is used for RE data acquisition, which for 3-D modelling, is the collection of geometric data that represent a physical object. There are Tyree main technologies for RE data acquisition: contact, noncontact and destructive. Outputs of the RE data acquisition process are 2-D cross-sectional images and point clouds that define the geometry of an object. RE software is employed to transform the RE data produced by RE hardware into 3-D geometric models. The final outputs of the RE data processing chain can be one of two types of 3-D data: (i) polygons or (ii) NURBS (non uniform rational B-splines). Polygon models, which are normally in the STL, VRML, or DXF format, are commonly used for rapid prototyping, laser milling, 3-D graphics, simulation, and animations. NURBS surfaces or solids are frequently used in computer-aided design, manufacturing, and engineering (CAD-CAM-CAE) applications.

In this chapter, hardware and software for RE are presented. Commercially available RE hardware based on different 3-D data collection techniques is briefly introduced. The advantages and disadvantages of various data acquisition methods are outlined to help in selecting the right RE hardware for specific applications. In the RE software section, end-use RE applications are classified and typical commercial RE packages are reviewed. The four RE phases used in a RE data processing chain are highlighted, and the fundamental RE operations that are necessary for completing the RE data processing chain are presented and discussed in detail.

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3.2 *Reverse Engineering Hardware*

3.2.1 Contact Methods

Contact methods use sensing devices with mechanical arms, coordinate measurement machines (CMM), and computer numerical control (CNC) machines, to digitize a surface (Fig. 3.1). There are two types of data collection techniques employed in contact methods:

1. point-to-point sensing with touch-trigger probes and

2. analogue sensing with scanning probes.

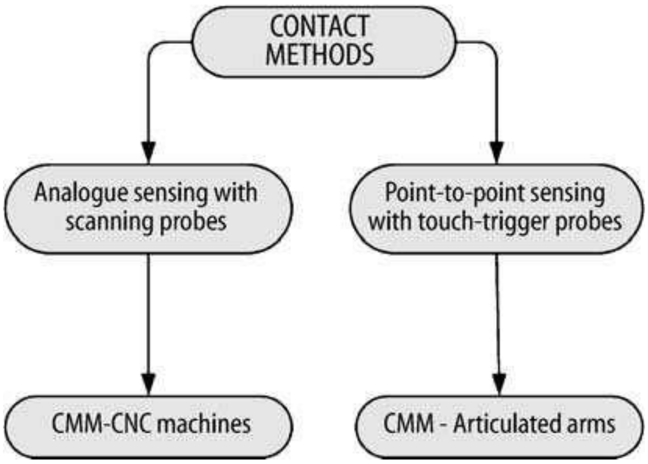

Figure 3.1. RE hardware classification–contact methods

In the point-to-point sensing technique, a touch-trigger probe is used that is installed on a CMM or on an articulated mechanical arm to gather the coordinate points of a surface. A manually operated, articulated mechanical arm with a touch-trigger probe allows multiple

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degrees of freedom (DOF) of movement to collect the measurement points (Figure 3.2). A CMM with a touch-trigger probe can be programmed to follow planned paths along a surface. A CMM provides more accurate measurement data compared to the articulated arm. However, the limitation of using CMM is the lack of number of DOF so that a CMM Carnot be used to digitize complex surfaces in the same way as an articulated arm.

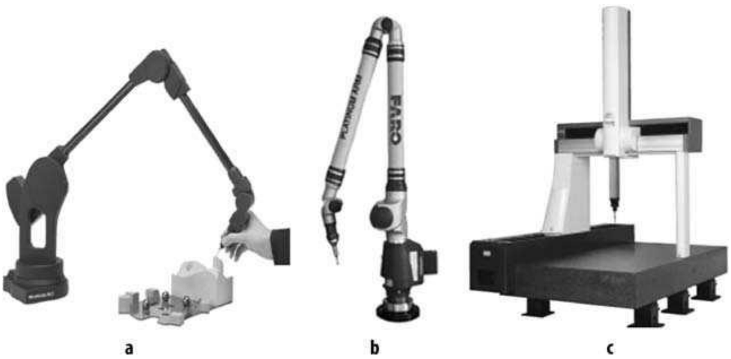

Figure 3.2. (a) MicroScribe MX Articulated Arm from Immersion Corporation, (b) Faro Arm–Platinum articulated arm from FARO Technologies, (c) Mitutoyo CMM machine–CRA Apex C model 2005)

In analogue sensing, a scanning probe is used that is installed on a CMM Or CNC machine (Figure 3.3). The scanning probe provides a continuous deflection output that can be combined with the machine position to derive the location of the surface. When scanning, the probe stylus tip contacts the feature and then moves continuously along the surface, gathering data as it moves. Therefore, throughout the measurement, it is necessary to keep the deflection of the probe stylus within the measurement range of the probe. The scanning speed in analogue sensing is up to three times faster than in point-to-point sensing.

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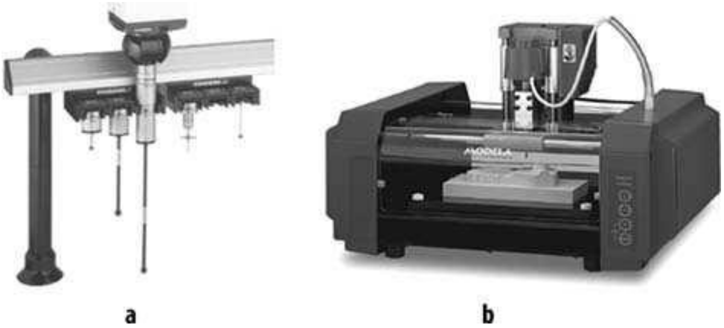

Figure 3.3. (a) SP25M scanning probes from Renishaw, (b) Roland DGA Corp. MDX-15/20 scanning and milling machine, using the Roland Active Piezo Sensor for 3-D scanning.

3.2.2 Noncontact Methods

In noncontact methods, 2-D cross-sectional images and point clouds that represent the geometry of an object are captured by projecting energy sources (light, sound, or magnetic fields) onto an object; then either the transmitted or the reflected energy is observed. The geometric data for an object are finally calculated by using triangulation, time-of-flight, wave-interference information, and image processing algorithms. There is no contact between the RE hardware and an object during data acquisition.

There are different ways to classify RE hardware that uses noncontact RE methods for data acquisition. These classifications are based on the sensor technologies (Tamas et al. 2005) or data acquisition techniques [12] employed. Figure 3.4 presents a classification of noncontact RE hardware based on data acquisition techniques. The advantages and disadvantages of noncontact methods compared to contact methods are as follows.

Advantages:

- no physical contact;

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- fast digitizing of substantial volumes;

- good accuracy and resolution for common applications;

- ability to detect colours;

- ability to scan highly detailed objects, where mechanical touch probes May be too large to accomplish the task.

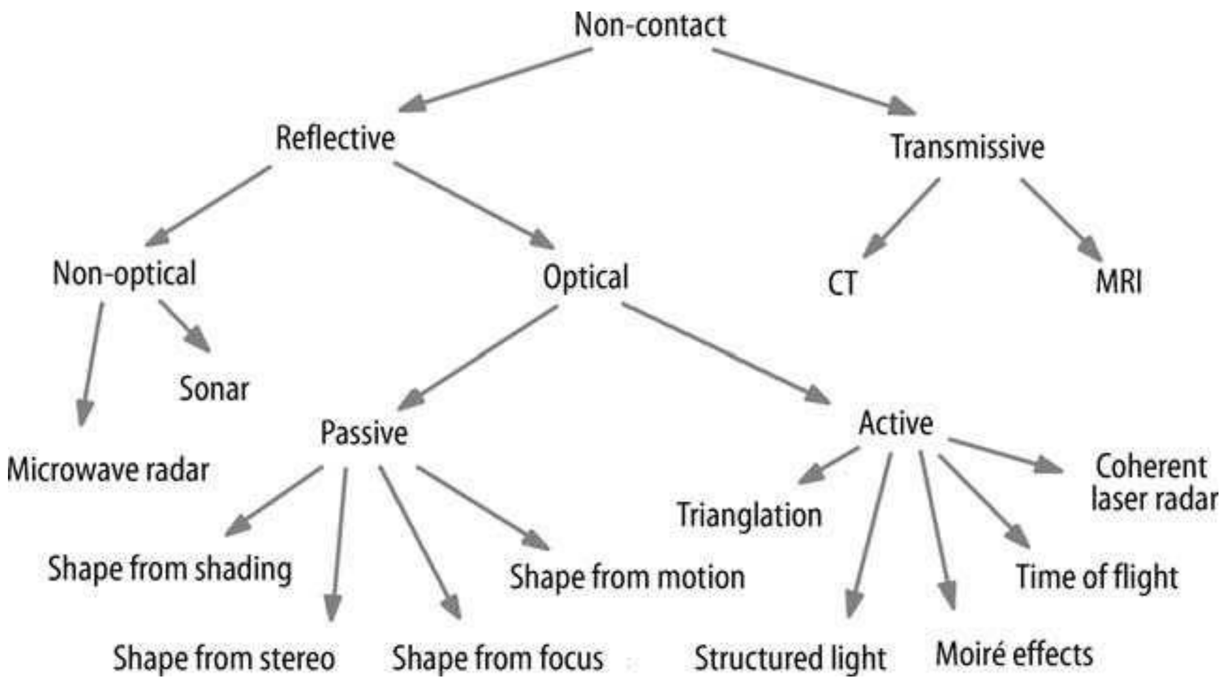

Figure 3.4. RE hardware classification–noncontact methods

Disadvantages:

- possible limitations for coloured, transparent, or reflective surfaces;

- lower accuracy.

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3.2.2.1 *Optical Techniques - Triangulation*

Most laser scanners use straightforward geometric triangulation to determine the surface coordinates of an object. Triangulation is a method that employs locations and angles between light sources and photosensitive devices (CCD–charge-coupled device camera) to calculate coordinates. Figure 3.5. shows two variants of triangulation schemes using CCD cameras: single and double CCD camera. In a single camera system, a device transmits a light spot (or line) on the object at a defined angle. A CCD camera detects the position of the reflected point (or line) on the surface. In a double camera system, two CCD cameras are used. The light projector is not involved in any measuring functions and may consist of a moving light spot or line, moving stripe patterns, or a static arbitrary pattern [13].

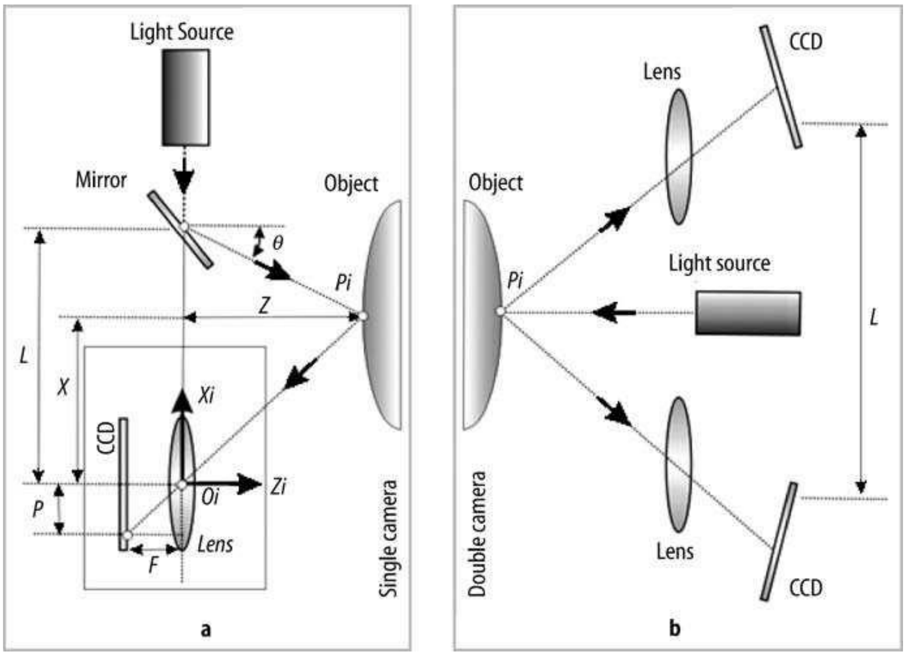

Figure 3.5. Triangulation methods: (a) single and (b) double camera arrangement

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Optical Techniques - Structured Light

In structured-light techniques [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24], a light pattern is projected at a known angle onto the surface of interest and an image of the resulting pattern, reflected by the surface, is captured. The image is then analyzed to calculate the coordinates of the data point on the surface.

A light pattern can be (i) a single point; (ii) a sheet of light (line); and (iii) a strip, grid, or more complex coded light [25] (Figure 3.6, Figure 3.7).

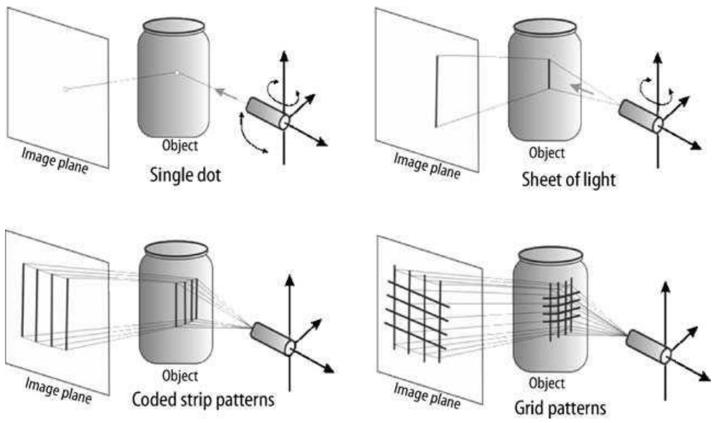

Figure 3.6. Different light patterns used in structured-light techniques

The most commonly used pattern is a sheet of light that is generated by fanning out a light beam. When a sheet of light intersects an object, a line of light is formed along the contour of the object. This line is detected and the X,Y,Z coordinates of hundreds of points along the line are simultaneously calculated by triangulation. The sheet of light sweeps the object as the linear slide carrying the scanning system moves it in the X direction while a sequence of images is taken by the camera in discrete steps. An index number k is assigned to each of the images in the order they are taken. Therefore, each k corresponds to the X position of the sheet of

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light. For each image k, a set of image coordinates (i, j) of the pixels in the illuminated stripe is obtained. The triples (i, j, k)'s are the range image coordinates; they are transformed to (x, y, z) world coordinates using a calibration matrix.

To improve the capturing process, a light pattern containing multiple strips is projected onto the surface of an object. To distinguish between different strips, they must be coded approximately so that the correspondence problem is solved without ambiguity. Structured-light systems have the following strong advantages compared to laser systems, and these features have resulted in favoring structured-light systems for digitizing images of human beings:

- the data acquisition is very fast (up to millions of points per second)

- colour texture information is available

- structured-light systems do not use a laser.

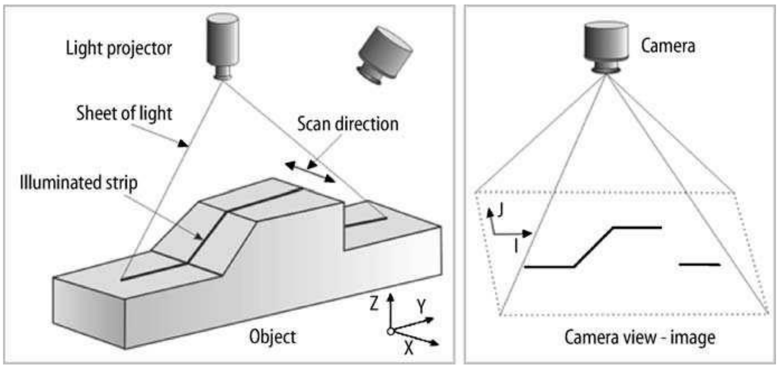

Figure 3.7. 2-D image acquisition in the structured-light technique using a sheet-of-light pattern

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Optical Techniques - Interferometry (Moiré Effects)

The interferometry technique is well known in dimensional inspection as well as in flatness and deformation measurements [26, 27, 28]), in which structured-light patterns are projected onto a surface to produce shadow moiré effects [29, 30]. The light contours produced by moiré effects are captured in an image and analyzed to determine distances between the lines. This distance is proportional to the height of the surface at the point of interest, and so the surface coordinates can be calculated.The moiré technique gives accurate results for 3-D reconstruction and measurement of small objects and surfaces. However, it has limitations for larger objects because precision is sacrificed for range. Figure 3.8. shows the formation of moiré fringes by superimposing a line pat tern with concentric circles and two other line patterns that vary in line sparing and rotation.

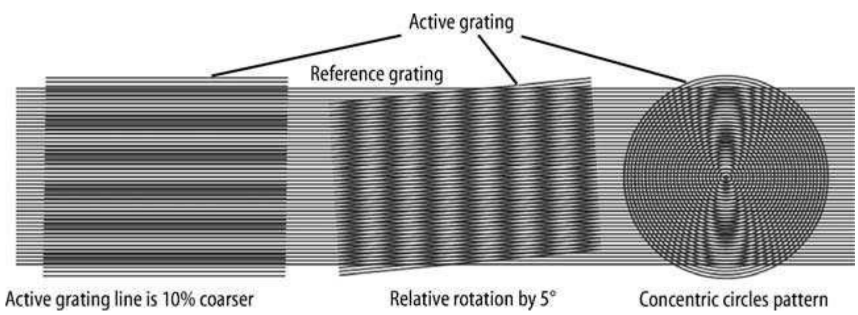

Figure 3.8. Formation of moiré fringes

Optical Techniques - Time of Flight (TOF)

The principle behind all time-of-flight (TOF) [18, 31, 32, 33, 34] implementations is to measure the amount of time (t) that a light pulse (i.e., laser electromagnetic radiation) takes to travel to the object and return. Because the speed of light (C) is known, it is possible to

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determine the distance traveled. The distance (D) of the object from the laser would then be equal to approximately one half of the distance the laser pulse traveled: D = C × t/2.

Figure 3.9 illustrates in block diagram form how a time-of-flight laser scanner works. For all practical purposes, the angle θ is very small and thus has no effect on the accuracy of the TOF distance measurement. The high velocity of light allows TOF scanners to make hundreds, or even thousands of measurements per second. The advantage of TOF techniques is that they can digitize large, distant objects such as buildings and bridges. The accuracy of RE hardware based on TOF is reasonable and approximately between a few millimeters and two Or three centimeters for long-range scanners. The accuracy depends on the pulse width of the laser, the speed of the detector, and the timing resolution; the shorter the pulse and the faster the detector, the higher the accuracy of the measurement.

The main disadvantage is that TOF scanners are large and do not capture an object's texture, only its geometry. They are not practical for fast digitization of small and medium-sized objects. Moreover, it takes time to complete the digitization process because the object (or environment) has to be swept Turing scanning.

A variation on the TOF method is the phase shift method for determining distance measurements. Distance is computed by comparing the phase shift between an emitted wavelength and the received light. The Surphaser Model 25 developed by Surphaser Inc. (2005) is a typical commercial system. The accuracy of a phase-shift system is higher than that of traditional TOF machines. The range accuracy of the Surphaser Model 25 is 25 µm, and the angular accuracy is 0.003°. An important consequence of using phase-shift detection is that the system uses a single line of sight for its work. This means that the laser light travels the same path from the scanner to the surface and back again which enables scanning the inside of holes, cavities, and concave surfaces.

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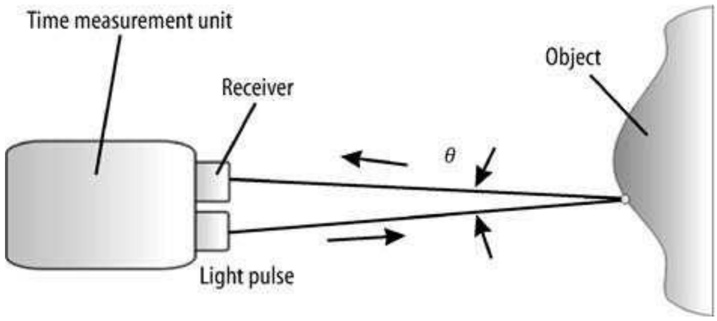

Figure 3.9. Principle of TOF scanners

Optical Techniques - Passive Methods

Passive methods reconstruct a 3-D model of an object by analyzing the images to determine coordinate data. It is similar to (active) structured-light methods in its use of imaging frames for 3-D reconstruction; however, in passive methods, there is no projection of light sources onto the object for data acquisition.

There are many different passive methods, including shape from shading, shape from stereo, shape from motion, shape from focus/defocus, shape from silhouette, and volumetric reconstruction. The typical passive methods are shape from shading [35, 36, 37, 38, 39, 40, 41,42] and shape from stereo [43, 44].

Shapes from shading (SFS) methods are used to reconstruct a 3-D representation of an object from a single image (2-D input) based on shading information. The first SFS technique was developed by Horn in the early 1970s [35, 36]. These are the main disadvantages of this metod [45]:

- the shadow areas of an object cannot be recovered reliably because they do not provide enough intensity information;

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- the method cannot be applied to general objects because it assumes that the entire surface of an object has the same reflectance;

- the method is very sensitive to noise because the computation of surface gradients is involved.

Shape from stereo or stereovision refers to the extension of SFS to a class of methods that use two or more images from different viewpoints for shadingbased 3-D shape recovery. Normally, two cameras are coordinated to generale 3-D information about an object by automatically finding corresponding features in each of the two images; then triangulation is used to measure the distance to objects containing these features by intersecting the lines of sight from each camera to the object. Compared to SFS methods, there is improved accuracy. However, finding correspondence between images is extremely difficult and can produce erroneous results from mismatches.

To solve the problem of finding correspondence, stereovision techniques can be combined with colour structured-light techniques for 3-D range data acquisition [19].

Although they require very simple hardware, passive methods do not produce accurate 3-D data. Active optical methods can overcome many of of the problems in passive methods and thus result in more accurate solutions.

Optical Techniques - Coherent Laser Radar

Recently, the advent of a new type of laser radar frequency-modulated coherent laser radar (FMCLR), created a new generation of FMCLR instruments. They can measure large-scale geometry precisely. A typical commercial RE machine in this category is a MetricVision system (MV224 and MV260 models) from Metris (2005). The accuracy (2σ) of the MetricVision system is 16 µm at 1 m, 100 µm AT 10 m, and 240 µm at 24 m. The MetricVision system operates by using a sensor to direct a focused invisible infrared laser beam to a point and coherently processes the reflected light. As the laser light travels to and from the target, it also travels

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through a reference path of calibrated optical fibre in an environmentally controlled module. The two paths are combined to determine the absolute range to the point. A very wide laser-modulation bandwidth (100 GHz) makes precise measurement possible on a millisecond timescale. The distance measurement is then combined with positional information from two precision encoders to determine a point on a surface in space.

3.2.2.2. Transitive Techniques

Computerized tomography (CT) is a powerful transmissive approach for 3-D reconstruction. CT has revolutionized the medical diagnostic field since the 1970s [46, 47, 48]. It has also been called computerized axial tomography (CAT), computerized transaxial tomography (CTAT), and digital axial tomography (DAT). CT is a nondestructive method that allows three-dimensional visualization of the internals of an object. It provides a large series of 2-D X-ray cross-sectional images taken around a single rotational axis.

Figure 3.10 presents the CT working principle of generating 2-D cross-sectional images. By projecting a thin X-ray or Y-ray beam through one plane of an object from many different angles and measuring the amount of radiation that passes through the object along various lines of sight, a map of attenuation coefficients (a density map or cross-sectional image) for the scanned surface is reconstructed.

CT is widely used for medical applications; however, it has been extended and adapted to a wide variety of industrial and 3-D modelling tasks [49, 50, 51, 52, 53]). Today, industrial CT 49, 54, 55, 56] and related technologies (digital computed laminography) [57, 58, 59] are commercially available and specialized for industrial applications. High-resolution X-ray CT and micro CT scanners can resolve details as small as a few tens of microns, even when imaging objects are made of high-density materials. It is applicable to a wide range of materials, including rock, bone, ceramic, metal, and soft tissue.

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Magnetic resonance imaging (MRI) (Donald et al. 2004[60]; Mark and Richard 2003[61]) is a state-of-the-art imaging technology that uses magnetic fields and radio waves to create high-quality, cross-sectional images of the body without Rusing radiation. When hydrogen protons in the human body are placed in a strong magnetic field, by sending in (and stopping) electromagnetic radio-frequency pulses, these protons emit signals. These signals are collected and processed to construct cross-sectional images. Compared to CT, MRI gives superior quality images of soft tissues such as organs, muscle, cartilage, ligaments, and tendons in many parts of the body.

CT and MRI are powerful techniques for medical imaging and reverse engineering applications; however, they are the most expensive in terms of both hardware and software for data processing.

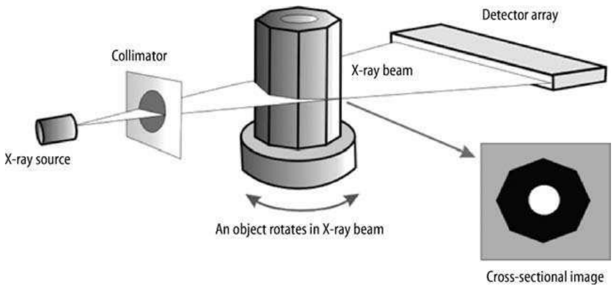

Figure 3.10. Working principle of the CT scanner

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4 Application of Reverse Engineering

Reverse engineering is justified to be used primarily where there is a need to duplicate the structure of an object that already physically exists. However, it is used when there is no form of recording the structure of an existing object that could constitute the basis for its production. In engineering work, it may involve both the construction of new products and the design of spare parts for used elements. It is most often used in technical industries, such as the aviation, automotive, shipbuilding and medical industries [61].

It enables the examination of objects or competitive products in order to determine how they operate, the methods and methods used in their construction and the costs of their production. Therefore, it allows obtaining key information enabling the secondary construction of the tested products. In industry, it also makes it possible to recreate device documentation and determine the composition of components of a specific object. Creating duplicates also enables the construction of models on which it is possible to perform broadly understood numerical analyzes of behaviour under the influence of changing operating conditions, as well as to test the strength of individual elements and their entire assemblies.
In IT fields, it is used to reproduce source program codes using their executable codes [61].

Recently, the development of reverse software engineering has also been visible. It includes processes related to the analysis of both the structure and operation of various types of computer programs (both those controlling the operation of network and industrial devices, as well as those intended for mobile devices, servers and personal computers[6].

4.1 Applications in Mechanical Industries

Reverse engineering finds wide applications in mechanical industries, serving various purposes. It is used to create a 3D model of a physical part when documentation is lost, maintain digital 3D records of products, assess competitor products, analyze product workings, inspect and compare actual geometry with CAD models, and measure tool wear.

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Applications of Reverse Engineering in Mechanical Engineering

1. Creation of 3D models of existing parts [61]:
    - Digital documentation: Reverse engineering can be used to scan and create 3D models of existing parts that lack technical documentation. This enables digital archiving and facilitates product data management.
    - Modification and improvement of existing designs: 3D models obtained from reverse engineering can be used as a basis for modifying and improving existing designs. This allows for faster and cheaper implementation of design changes.
    - Analysis and optimization: 3D models can be used for structural analysis, fluid flow simulation, and other engineering analyzes. This allows for the optimization of designs for performance and safety.

2. Production of spare parts [62]:
    - Prototyping and manufacturing: Reverse engineering enables rapid prototyping and manufacturing of spare parts for machines and devices that have been discontinued.
    - Repair and regeneration: 3D models obtained from reverse engineering can be used for 3D printing or manufacturing molds for casting damaged or worn parts.
    - Customization and personalization: Reverse engineering allows for the customization and personalization of spare parts to individual customer needs.

3. Development of new products [63]:
    - Benchmarking and competitor analysis: Reverse engineering can be used to analyze competitor products, which allows for identifying their strengths and weaknesses and drawing inspiration for designing your own products.
    - Innovation and improvements: Researching existing design solutions can be a starting point for innovation and developing new, improved products.
    - Intellectual property protection: Reverse engineering can be used to analyze potential intellectual property infringements.

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4. Reverse engineering in research processes [64]:

- Failure analysis: Reverse engineering can be used to analyze failed components to identify the causes of failure and develop preventive solutions.
- Materials and process research: Reverse engineering enables the study of the structure of materials and the analysis of technological processes used to manufacture components.
- Development of new methods and tools: Reverse engineering creates opportunities for the development of new methods and tools to support design and manufacturing.

4.1.1 CASE STUDY

The article "Application of reverse engineering techniques in mechanics system services" by Michal Dúbravþík and Štefan Kender [65] discusses the use of reverse engineering techniques in the servicing of mechanical systems. Damage of machine parts is a serious problem. It affects production fluency and causes financial losses due machine malfunction. Most threatened are components like transmission parts, tools or electronics. The authors as example show case of a damaged transmission gear wheel. Under mechanical stress of these parts can cause a progressive abrasion or damage. In case if the gear wheel is made from brittle material, there is much higher risk of damage. Our example of modern RE techniques application shows transmission gear wheel made from plastic material. This was irretrievably damaged under machine running (Figure 4.1.). As it came to snap of part of wheel it doesn't allow another machine running. Damaged gear wheel like this should be changed for a new one.

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Figure 4.1. Damaged component – gear-wheel [65].

To eliminate machine failure due part damage, the authors decided to apply reverse engineering. The damaged part was 3D scanned and aroused point´s cloud was getting into CAD part. A missing part of the gear wheel had to be added in CAD, and finally a new gear wheel was created using rapid prototyping [65].
The authors argue that these techniques can be used to:

- Understand the design and operation of mechanical systems: Reverse engineering can be used to create a digital 3D model of an existing mechanical system. This model can then be used to analyze the design and operation of the system, identify potential problems, and develop repair plans.
- Improve service processes: Reverse engineering techniques can be used to create digital service instructions and procedures. These instructions can then be used by service technicians to service mechanical systems faster and more efficiently.
- Design new mechanical systems: Reverse engineering techniques can be used to analyze existing mechanical systems and identify their shortcomings. This information can then be used to design new mechanical systems that are more efficient, reliable, and easier to service.

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The authors present several examples of the use of reverse engineering techniques in the servicing of mechanical systems. For example, reverse engineering has been used to [65]:

- Reconstruct a damaged turbine rotor: A digital 3D model of the rotor was created using laser scanning. This model was then used to analyze the cause of the failure and design a new rotor.

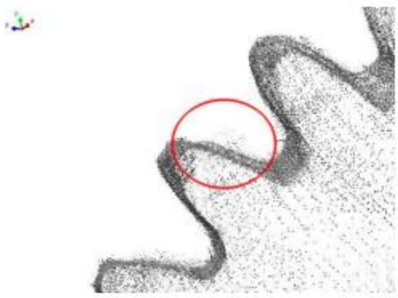

Figure 4.2. Model of 3D scanning with inaccuracy [65]

- Improve the service process of a gearbox: Digital service instructions were created for a gearbox. These instructions included detailed information on the disassembly, assembly, and repair of the gearbox.
- Design a new brake system: Existing brake systems were analyzed using reverse engineering techniques. This information was then used to design a new brake system that was more efficient and easier to service.

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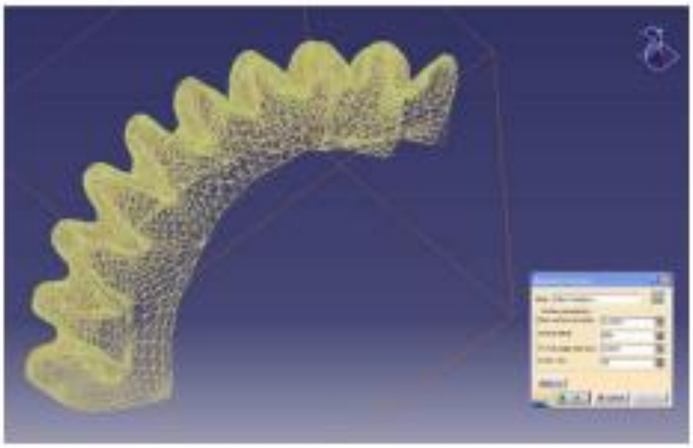

Figure 4.3. Mesh of a gear wheel part [65].

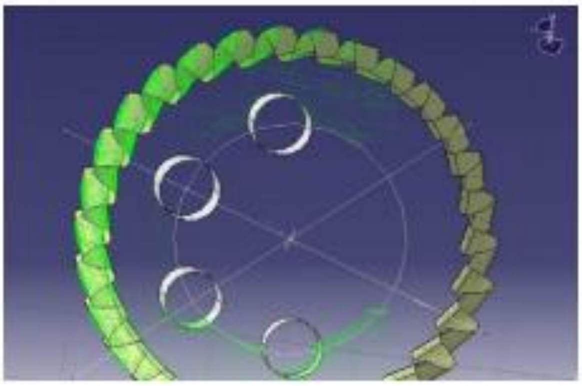

Figure 4.4. Base geometry of gear wheel [65]

- The authors conclude that reverse engineering techniques can be a valuable tool for companies that service mechanical systems. These techniques can help companies to better understand the design and operation of mechanical systems, improve service processes, and design new mechanical systems.

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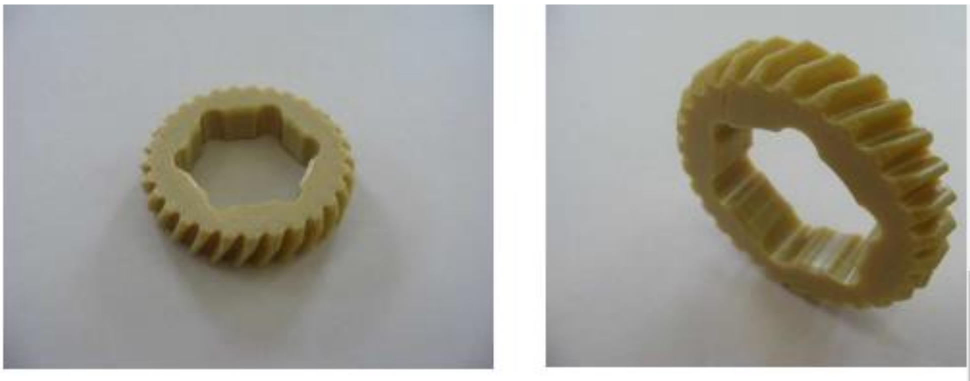

Figure 4.5. New gear wheel made from ULTEM 9085 [65]

4.2 *Applications in Medical Life Sciences*

Reverse engineering plays a crucial role in various aspects of medical life sciences, offering significant benefits for:

1. Medical device development and improvement :

- Understanding existing device design and functionality: Reverse engineering can be used to analyze existing medical devices, creating 3D models for further investigation. This allows for a deeper understanding of their design principles, material properties, and potential limitations.[66]
- Developing new and improved medical devices: By studying existing devices, engineers can identify areas for improvement and develop new devices with enhanced features, functionalities, or safety protocols. This can lead to more efficient, effective, and accessible medical treatments.[67]
- Creating patient-specific implants and prosthetics: Advanced techniques like 3D printing and reverse engineering can be combined to create customized implants and prosthetics that perfectly fit individual patients' needs, improving treatment outcomes and patient comfort.[68]

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2. Analyzing and researching biological structures:

- Reconstructing complex biological structures: Reverse engineering can be used to analyze and reconstruct 3D models of intricate biological structures like organs, tissues, and bones. This facilitates medical research and training by providing accurate and detailed visualizations.[69]
- Developing biocompatible materials: By understanding the structure and properties of natural tissues, researchers can design and develop biocompatible materials that are readily accepted by the human body. This advancements are crucial for applications like implants, prosthetics, and drug delivery systems.[70]

3. Drug delivery and pharmaceutical research:

- Understanding drug delivery mechanisms: Reverse engineering can analyze existing drug delivery systems, revealing insights into their release mechanisms, effectiveness, and potential targeting methods. This knowledge helps in developing improved drug delivery systems with targeted drug release and reduced side effects.[71]
- Drug discovery and development: Studying the structure and function of biological targets like proteins and enzymes can be facilitated by reverse engineering techniques. This knowledge helps in designing and developing new drugs that specifically target these biological targets, leading to more effective treatments.[72]

4. Medical device repair and maintenance:

- Understanding device functionality for repairs: When medical devices malfunction, reverse engineering can help technicians understand their internal structure and functionality, facilitating efficient repairs and maintenance. This can potentially extend the lifespan of crucial medical equipment and reduce overall healthcare costs.[73]

5. Forensic medicine and education:

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- Analyzing and reconstructing fractured bones: In forensic medicine, reverse engineering can analyze fractured bones to help reconstruct the events leading to the injury. This information can be crucial for legal investigations and accident reconstruction.[74]
- Creating educational and training materials: By studying the structure and function of medical devices and biological systems through reverse engineering, valuable insights can be gained for creating educational and training materials for medical professionals.[75]
- Overall, reverse engineering offers a valuable set of tools and techniques for various applications in medical life sciences, contributing to advancements in medical device development, biological research, drug discovery, and healthcare delivery.[75]

4.3 *Applications in Software Industries*

Reverse engineering plays a crucial role in various aspects of the software industry, offering benefits in several areas:

1. Recovering Lost or Corrupted Data: When software encounters crashes or malfunctions, data loss or corruption can occur. Reverse engineering can be used to analyze the software's structure and functionality, potentially enabling the recovery of lost or corrupted data. [78]

2. Understanding Legacy Code and Systems: Many software projects involve maintaining and updating older codebases (legacy systems).[79] Reverse engineering helps developers understand the architecture, logic, and data flow within these systems, facilitating maintenance, debugging, and modernization efforts.[80]

3. Identifying Security Vulnerabilities: By analyzing the software's code and underlying functionalities, reverse engineering can help identify potential security vulnerabilities and

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weaknesses.[81] This allows developers to proactively address these issues and enhance the software's security posture.

4. Creating Compatible Software with Existing Systems: When developing new software, it's often essential to ensure compatibility with existing systems.[82] Reverse engineering can be used to understand the communication protocols and data formats used by existing systems, enabling the creation of compatible software that interacts seamlessly with them.

5. Migrating Software to New Platforms or Technologies: As technology evolves, migrating software to new platforms or technologies might become necessary. [83] Reverse engineering assists in understanding the original software's design and functionality, enabling the development of a new version compatible with the target platform or technology.

6. Debugging Complex Software Issues: When encountering complex software bugs or glitches, traditional debugging methods might not suffice.[84] Reverse engineering can provide deeper insights into the software's internal workings, aiding developers in pinpointing the root cause of the issue and implementing effective solutions.

7. Improving Software Performance and Efficiency: By analyzing the code structure and execution flow through reverse engineering, developers can identify bottlenecks and inefficiencies within the software. [85] This knowledge allows them to optimize the code and improve the software's overall performance and efficiency.

8. Creating Educational and Training Materials: By studying the design and implementation of existing software through reverse engineering, valuable insights can be gained for creating educational and training materials for developers. [86] This can be particularly beneficial for understanding software architecture, design patterns, and best practices.

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Overall, reverse engineering serves as a versatile tool in the software industry, contributing to various tasks, from data recovery and legacy system maintenance to security analysis, software compatibility, and performance optimization.

4.4 *Applications in Film Entertainment or Animation Industry*

In the film entertainment or animation industry, reverse engineering provides several advantages. It animates objects using reverse-engineered human skeletons, performs 3D scanning for rapid surfacing of scale models, supports online marketing and presentations, and brings real-life forms into the virtual gaming industry. [87]

For example, the movie "Gravity," winner of the 86th Academy Awards, extensively used reverse engineering to create virtual environments, with physical sets limited to the interiors of space capsules and portions of the ISS space station.

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5 Conclusion

Reverse engineering is the practice of replicating an object, artefact, or software that lacks documentation in order to uncover its design, materials, specifications, or functions. The process involves examining a system or component to understand its structural and functional aspects by analyzing detailed CAD data. This process typically begins with digital measurements of the component using optical scanners (non-contact) or CMMs (contact), followed by creating a 3D model from the obtained point data using CAD/CAM/CAE or similar software.

Reverse engineering proves highly effective in situations where design modifications are needed for a product lacking its original CAD model. It also plays a crucial role in inspecting complex shapes for wear, which would otherwise be challenging, time-consuming, and costly to do manually. Additionally, it enables competitive benchmarking by revealing insights into competitors' product design secrets.

In the medical industry, reverse engineering is invaluable for simulating the results of artificial implants before their actual implementation in the human body. This process not only saves time and money but can also be life-saving. Therefore, the primary objective of reverse engineering is to reduce lead times, consequently shortening manufacturing cycles.

As businesses strive to overcome time constraints and innovate products in today's competitive market, reverse engineering approaches are gaining popularity. However, there is still room for improvement in these methods, particularly in terms of efficiency and accuracy. Many reverse engineering algorithms require further refinement to minimize errors and enhance results. By continually refining reverse engineering processes, we can produce higher-quality products and expand the scope of its applications in the future.

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Erasmus+ Programme Key Action 2 Cooperation Partnerships for Higher Education (KA220-HED)
Project No: 2023-1-RO01-KA220-HED-000155412
Project title: European Network for Additive Manufacturing in Industrial Design for Ukrainian Context – Acronym: AMAZE

MODULE 5

Computer Programming

Project Title	**European Network for Additive Manufacturing in Industrial Design for Ukrainian Context 2023-1-RO01-KA220-HED-000155412**
Output	**IO1 - AMAZE e-book for industrial design for complex parts**
Module	**Module 5 Computer Programming**
Date of Delivery	**March 2024**
Authors	**Sergio VIZCAINO, Beatriz Gloria BONILLA GARCIA, César Arcadio BONILLA GARCIA**
Version	**FINAL VARIANT, *date***

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1 Introduction in programming of Additive Manufacturing technologies

Additive manufacturing plays a crucial role in the process of creating three-dimensional objects by layering successive layers of material. This discipline involves the creation of specific instructions that guide 3D printing machines to build complex geometries from digital models. As additive manufacturing technology advances, programming has become an essential component to optimize efficiency and the quality of the final product. Programmers in this field must consider not only the geometry of the object but also the material properties, printing parameters, and physical constraints of the machine.

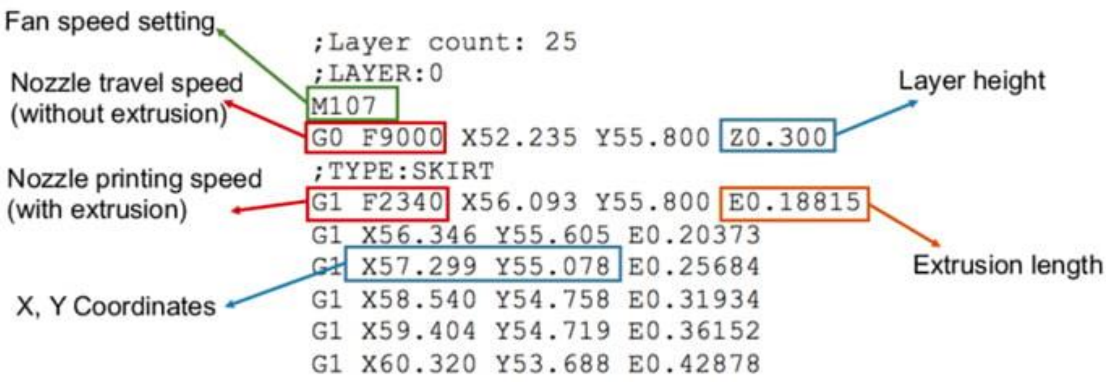

Fig.1. Example of code

Programming for additive manufacturing encompasses various aspects, ranging from toolpath generation to the assignment of printing parameters such as temperature and deposition speed. Optimizing these factors is essential to ensure the structural and functional integrity of the printed object. Programming algorithms must adapt to the specific characteristics of each 3D printing technology, such as Fused Deposition Modeling (FDM), Stereolithography (SLA),

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or Selective Laser Sintering (SLS). Additionally, programming in additive manufacturing may also involve implementing optimization strategies to reduce printing times and minimize material waste.

Fig.2. 3D printer

As additive manufacturing integrates into various industries, programming becomes more sophisticated and personalized. Programmers must consider not only the technical aspects but also the specific design and functionality requirements of the final product. Collaboration between design experts and programmers is essential to harness the full capabilities of additive manufacturing and overcome inherent challenges. In summary, programming in additive manufacturing involves not only the creation of code but also the intelligent optimization of processes to drive innovation and efficiency in the production of components and products.

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Fig.3. Designing in 3D

1.1. Key task of programming

- Toolpath Generation

Develop algorithms that determine the optimal path for the printing tool (such as the nozzle in FDM or the laser in SLS) to deposit material layer by layer.

Objective: Minimize printing time and optimize manufacturing efficiency without compromising the quality of the object.

- Print Parameter Assignment

Define the specific values of print parameters, such as temperature, deposition speed, and resolution, to achieve desired properties in the final object.

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- Customize

Customize programming algorithms to adapt to specific 3D printing technologies, such as FDM, SLA, SLS, among others.

Objective: Leverage the unique features and advantages of each technology, maximizing efficiency and quality in the manufacturing process.

- Time Optimization:

Develop programming strategies that reduce printing times without sacrificing product quality.

Objective: Improve efficiency and profitability in additive manufacturing by minimizing the time required to produce each object.

- Consideration of Material Properties:

Integrate information about the physical and chemical properties of the printing material into the programming process.

Objective: Ensure that the material's behavior aligns with design specifications and desired characteristics of the final object.

- Collaboration between Designers and Programmers:

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Facilitate communication and collaboration between designers and programmers to address aesthetic and functional aspects of the printed object.

Objective: Achieve a balance between design goals and programming requirements to obtain optimal results in additive manufacturing.

Together, these tasks and objectives highlight the importance of programming in additive manufacturing to ensure success and efficiency in creating three-dimensional objects through 3D printing.

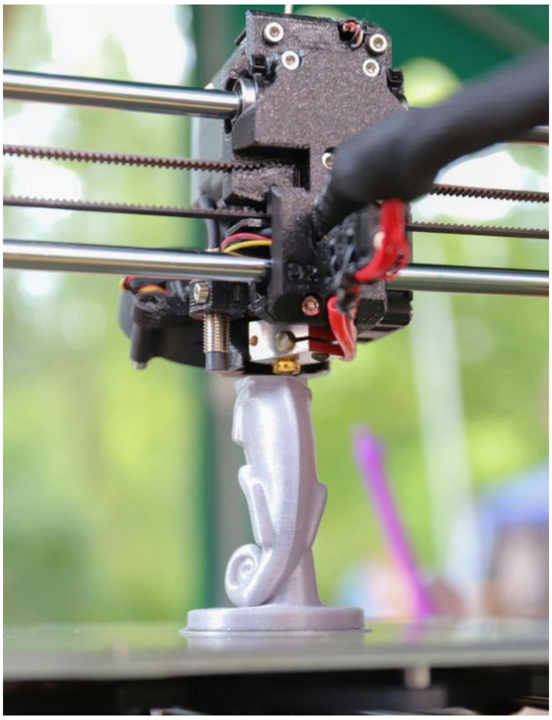

Fig.4. Printing in 3D

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2 3D Modeling

3D modeling is a fundamental discipline in the field of design and the creation of three-dimensional visual content. This technique involves the digital creation of representations of objects or environments in three dimensions, providing a more realistic and detailed perspective than traditional two-dimensional models.

2.1. Polygonal Modeling:

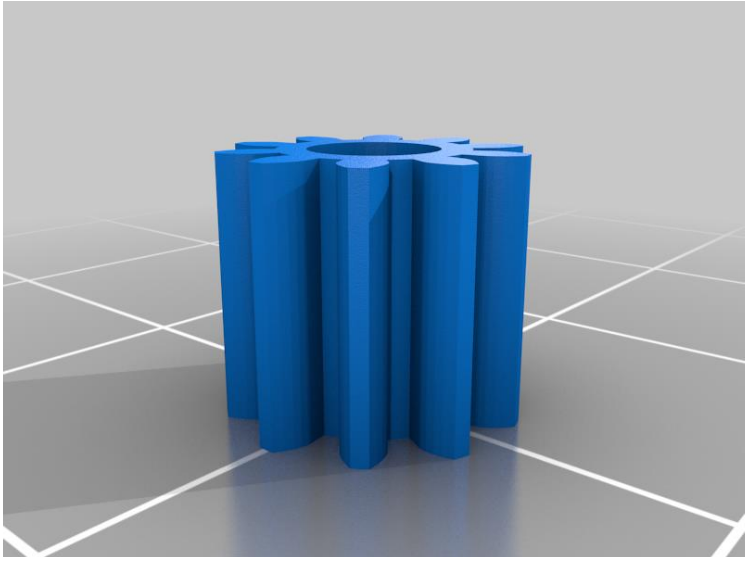

Fig.5. Polygonal model

Polygonal modeling in additive manufacturing refers to the creation of three-dimensional models using polygons, which are geometric shapes composed of vertices, edges, and faces.

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This type of modeling is commonly used in the additive manufacturing industry, which includes technologies such as 3D printing.

The 3D modeling is a fundamental discipline in the field of design and the creation of three-dimensional visual content. This technique involves the digital creation of representations of objects or environments in three dimensions, providing a more realistic and detailed perspective than traditional two-dimensional models.

Key Aspects of Polygonal Modeling in the Context of Additive Manufacturing:

File Formats: STL, OBJ, and PLY – In polygonal modeling for additive manufacturing, models are often saved in file formats such as STL (Standard Triangle Language) or OBJ (Wavefront OBJ). These formats store information about the model's geometry by defining triangles that form the object's surface.

For 3D printing, an approximate mesh is used because printers cannot handle excessively high resolutions, and other ways of encoding geometry are unnecessary for 3D printing. The approximate mesh uses tessellation, the process of generating a surface of an object with geometric shapes (usually triangles). This way, there are no overlaps or gaps. With this process, it is possible to store the model's appearance and other details like color or texture.

This leads us to the three file formats commonly used in 3D printing: STL, OBJ, and PLY.

The most common file format that uses an approximate mesh and is generally used for 3D printing is the STL file. In the STL format, the tiles used are triangles (called facets), covering the surface of the 3D shape. Using STL has several advantages over other file formats. Firstly,

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it is universally recognized and used most frequently, facilitating collaboration. STL files are also simple and small, as they only store information for each facet, making processing faster.

An STL file describes an unstructured raw triangulated surface by the unit normal and the vertices (ordered by the right-hand rule) of the triangles using a three-dimensional Cartesian coordinate system. STL files do not contain scale information, and the units are arbitrary.

However, STL files have a significant drawback – as tessellation only covers the surface, the surface geometry lacks color or texture representation. If a single color or texture is desired, which is most often the case, then STL files are excellent. However, with improved printers and the demand for color, other formats are gaining popularity.

The next two file formats, OBJ and PLY, were created to address the lack of color in STL files. Both can store properties such as color and texture. Although not as widespread as STL files, both OBJ and PLY are well-known and widely used for their ability to store color and texture along with other details. Both file formats benefit from enhanced 3D printers and are considered more relevant in the future than STL files.

- OBJ is a geometry definition file format first developed by Wavefront Technologies for its Advanced Visualizer animation package in the 1980s. The OBJ file format is open and has been adopted by other 3D graphics application providers. The OBJ file format is a simple data format that represents only 3D geometry, i.e., the position of each vertex, the UV position of each texture coordinate vertex, vertex normals, and faces that make each polygon defined as a list of vertices and texture vertices. Vertices are stored counterclockwise by default, making explicit declaration of face normals unnecessary. OBJ coordinates have no units, but OBJ files can contain scale information in a human-readable comment line.

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- PLY is a computer file format created by Greg Turk in 1994 at Stanford University known as the Polygon File Format or Stanford Triangle Format. It was designed primarily to store three-dimensional data from 3D scanners. The data storage format supports a relatively simple description of a single object as a list of nominally flat polygons. A variety of properties can be stored, including color and transparency, surface normals, texture coordinates, and confidence values for the data. The format allows for different properties for the front and back of a polygon. Its design was inspired by the Wavefront .OBJ format. However, the OBJ format lacked extensibility for arbitrary properties and groupings, leading to the introduction of the "property" and "element" keywords to generalize notions of vertices, faces, associated data, and other groups.

Triangles and Meshes: Polygonal models are composed of triangles that form a three-dimensional mesh. Each triangle is defined by three vertices in 3D space. The denser the mesh (more triangles), the higher the model's resolution, but the file size will also increase.

Modeling Software: To create polygonal models, 3D modeling software such as Blender, Autodesk Maya, 3ds Max, Rhinoceros 3D, among others, is used. These programs allow designers to create and manipulate polygonal geometry with ease.

Mesh Optimization: Before 3D printing a model, it is essential to optimize the mesh to ensure efficiency in manufacturing. This may involve simplifying geometry, correcting errors, and reducing the number of unnecessary polygons.

3D Printing: Once the polygonal model has been created and optimized, a 3D print preparation software is used to convert the model into a set of instructions that the 3D printer can understand. These instructions include details about layer structure, material temperature, and other printing parameters.

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In modeling for additive manufacturing, it is crucial to consider certain aspects, such as overhangs, incline angles, and supports. These elements help ensure a successful print and the structural integrity of the final object.

In summary, polygonal modeling is a fundamental part of the additive manufacturing process, enabling designers to create detailed and complex models that can be 3D printed using various additive manufacturing technologies.

2.2 Types of modeling

Modeling NURBS (Non-Uniform Rational B-Splines):

NURBS modeling is a 3D modeling technique that utilizes mathematical curves and surfaces to represent three-dimensional shapes. Unlike polygonal modeling, which uses polygons to define geometry, NURBS modeling is based on mathematical functions called splines to represent smooth and curved surfaces.

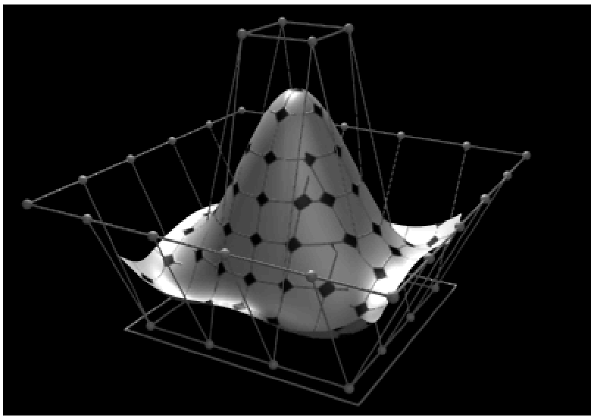

Fig.7. Example of NURBS model

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Some key aspects of NURBS modeling:

NURBS Curves: In NURBS modeling, NURBS curves are the fundamental building blocks. These curves are defined by control points that influence the curve's shape and direction. Additionally, NURBS curves are flexible and allow adjusting the weighting of control points to control curvature and shape more precisely.

NURBS Surfaces: NURBS surfaces are extensions of NURBS curves in two dimensions. They are created by combining multiple NURBS curves in two directions to form a continuous and smooth surface. Similar to curves, control points and weights influence the shape and curvature of the NURBS surface.

Mathematical Precision: The main advantage of NURBS modeling is its mathematical precision. NURBS curve and surface representations are exact and can be manipulated with great precision, making this method suitable for applications requiring a high level of detail and accuracy, such as in the automotive, aerospace, and product design industries.

Non-Destructive Editing: A significant feature of NURBS modeling is the ability to perform non-destructive edits. You can adjust the shape of a NURBS curve or surface without losing the original information, facilitating iteration in the design process.

File Formats: Models created with NURBS can be saved in file formats such as IGES (Initial Graphics Exchange Specification) or STEP (Standard for the Exchange of Product Data), which are standards for data exchange in computer-aided design (CAD). Some 3D modeling programs supporting NURBS modeling include Rhino (Rhinoceros 3D), Alias AutoStudio, CATIA, and certain Autodesk software modules like Alias Surface.

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NURBS modeling is particularly useful in applications requiring precision and smooth surfaces, such as in industrial prototyping and product design. Its ability to represent complex shapes with high accuracy makes it a valuable choice across various industries.

2.2.1. Volumetric Modeling:

Volumetric modeling is a technique used in 3D graphics and digital design to represent and manipulate three-dimensional objects as solid volumes. Unlike polygonal and NURBS modeling, which focus on surface representation, volumetric modeling deals directly with representing the interior and exterior of a 3D object.

Fig.8. Example of volumetric model

Here are some key aspects of volumetric modeling:

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Volume Representation: Instead of describing the surface of an object using polygons or curves, volumetric modeling focuses on describing the actual volume of the object. This involves working with data representing the density or composition of material at each point within the object.

Voxels: A voxel (volumetric element) is the three-dimensional equivalent of a pixel in 2D. Rather than being a two-dimensional unit like a pixel, a voxel contains three-dimensional information. This information can include color, density, temperature, etc. Volumetric models are constructed using a matrix of voxels.

Volumetric Boolean Operations: Volumetric modeling is especially useful for performing boolean operations on solid objects, such as union, intersection, or subtraction of two objects. This allows the creation of more complex shapes and precise manipulation of volumes.

Medical and Industrial Data: Volumetric modeling is commonly used in fields such as medical visualization to represent internal body structures from medical imaging data like computed tomography (CT) or magnetic resonance imaging (MRI). It is also applied in fluid simulation, terrain representation in geology, and material representation in industry.

Ray Casting and Ray Tracing: To visualize volumetric models, techniques like ray casting and ray tracing are used, simulating how light rays interact with different materials and densities within the volume, generating realistic images.

Volumetric Modeling Software: Some programs and libraries that support volumetric modeling include medical visualization programs like 3D Slicer, simulation software like

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Blender (with fluid simulation modules), and specialized libraries like VTK (Visualization Toolkit).

Volumetric modeling is essential in areas where accurate representation of the interior of an object is crucial, such as in medicine, physical simulations, and scientific visualization. This approach offers a detailed and realistic representation of the internal structure of objects, making it valuable in various disciplines.

2.2.2. Parametric Modeling:

Parametric modeling is an approach in design and modeling that uses parameters and relationships between elements to define and control the shape and features of a model. Instead of creating a static representation, parametric modeling allows adjusting and modifying the design by manipulating predefined parameters.

Fig.9. Example of parametric model

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Here are some key aspects of parametric modeling:

Parameters and Relationships: In parametric modeling, objects are defined through parameters and mathematical relationships. Parameters are values that can be adjusted, and relationships are equations or constraints that define how those parameters interact.

Design History: A distinctive feature of parametric modeling is the ability to track design history. Each action taken on the model is stored as a parametric operation. This allows making changes at any point in the design process and seeing how they affect the model.

Parameters

Setting Print Parameters in Additive Manufacturing: Considerations on Object Orientation

Setting print parameters in additive manufacturing is a combination of technical knowledge, practical experience, and adaptation to the specific characteristics of the material and technology used. Continuous optimization of these parameters significantly contributes to achieving successful and efficient outcomes in the 3D printing process.

1. Object Orientation:

Object orientation in additive manufacturing is a crucial aspect that can have a significant impact on the quality, strength, and efficiency of the 3D printing process. The way an object is placed on the build platform can affect various aspects of the final product. Here are key considerations regarding object orientation in additive manufacturing:

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2. Adhesion to the Platform:

Object orientation affects the amount of contact area with the build platform.

Good initial contact is essential to prevent detachment during printing.

3. Supports and Support Structures:

Orientation impacts the generation and efficiency of support structure removal.

Placing the piece in a way that minimizes and allows easy access to support elements improves post-processing efficiency.

4. Deformations and Residual Stress:

Orientation influences internal stresses and potential deformations during and after printing. Avoiding sharp angles and regions prone to stress accumulation can reduce the likelihood of deformations.

5. Surface Quality:

Orientation can affect the surface quality of the printed piece.

Placing the critical surface facing upward or in a position that minimizes contact with supports can enhance aesthetics.

6. Printing Time:

Orientation can influence the total printing time.

Reducing unnecessary support layers and optimizing orientation can expedite the process without compromising quality.

7. Mechanical Properties:

Orientation affects the mechanical properties of the printed piece.

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Placing the piece so that layers align with the main load directions can enhance strength and durability.

8. Compatibility with Specific Technologies:

Different printing technologies may have specific orientation requirements.

Some technologies, like SLA, may require particular orientations to optimize quality and precision.

9. Material Efficiency:

Orientation can affect the amount of material needed.

Minimizing support usage and optimizing layer distribution can reduce material waste.

10. Geometric Considerations:

The shape and geometry of the object also influence optimal orientation.

Design elements such as overhangs or thin areas must be considered when determining orientation.

11. Iterative Testing:

Experimenting with different orientations may be part of the trial-and-error process.

Iterative testing allows adjusting orientation to strike the right balance between quality and efficiency.

In summary, object orientation in additive manufacturing is a strategic aspect that requires careful evaluation. Manufacturers and designers should consider multiple factors to achieve optimal results, and iteration based on experience is key to refining orientation based on the specific characteristics of each 3D print.

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3 Print Path Generation:

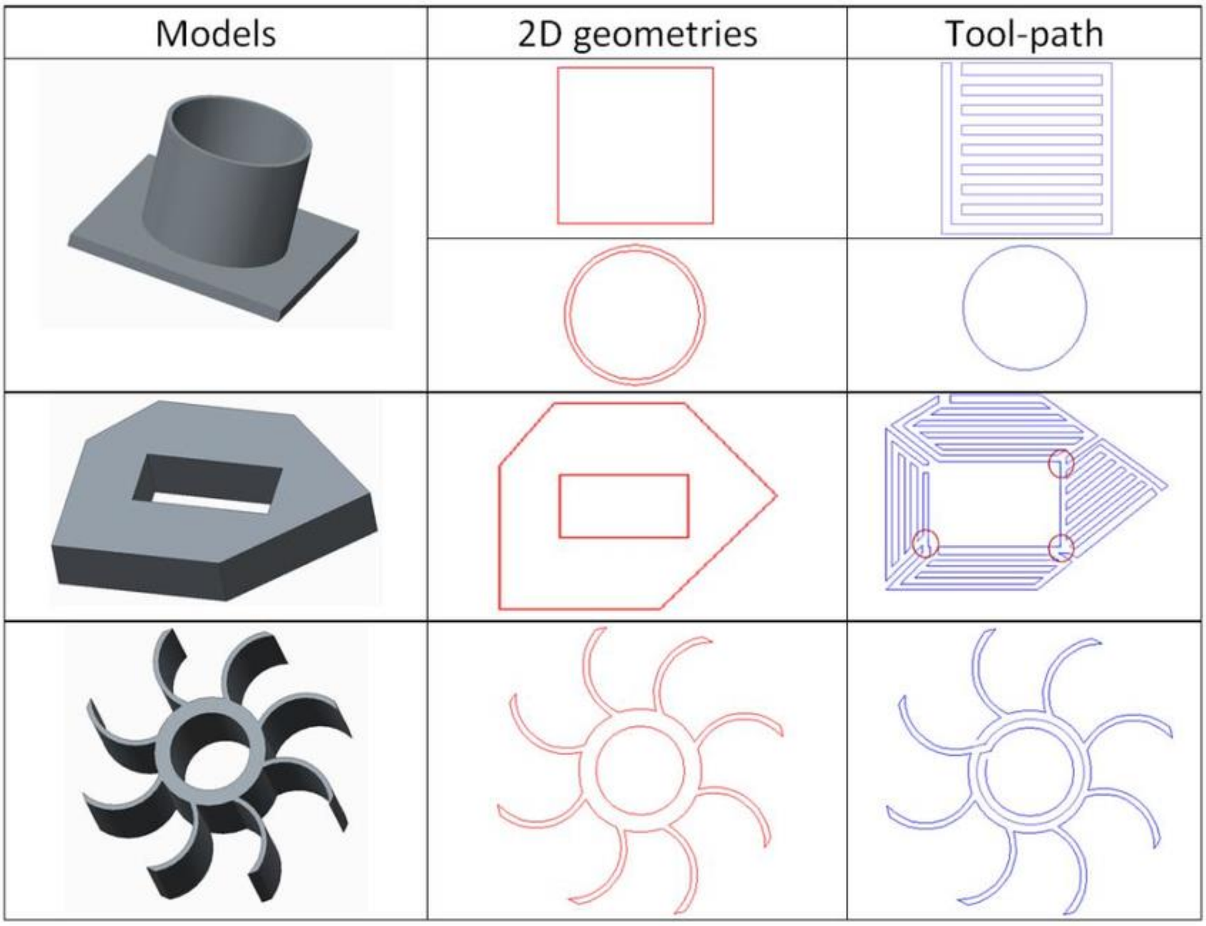

Fig.10. Examples of path generation

Slicing: Dividing the 3D model into layers and generating printing paths for each layer. This involves converting the model into a series of 2D layers to be printed on top of each other.

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Supports: Generating support structures for areas of the model that cannot be printed in the air. These supports are necessary to maintain stability during printing.

Infill: Determining the internal infill configuration of the object to optimize strength and material efficiency.

C. Optimization Algorithms:

Path Optimization: Developing algorithms that optimize printing paths to reduce printing time and minimize material consumption.

Topological Optimization: Using algorithms to optimize the topology of the object, removing unnecessary material, and improving structural efficiency.

Support Optimization: Implementing algorithms that reduce the number of required supports without compromising the quality of the printed object.

D. Simulation and Verification:

Printing Simulation: Performing virtual simulations of the printing process to identify potential issues such as collisions, deformations, and other defects.

Quality Verification: Implementing analysis tools to verify the quality of the printed object in terms of dimensional accuracy, strength, and other specific properties.

Iterative Adjustments: Making adjustments to the design and printing parameters as needed, based on the results of simulation and verification.

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4 Programming

Programming in additive manufacturing is a complex process that encompasses everything from the creation of the 3D model to the optimization of printing and the verification of the final object's quality. It involves the application of knowledge in design, materials, optimization algorithms, and simulation.

In the context of additive manufacturing, various programming languages and platforms are used to control and manage the printing processes. Here are some of them:

4.1. G-code and M-code:

G-code consists of G and M commands, each assigned to a specific movement or action. The combination of these commands enables the 3D printer to understand which pattern to follow in order to create the final piece. As mentioned, it is a language generated automatically by the slicing software when converting the design into an STL file. In this case, we will focus specifically on FDM 3D printers, so terms like extruder, print bed, or thermoplastic filaments will be referenced. Among the different types of commands interpreted by the 3D printer, there are movement, extrusion, heating, and detection commands in a sequence. This forms the basis for understanding the importance of this language. However, let's now look at the numerical composition of a G-code to be able to read the command in question.

First, we need to understand the difference between G-code and M-code. Both are commands included in the file and tell the printer how and where to extrude the material. The only difference is that G-codes are universally understood by printers using G codes, and M-codes are codes specific to individual printer lines. As seen in the image below, the language consists of various alphanumeric parameters. The basic elements we need to know when reading such a code are the different alphanumeric values.

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The letters X / Y / Z refer to the three axes of the 3D printer that mark the coordinates. Any X value above 0 moves the print head to the right, any Y value above 0 moves the print head backward, and any Z value above 0 moves the print head upward. On the other hand, the letter F is understood as the speed at which the nozzle moves (indicated in mm/minute), while the letter E refers to the length of the movement (indicated in millimeters). Sometimes, we may find text followed by the symbol ";" which serves to provide information about the commands; these comments are not part of the code. Once the way G-codes can be read is understood, let's see which ones are most common for manufacturing a part.

G-Code words			
G0	Rapid Linear Motion	**G59.2**	Select Coordinate System 8
G1	Linear Motion at Feed Rate	**G59.3**	Select Coordinate System 9
G2	Arc at Feed Rate	**G80**	Cancel Modal Motion
G3	Arc at Feed Rate	**G81**	Canned Cycles – drilling
G4	Dwell	**G82**	Canned Cycles – drilling with dwell
G10	Set Coordinate System Data	**G83**	Canned Cycles – peck drilling
G17	X-Y Plane Selection	**G85**	Canned Cycles – boring,no dwell, feed out
G18	Z-X Plane Selection	**G86**	Canned Cycles – boring, spindle stop, rapid out
G19	Y-Z Plane Selection	**G88**	Canned Cycles – boring, spindle stop, manual out
G20	Length Unit inches	**G89**	Canned Cycles – boring, dwell, feed out
G21	Length Unit milimeters	**G90**	Set Distance Mode Absolute
G28	Return to Home	**G91**	Set Distance Mode Incremental
G30	Return to Home	**G92**	Coordinate System Offsets
G53	Move in Absolut Coordinates	**G92.1**	Coordinate System Offsets
G54	Select Coordinate System 1	**G92.2**	Coordinate System Offsets
G55	Select Coordinate System 2	**G92.3**	Coordinate System Offsets
G56	Select Coordinate System 3	**G93**	Set Feed Rate Mode units/minutes
G57	Select Coordinate System 4	**G94**	Set Feed Rate Mode inverse time
G58	Select Coordinate System 5	**G98**	Set Canned Cycle Return Level
G59	Select Coordinate System 6	**G99**	Set Canned Cycle Return Level
G59.1	Select Coordinate System 7		

Fig.11. G-Code words

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The G1 command is the most basic of all; in fact, it constitutes 95% of the total file. It is a code that instructs the 3D printer to perform a linear movement while depositing material to the specified location in the coordinates provided. So, when we read the code "G1 X10 Y20 F1200," we are telling the printer to move to the position X=10mm Y=20mm on the bed at a slower speed of 1200 mm/min. In contrast to this command, the G0 has the same principle of movement but without extruding material through the nozzle.

G28. This command is used for the machine to execute the startup sequence, which will move the print head to the farthest edges of the machine until it makes contact with the stops. If an axis is not specified, the machine will automatically move all three, but X, Y, Z can always be added to the command. It's a useful way to quickly move an axis out of the way, especially when finishing the print.

G92. Orders the printer to set the current position of its axes. This can be useful if you want to change or compensate for the location of one of the axes. It is usually done at the beginning of each layer or just before a main or retraction command.

M104. This code is used to heat an extruder, and you must indicate which one (in the case of a dual extrusion 3D printer) as well as the desired temperature. Thus, the command "M104 S200 T0" will instruct the machine to heat extruder T0 (in the case of dual extrusion, we would have T0 and T1) to a temperature of 200 degrees Celsius, indicated with the letter "S." The other version of this G-Code, specifically M109, will instruct the printer to wait for the extruder to reach the temperature before proceeding with any other command.

M140 and M190. They are very similar to the ones mentioned earlier, except in this case, it does not refer to the extruder but to the print bed. In this case, the letter "T" indicating the extruder to heat is omitted.

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Some examples of common G-code commands in 3D printing include:

G0 and G1: Rapid movement and controlled movement, respectively.
G28: Move to the home position.
G92: Set current coordinates.
G90 and G91: Set absolute and relative coordinates, respectively.
M-code (Function Code):
M-codes are used to control auxiliary functions and accessories of the machine. Although some M-codes are standard, their usage may vary between different machines and manufacturers. In 3D printing, common M-codes include:

M104: Set extruder temperature.
M109: Wait for the extruder to reach a specific temperature.
M140: Set heated bed temperature.
M190: Wait for the heated bed to reach a specific temperature.
Practical Example:
Let's say we want to print an object with a 3D printer. The generated G-code could include instructions such as:

```
; Start of G-code
G28 ; Move to the home position
G92 E0 ; Reset extruder position
M104 S200 ; Set extruder temperature to 200°C
M140 S60 ; Set heated bed temperature to 60°C
; Start of printing
G1 F1500 E10 ; Initial extrusion
```

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```
G1 F1500 Z0.2 ; Move to layer height 0.2 mm
; ... Rest of the code for printing layers ...
; End of G-code
M107 ; Turn off the layer fan
M104 S0 ; Turn off the extruder
M140 S0 ; Turn off the heated bed
G28 ; Move to home position at the end
```

In this example, G-code commands are used to control movements and speeds, and M-codes are used to control the temperature of the extruder and heated bed.

It is important to note that specific codes may vary depending on the printer's firmware and the slicer program used to generate the G-code. The G-code is essential for translating the digital design into physical movements and controlling all aspects of the 3D printing process.

Software Slicers:

Slicers are fundamental tools in additive manufacturing, responsible for converting 3D models into specific instructions for 3D printers. Here are some of the most popular slicer software:

1. Cura:
   - Developed by Ultimaker, a leading FDM 3D printer manufacturer.
   - Open-source, free, and compatible with most desktop 3D printers.
   - Supports various 3D formats like STL, X2D, 3MF, OBJ, as well as image formats like BMP, PNG, GIF, JPG.
   - User-friendly interface suitable for both beginners and professionals.

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- Features include path visualization, material usage, and print time calculation.

2. 3DPrinterOS:
   - Comprehensive cloud-based slicer accessible via a browser, Windows, or Mac.
   - Offers slicing applications like Cloud Slicer, Slicer 2, and Marketbot Slicer.
   - Suitable for managing files across a range of machines in a company.

3. IdeaMaker:
   - Free 3D slicer with a user-friendly interface, often preferred for its ergonomics.
   - Released by Raise3D, a 3D printer manufacturer.
   - Simple to use, with only four clicks needed to prepare various file formats (3MF, OBJ, STL).
   - Can be customized for advanced functionality and printer management.

4. PrusaSlicer:
   - Developed by Prusa Research, well-integrated with Prusa printers.
   - Offers advanced configurations for users seeking greater control over the printing process.

5. Simplify3D:
   - Designed for professional users, compatible with Windows and Mac.
   - Supports almost all 3D printers and allows easy addition of new devices.
   - Includes a pre-print simulation for testing and identifying potential issues.

6. SliceCrafter:
   - Web-based slicer allowing users to upload 3D models directly in the browser.
   - User-friendly interface suitable for beginners.

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7. MatterControl:
   - Slicer and 3D printer control software with an intuitive interface.
   - Offers tools for basic 3D model design and editing, along with slicing functionality.

8. KISSlicer:
   - Fast, multi-platform application compatible with Windows, Mac, Linux, or Raspberry Pi.
   - Versions include both free and professional, offering advanced features like dual extrusion.

9. CraftWare:
   - Simple and user-friendly slicer suitable for beginners.
   - Offers a friendly interface and basic configuration options.

When choosing a slicer, it's crucial to consider compatibility with your 3D printer, ease of use, advanced features you may need, and whether you prefer an open-source or commercial solution. The choice of slicer can significantly impact the quality of your prints and your overall experience in additive manufacturing.

Other Mentioned Slicers:

- Repetier-Host:
  - Open-source and free slicer compatible with Windows, Mac, and Linux.
  - Supports up to 16 extruders and allows simultaneous management of multiple filaments and colors.

- OctoPrint:
  - Free and open-source slicer with a web interface for 3D printers.

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- Compatible with Raspberry Pi, Windows, Mac, Linux, enabling control from a web browser or other devices.

- AstroPrint:
  - Browser-based slicer compatible with Raspberry Pi and pcDuino.
  - Provides slicing capabilities and allows monitoring of 3D printers from any internet-connected device.

The 3D printing software operates in two modes. The simple mode allows you to choose the material and desired quality before sending it to the 3D printer. In advanced mode, you can fine-tune the settings to achieve more intricate results.

Advanced Programming Tools:

OpenSCAD: It is a programming language for creating parametric 3D models. Users can write scripts instead of designing visually, allowing precise control over the dimensions and geometry of the model.

Python with Additive Manufacturing API: Some 3D printers and control software offer Application Programming Interfaces (APIs) that enable users to use programming languages like Python to control and automate additive manufacturing processes.

Materialise Magics Scripting: Magics is software used in preparing STL files for additive manufacturing. It provides scripting capabilities that allow users to automate tasks and customize workflows.

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These tools and languages play a crucial role in programming and controlling 3D printers, from model preparation to generating specific instructions for printing. The choice of platform and language depends on factors such as the printer used, project requirements, and user preferences.

4.3 Practical Examples of Programming in Additive Manufacturing:

Optimization of Topology:

Description: A manufacturer of lightweight components for the aerospace industry utilizes topological optimization algorithms to reduce the weight of parts while maintaining their structural strength.

Fig.12. Components from different types of industry

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Programming: They employ parametric design software and optimization algorithms to automatically adjust the topology of the component, generating more efficient models for additive manufacturing.

Rapid Prototyping Production:

Description: A product design company uses additive manufacturing for the rapid creation of prototypes. An automated workflow is implemented that converts design models into G-code using custom slicing software.

Programming: A script is developed to automate file preparation, adjusting print parameters automatically based on prototype specifications.

Printing Multiple Parts:

Description: A medical device factory prints several parts in a single printing process to improve efficiency. This involves generating paths and supports for multiple models on a single print bed.

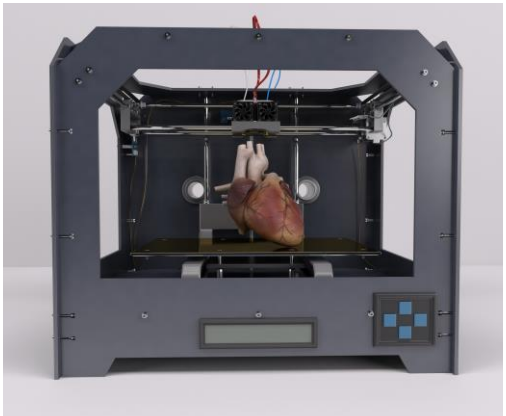

Fig.14. Example of medical component

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Programming: A program is developed to organize and optimize the arrangement of multiple models on the print bed, minimizing time and material usage.

4.4. Common problems in programming:

Deformation during Printing:

Solution: Simulation software is used to anticipate potential deformation issues. Parameters such as model orientation, heated bed temperature, and cooling speed are adjusted to minimize deformation.

Layer Adhesion Problems:

Solution: Adjustments are made to printing parameters, such as nozzle temperature and print speed, to enhance layer adhesion. Support settings are also adjusted to provide a solid foundation.

Optimization of Printing Time:

Solution: Optimization algorithms are employed to reduce printing time. This may involve optimizing trajectories, modifying layer density, and configuring parameters to achieve a balance between speed and quality.

Unsatisfactory Surface Quality:

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Solution: Parameters such as layer resolution, print speed, and retraction settings are adjusted to enhance surface quality. Additionally, post-processing steps like sanding or polishing can be performed to further improve the appearance of the printed object.

These examples and solutions illustrate how programming in additive manufacturing addresses specific challenges and optimizes the 3D printing process for different applications and industrial sectors. Adaptability and customization are key in programming to tackle common issues and maximize the efficiency of additive manufacturing.

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"Development of a CNC machine using embedded controls" of M. Nasralla, et al.

https://www.vacodir.com.uy/diferencias-de-los-formatos-de-impresion-3d-stl-vs-obj-vs-ply/

https://www.obico.io/blog/2020/07/09/3d-print-printing-quality-guide/

https://www.freepik.es/foto-gratis/imprimiendo-corazon-humano_879918.htm#page=2&query=Deformation%20during%20printing%203d&position=

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Erasmus+ Programme Key Action 2 Cooperation Partnerships for Higher Education (KA220-HED)
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MODULE 6

Sensors and Electronics

Project Title	**European Network for Additive Manufacturing in Industrial Design for Ukrainian Context 2023-1-RO01-KA220-HED-000155412**
Output	**IO1 - AMAZE e-book for industrial design for complex parts**
Module	**Module 6 Sensors and Electronics**
Date of Delivery	**March 2024**
Authors	**Băilă Diana, Zaharia Cătălin**

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AMAZE

CONTENTS

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1.The Importance of Electronics and Sensors in Industrial Design

Industry 4.0, through the integration of smart sensors and IoT technology, serves as a bridge between the physical and digital realms.

In smart manufacturing facilities, the utilization of smart sensors presents opportunities for failure prediction, efficiency enhancement, and real-time monitoring, all contributing to the development of intelligent factories. Sensors play a major role in automating factory operations, rendering the system more sophisticated. Various types of sensors are accessible, tailored to specific applications, with many being mass-produced and affordable. Common sensor types include position sensors, pressure sensors, flow sensors, temperature sensors, and force sensors. They find applications across diverse sectors such as motorsport, healthcare, industry, aerospace, agriculture, and everyday life [1-50].

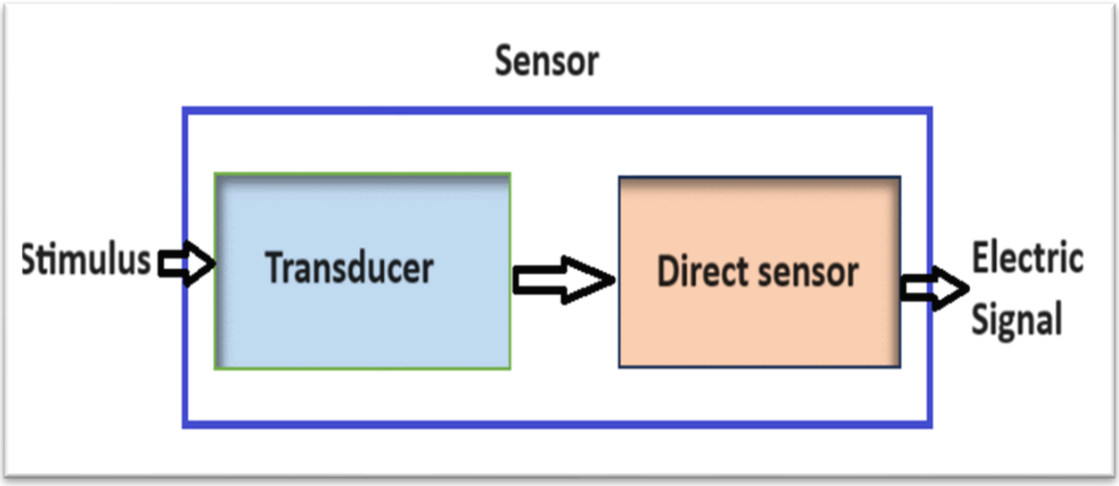

Fig.1. Schematic diagram of a sensor with input & output signal

The objective of Industry 4.0 is to increase efficiency through automation. Sensors are vital components of Industry 4.0, allowing several transitions such as changes in positions, length, height, external and dislocations in industrial production facilities to be detected, measured, analysed, and processed. Smart factories will also enhance sustainability by tracking

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real-time output, and automated control systems will minimise potential factory maintenance costs. It can also be seen that digitalisation can improve production mobility, which gives advanced manufacturing firms a competitive advantage. This chapter presents sensors and their various types, along with significant capabilities for manufacturing. The step-by-step working Blocks and Quality Services of Sensors during implementation in Industry 4.0 are elaborated diagrammatically. Finally, we identified thirteen significant applications of sensors for Industry 4.0. Industry 4.0 provides an excellent opportunity for the development of the sensor market across the globe. In Industry 4.0, sensors will enjoy higher acceptance rates and benefit from a fully enabled connecting and data exchange and logistics integration. In the coming years, sensor installations may grow in process management, automated production lines, and digital supply chains [1-50].

2. Types of sensors and their applications in Industries/manufacturing

All sensor types can be categorized into analogue and digital variants. However, within electronic applications, certain sensors are particularly prevalent. These include pressure sensors, touch sensors, IR sensors (infrared sensors), ultrasonic sensors, temperature sensors, proximity sensors, and others.

Light Sensors

The light sensor functions to detect light and typically produces a voltage difference. In robotics, light sensors come in two main types: photovoltaic cells and photoresistors. Photovoltaic cells are employed to convert solar radiation energy into electrical energy, making them ideal for use in solar-powered robots. Conversely, photoresistors adjust their resistance based on light intensity; as light increases, resistance decreases. These light sensors are generally cost-effective, making them widely utilized in robotics.

Sound Sensor

A sound sensor detects a sound and converts it into an electrical signal. By applying this type of sensor, robots can navigate through sound, even to the point of creating a sound-controlled robot that recognizes and responds to specific sounds or series of sounds, to carry out certain tasks.

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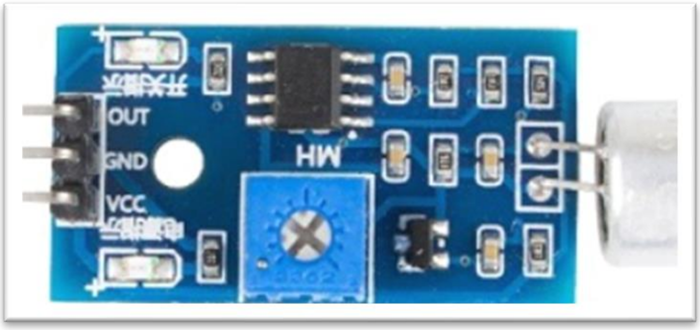

Fig.2. Sound sensor [5]

Temperature Sensor

A temperature sensor is employed to detect fluctuations in environmental temperature. It operates primarily on the principle of voltage difference to measure temperature changes and derive the corresponding temperature values of the surroundings. Various types of temperature sensor integrated circuits (ICs) are available for temperature detection, such as LM34, TMP37, TMP35, TMP36, LM35, and others. These sensors are essential for robots operating in diverse and extreme weather conditions, ranging from icy glaciers to scorching deserts [1-50].

Fig.3. Thermistor [3]

Contact Sensor

Contact sensors, commonly referred to as touch sensors, are primarily designed to detect changes in velocity, position, acceleration, torque, or force at the joints of a manipulator and its end-effector in robots. Physical contact is required for these sensors to efficiently direct the

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robot to act accordingly. The sensor is executed in different switches such as a limit switch, button switch, and tactile bumper switch.

Contact sensors are frequently utilized in obstacle avoidance robots. When these sensors detect an obstacle, they transmit a signal to the robot, prompting it to execute various actions such as reversing, turning, or halting altogether [1-50].

Proximity Sensor

In robotics, a proximity sensor is used to detect objects that are close to a robot and measure the distance between a robot and particular objects without making physical contact. This is possible because the sensors use magnetic fields to sense the objects in question. Proximity sensors are typed into photoresistors, infrared transceivers, and ultrasonic sensors.

Infrared (IR) Transceivers

An infrared (IR) transceiver or sensor is designed to measure and detect infrared radiation present in its surroundings. These sensors can be categorized as either active or passive. Active infrared sensors function by both emitting and detecting infrared radiation, typically comprising a light-emitting diode (LED) and a receiver. These active transceivers are commonly utilized as proximity sensors, often found in robotic obstacle detection systems.

On the other hand, passive infrared (PIR) sensors solely detect infrared radiation without emitting it from the LED. These passive sensors are primarily employed in motion-based detection systems.

Ultrasonic Sensor

An ultrasonic sensor is a device that measures the distance of a specific object by emitting ultrasonic sound waves and converts the reflected sound into an electrical signal. Ultrasonic sensors radiate sound waves toward an object and determine its distance by detecting reflected waves. This is why they are mainly used as proximity sensors, applied in robotic obstacle detection systems and anti-collision safety systems.

Photoresistor

Photoresistors, also known as light-dependent resistors (LDR), are devices that alter their resistance based on the intensity of light incident upon them. Because of their sensitivity to light, they are commonly utilized to detect the presence or absence of light and to measure light intensity. In photoresistors, increased light results in decreased resistance [1-50].

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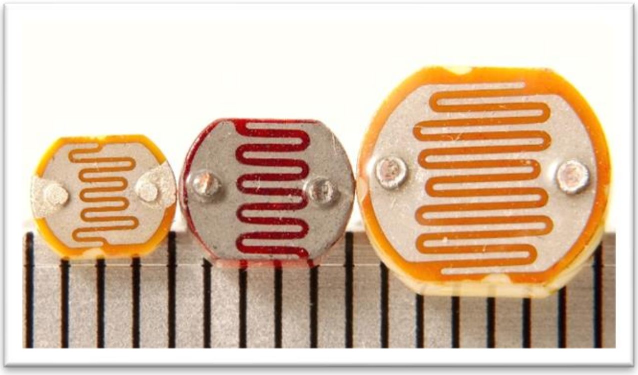

Fig.4. Photoresistors [4]

Distance Sensor

Distance sensors are employed to determine the distance between objects without requiring physical contact. These sensors operate by emitting a signal and measuring the time it takes for the signal to return. The emitted signal can be infrared, LED, or ultrasonic waves, leading to the common association of distance sensors with ultrasonic technology.

Ultrasonic Distance Sensors

An ultrasonic distance sensor is a device that gauges the distance to an object by utilizing high-frequency sound waves. These sensors emit sound waves at frequencies higher than those audible to humans and subsequently wait for the waves to be reflected. By measuring the time elapsed between sending and receiving the ultrasonic wave and factoring in the speed of sound, the sensor calculates the distance to the target object [1-50].

3. Actuators used in Industries/manufacturing

An actuator is a component of a machine that produces force, torque, or displacement, usually in a controlled way, when an electrical, pneumatic or hydraulic input is supplied to it in a system (called an actuating system). An actuator converts such an input signal into the required form of mechanical energy. It is a type of transducer. In simple terms, it is a "mover". An actuator requires a control device (controlled by control signal) and a source of energy. The control signal is relatively low energy and may be electric voltage or current, pneumatic,

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or hydraulic fluid pressure, or even human power. In the *electric*, *hydraulic*, and *pneumatic* sense, it is a form of automation or automatic control.

The displacement achieved is commonly linear or rotational, as exemplified by linear motors and rotary motors, respectively. Rotary motion is more natural for small machines making large displacements. By means of a leadscrew, rotary motion can be adapted to function as a linear actuator (a linear motion, but not a linear motor) [1-50].

Types of actuators are:

- Soft actuator
- Hydraulic actuator
- Pneumatic actuator
- Electric actuator
- Electromechanical actuator (EMA)
- Electrohydraulic actuator
- Linear motor
- Rotary motor
- Thermal or magnetic actuators
- Mechanical actuator
- 3D printed soft actuators.

3D printed soft actuators

Many soft actuators are currently manufactured using multistep processes such as micro-molding, solid freeform fabrication, and mask lithography. However, these methods often involve manual fabrication, post-processing, and lengthy iterations to achieve fabrication maturity. To address these challenges, researchers are exploring more efficient manufacturing approaches for soft actuators.

One promising approach involves utilizing rapid prototyping methods, such as 3D printing, to fabricate soft actuators in a single step. By doing so, researchers aim to streamline the fabrication process, making it faster, more cost-effective, and simpler. Additionally, these methods enable the integration of all actuator components into a single structure, eliminating the need for external joints, adhesives, and fasteners.

Shape memory polymers represent a fascinating field of polymer innovation. Essentially, these materials have the ability to 'remember' their original shape and return to it when triggered by certain stimuli, such as heat or light. These materials possess a unique ability to 'remember' their original shape and return to it after being deformed. This phenomenon, known as the shape memory effect (SME), is observed in shape memory alloys (SMAs), shape memory polymers (SMPs), and shape memory hybrids (SMHs).

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Shape memory materials are categorized under “smart materials” or “intelligent materials”, which are responsive to external stimuli. The shape memory effect can be triggered by various stimuli such as heat, light, stress, moisture, electric or magnetic fields, pH, or chemical compounds. When exposed to these stimuli, these materials undergo controlled changes in their properties, particularly their shape, demonstrating their unique adaptive capabilities.

Shape memory polymer (SMP) actuators are the most similar to our muscles, providing a response to a range of stimuli such as light, electrical, magnetic, heat, pH, and moisture changes. They have some deficiencies including fatigue and high response time that have been improved through the introduction of smart materials and combination of different materials by means of advanced fabrication technology. The advent of 3D printers has made a new pathway for fabricating low-cost and fast response SMP actuators. The process of receiving external stimuli like heat, moisture, electrical input, light, or magnetic field by SMP is referred to as shape memory effect (SME). SMP exhibits some rewarding features such a low density, high strain recovery, biocompatibility, and biodegradability. Various 3D printing technologies have been employed for this purpose, including fused filament fabrication (FDM), direct ink writing (DIW), PolyJet, and vat polymerization methods such as stereolithography (SLA) and digital light processing (DLP).

Smart materials like photoresponsive polymers and composites exhibit the remarkable ability to undergo shape changes when exposed to light. These light-induced shape-changing polymer materials can be categorized into various types, including liquid crystal elastomers (LCE), hydrogels, light-activated shape memory polymers, and composites.

Photopolymers or light activated polymers (LAP) are another type of SMP that are activated by light stimuli. The LAP actuators can be controlled remotely with instant response and, without any physical contact, only with the variation of light frequency or intensity.

A need for soft, lightweight and biocompatible soft actuators in soft robotics has influenced researchers for devising pneumatic soft actuators because of their intrinsic compliance nature and ability to produce muscle tension.

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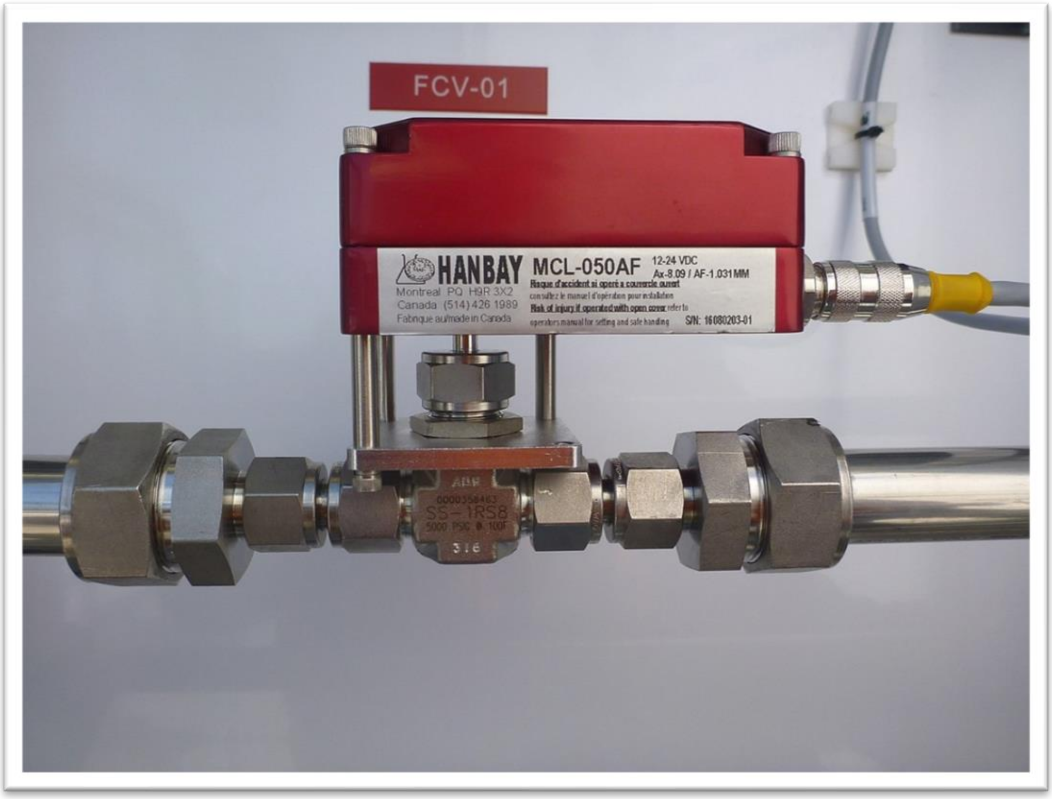

Fig.5. Electric valve actuator controlling a ½ needle valve [6]

Polymers such as dielectric elastomers (DE), ionic polymer–metal composites (IPMC), ionic electroactive polymers, polyelectrolyte gels, and gel-metal composites are common materials to form 3D layered structures that can be tailored to work as soft actuators. EAP actuators are categorized as 3D printed soft actuators that respond to electrical excitation as deformation in their shape.

The actuators are frequently used as mechanisms to introduce motion in industry, or to clamp an object to prevent motion. In electronic, actuators are a subdivision of transducers. They are devices which transform an input signal (mainly an electrical signal) into some form of motion [1-50].

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4. *Electronic components used for the manufacture of 3D hybrid printer, type DIY (do it yourself)*

In the last decade, additive manufacturing has greatly developed, and the manufacture of cheaper 3D hybrid (multitool) printers has increased. Hybrid 3D printers are equipped with interchangeable heads for manufacture and permit multiple types of processing such as 3D printing, CNC cutting, laser engraving or deposition of pasty materials. The objective of this paper was to manufacture a hybrid 3D printer prototype, type DIY (do it yourself) and was equipped with g-code software necessary for 3D printing process and for CNC cutting. The materials used for construction for this hybrid 3D printer are cheap and accessible and some of electronic components are reused and recovered from old equipment and the functional 3D hybrid printer obtained can be a model for sustainability of products.

The purpose of this research was to create a hybrid 3D printer prototype, recycling, and recovery of old electronic components, such as were used stepper motors from some old Xerox equipment, enabling sustainable development of the product. Hybrid 3D printers are multifunction printers that will replace traditional 3D printers in the future or min-CNC and will be finding in most households, because of their varied functionality. A hybrid 3D printer ZMorph is shown in figure 6 [1-50].

Hybrid 3D printers are equipped with several interchangeable heads: as simple 3D print head, 3D dual head, CNC head, laser engraving head and ceramic material deposition head.
Fused Deposition Modeling technology (FDM) uses a variety of filament-like materials of PLA, ABS, nylon, PVA, PET, PETG etc. [2]. The mechanical strength of the manufactured parts is very good, often existing 3D printers that are sold with 3D printed components in their composition [3]. Hybrid 3D printers used this technology for printing 3D parts.

The mechanical strength of the 3D printed parts is very good, often existing 3D printers that are sold with 3D printed components in their composition.

The hybrid prototype 3D printer made in this research also has in its composition, 3D printed parts, 3D printed directly on itself, like the red brackets of the printed table and the head CNC components.

FDM technology operates by building a CAD-designed product layer by layer. The object is first saved in an STL file format, which is then used by the 3D printer software to guide the printing process. This technology allows for the creation of supports, which are necessary for the fabrication of complex 3D printed parts.

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Prototypes produced using FDM technology typically do not require additional post-processing treatments and can be utilized immediately, featuring high-quality surface finishes.

The Additive Manufacturing technology helps identify any problems that may arise in the design and conception. [1-50]

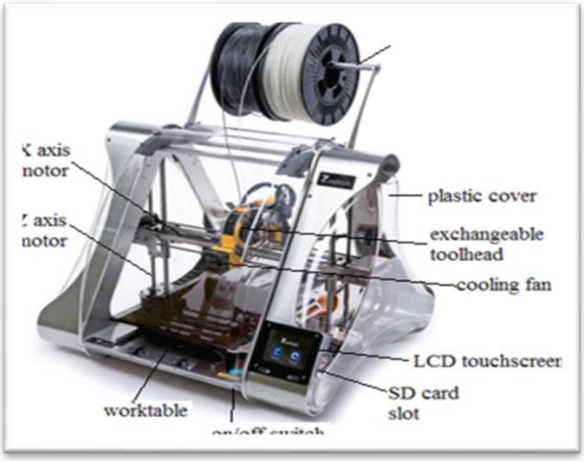

Fig.6. Commercial 3D hybrid printer ZMorph [7]

ZMorph printer can print layers up to 50 microns. ZMorph 3D hybrid printer is equipped with five interchangeable heads allowing printing, milling, drilling and engraving materials widely. The manufacturing dimensions of ZMorph printer are 300x235x165 mm. The manufactured materials of this printer are very different from PLA, ABS, special filaments wood, etc. The software used of this printer is Voxelizer. The cost of hybrid 3D printers can be relatively high, typically around 4000 euros. This research aims to develop a low-cost alternative, priced at approximately 500 euros, to be used for educational and research experiments [1-50].

4.1.Experimental research

The experimental research involves constructing a hybrid 3D printer using do-it-yourself (DIY) methods, utilizing low-cost materials and tools readily available in the market.

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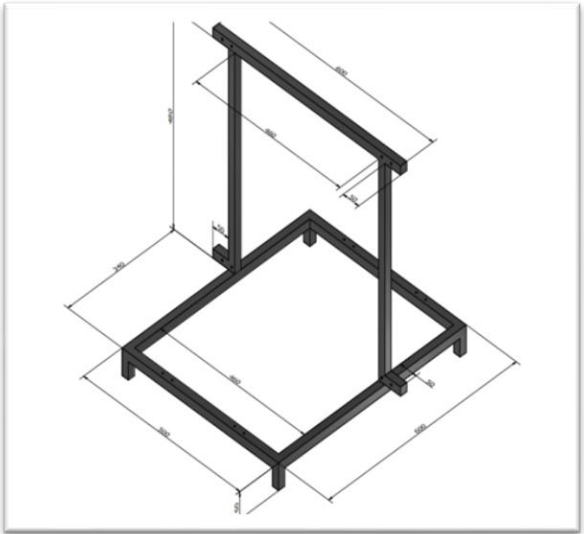

Fig.7. Structure design of 3D printer

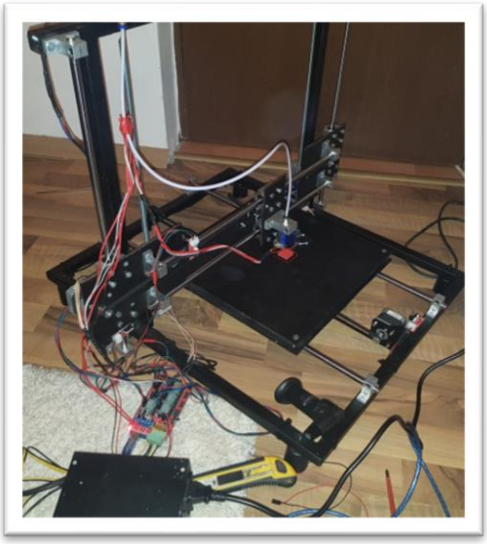

Fig.8. Assembly and welding of 3D printer parts

During the design stage, careful consideration was given to sizing the structural elements based on the dimensions of standard components used, such as clamps for SK10 and SK16, bearings for SC10UU, Ø10 linear guides, and NEMA17 motors. The 3D printer structure will be constructed using welded rectangular profiles measuring 20x20 mm, as illustrated in Figure 7 below.

In Figure 8, the cutting and drilling of PTFE material plates for the printing table were carried out. These plates will serve as the printing surface. Additionally, brackets and linear guides were attached to the fixed table, and bed springs and adjustable thumbscrews were disconnected to facilitate leveling. Linear bearings were installed on the cutting boards, and NEMA17 motors were attached to complete the construction process.

Regarding the electrical connections, various connections were established between the controller and stepper motors. To establish the electrical control network, the following components were used: an Arduino MEGA 2560 development board, a 1.4 Ramps SHIELD module, and 5 drivers 4988, as shown in Figure 9.

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Fig.9. Arduino MEGA 2560 board

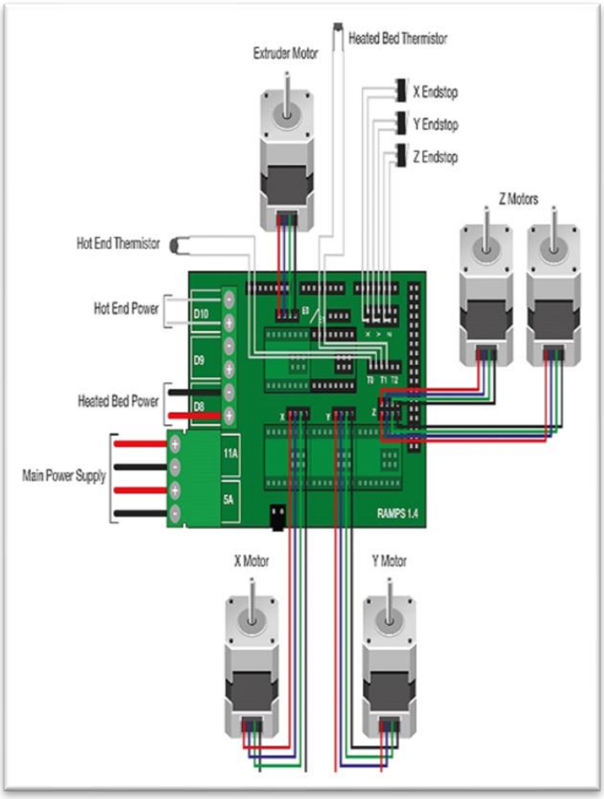

Fig.10. Electrical installation scheme

Figure 10 illustrates the electrical installation scheme, which incorporates a PC PSU 12V 14.6 power supply. Additionally, an endstop with a mechanical feeler, depicted in Figures 11 and 12, was utilized.

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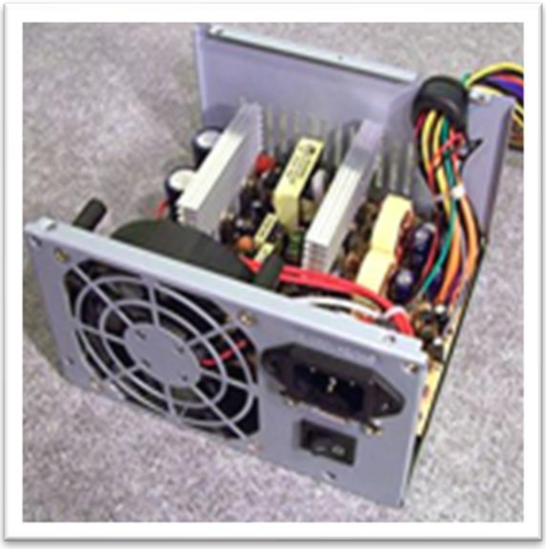

Fig. 11. Power supply PC PSU 12V 14.6

Fig. 12. Endstop with mechanical feeler

The single-pole stepping motors with 4 phases were converted into 2 phases by removing the "mid-point" of the coils A and B (MA:MB), as depicted in Figure 13.

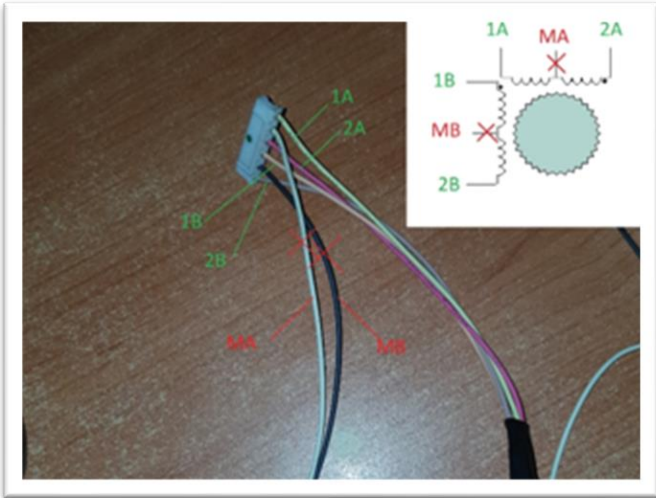

Fig. 13. Stepping motors

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The operation of the 3D printer involved scheduling and optimization using software. The implementation of the printer's physical parameters was achieved through the Marlin 1.1 code, as shown in Figure 14, which was uploaded to the Arduino MEGA 2560 development board [1-50].

```
/**
 * Default Axis Steps Per Unit (steps/mm)
 * Override with M92
 *                                      X, Y, Z, E0 [, E1[, E2[, E3[, E4]]]]
 */
#define DEFAULT_AXIS_STEPS_PER_UNIT   { 80, 100, 1600, 94.3 }
                              Fulie z20   Fulie z16   Surub P2   Extruder MK8
/**
 * Default Max Feed Rate (mm/s)
 * Override with M203
 *                                      X, Y, Z, E0 [, E1[, E2[, E3[, E4]]]]
 */
#define DEFAULT_MAX_FEEDRATE          { 300, 300, 5, 25 }

/**
 * Default Max Acceleration (change/s) change = mm/s
 * (Maximum start speed for accelerated moves)
 * Override with M201
 *                                      X, Y, Z, E0 [, E1[, E2[, E3[, E4]]]]
 */
#define DEFAULT_MAX_ACCELERATION      { 2500, 2500, 2500, 10000 }

/**
 * Default Acceleration (change/s) change = mm/s
 * Override with M204
```

Fig.14. Marlin1.1 code used for 3D hybrid printer prototype

```
#define TEMP_SENSOR_0 1
#define TEMP_SENSOR_1 0
#define TEMP_SENSOR_2 0
#define TEMP_SENSOR_3 0
#define TEMP_SENSOR_4 0
#define TEMP_SENSOR_BED 1
#define TEMP_SENSOR_CHAMBER 0
```

Fig. 15. Thermistor type used (100K)

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With its aid were set issues, like in figure 15:
- Port for the connection;
- Extruders number;
- Existence heated bed;
-Thermistor type used (100K);
-Maximum axes travel;
-Required number of steps per mm (the pitch of the threads);
-Point0 (homing point);
-Size table printed, as in figure 16;
-Maximum acceleration, as in figure 17;
-Maximum voltage motors.

```
#define X_HOME_DIR -1
#define Y_HOME_DIR -1
#define Z_HOME_DIR -1

// @section machine

// The size of the print bed
#define X_BED_SIZE 260
#define Y_BED_SIZE 260
// Travel limits (mm) after homing, corresponding to endstop positions.
#define X_MIN_POS 0
#define Y_MIN_POS 0
#define Z_MIN_POS 0
#define X_MAX_POS 260
#define Y_MAX_POS 260
#define Z_MAX_POS 280
```

Fig. 16. Size table printed programming

```
#define DEFAULT_ACCELERATION          2500    // X, Y, Z and E acceleration for printing moves
#define DEFAULT_RETRACT_ACCELERATION  3000    // E acceleration for retracts
#define DEFAULT_TRAVEL_ACCELERATION   2500    // X, Y, Z acceleration for travel (non printing) moves
```

Fig 17. Maximum acceleration programming.

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G-code can be generated using various programs, including Slic3r with its extension Pronterface or Simplify3D. These programs utilize models in "STL" format and offer calibration of printing parameters such as printing speed, infill density, wall thickness, layer height, filament width, and temperature settings, as depicted in Figure 18. Figure 19 showcases the physical 3D parts obtained by printing using the prototype of the hybrid 3D printer.

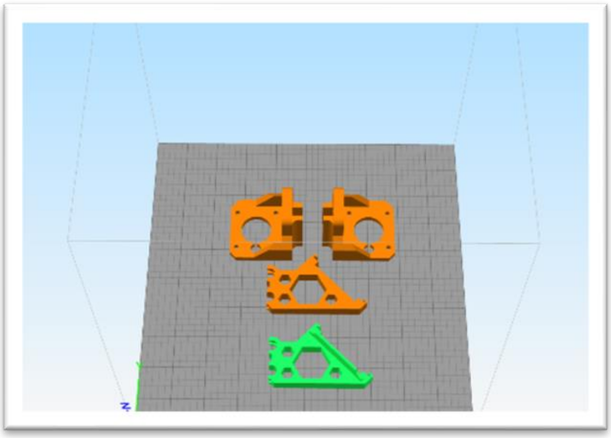

Fig.18. Simplify 3D program used to create G-code

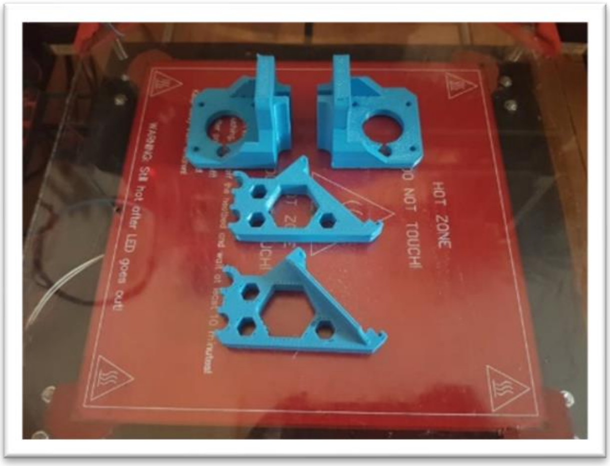

Fig. 19. Physical 3D printed parts

Figure 20 displays the components of the hybrid 3D printer, while Figure 21 showcases the interchangeable CNC tool head, with some components manufactured using 3D printing technology. Figure 22 illustrates the CNC drilling process performed on the 3D hybrid printer, utilizing the CNC head [1-50].

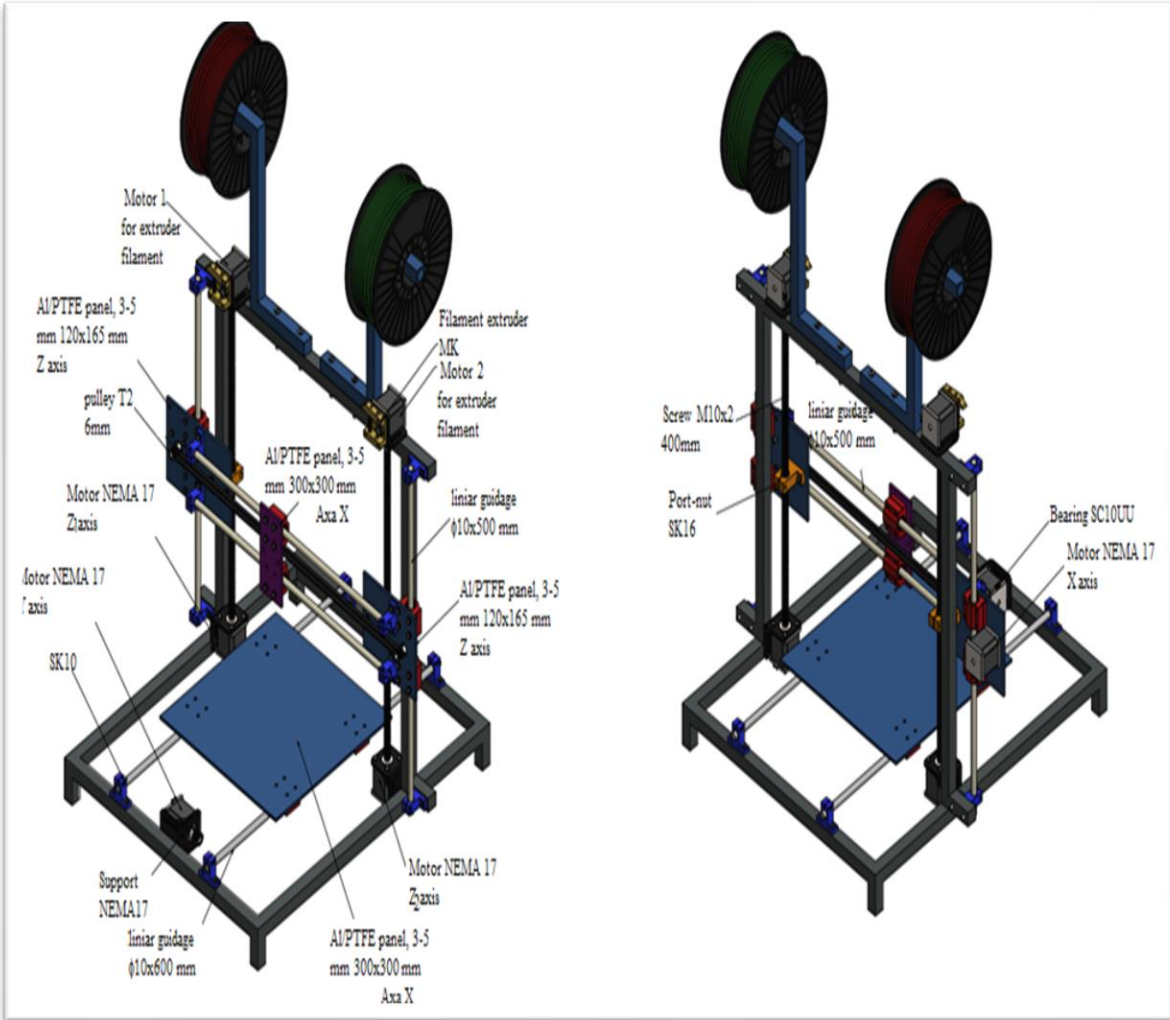

Fig.20. Components of hybrid 3D printer

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Fig.21. CNC head of 3D hybrid printer

Fig.22. CNC drilling on the 3D hybrid printer

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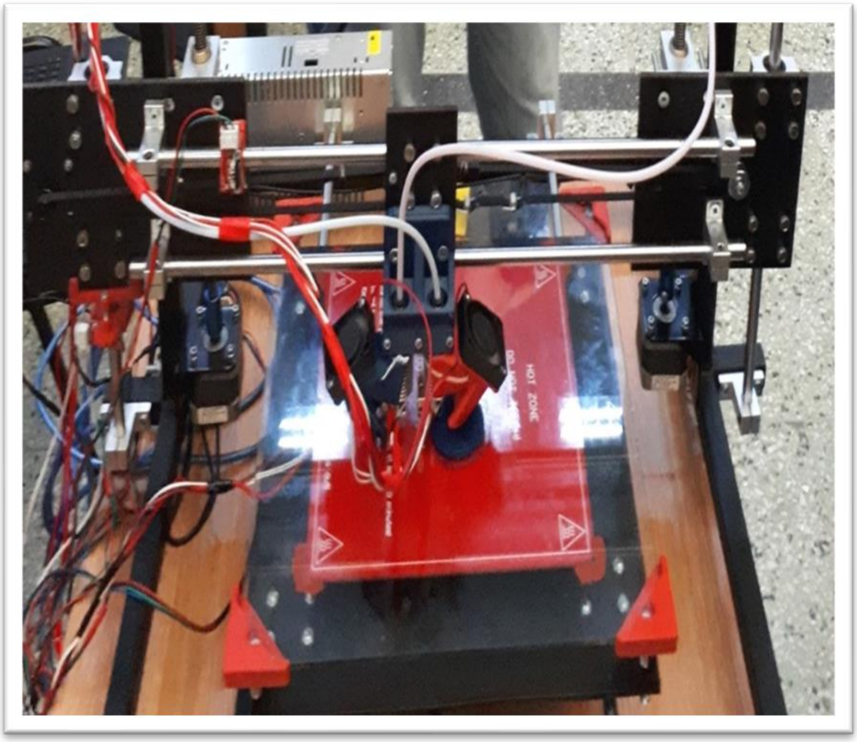

Fig.23. FDM extruder on the 3D hybrid printer

The research presented the practical implementation of a do-it-yourself (DIY) hybrid 3D printer using readily available tools and affordable materials found in most households. Additionally, some components utilized in the hybrid 3D printer were recycled from old electronic equipment, highlighting the potential for sustainable development in the production process.

The hybrid prototype 3D printer developed in this research was constructed on a limited budget and features a simple 3D print head (depicted in Figure 23) along with a CNC head. Simplify3D software was utilized for generating the G-code. Noteworthy aspects of this research include the innovative electronics, programming, and optimization software employed. The printer can produce components with dimensions of up to 300x300x200 mm, demonstrating a high precision of 0.2 mm.

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Project title: European Network for Additive Manufacturing in Industrial Design for Ukrainian Context – Acronym: AMAZE

MODULE 7

Virtual Reality (VR) and Augmented Reality (AR)

Project Title	**European Network for Additive Manufacturing in Industrial Design for Ukrainian Context 2023-1-RO01-KA220-HED-000155412**
Output	**IO1 - AMAZE e-book for industrial design for complex parts**
Module	**Module 7 Virtual Reality (VR) and Augmented Reality (AR)**
Date of Delivery	**March 2024**
Authors	**Sergio Vizcaino, Beatriz Gloria BONILLA GARCIA, César Arcadio BONILLA GARCIA**
Version	**FINAL VARIANT, *date***

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Contents

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1 Introduction to Virtual Reality (VR) and Augmented Reality (AR)

Virtual Reality (VR) and Augmented Reality (AR) are innovative technologies that offer distinct approaches to enhance additive manufacturing processes. In the realm of virtual reality, users are transported to entirely digital environments using devices such as VR headsets. This is particularly useful in additive manufacturing, where VR enables the creation of detailed simulations of the entire process, from initial design to the 3D printing phase. Engineers and operators can interact with three-dimensional models, adjust parameters, and conduct virtual tests before implementing processes physically. Furthermore, virtual reality facilitates operator training by providing practical simulations and remote collaboration, allowing dispersed teams to collaborate efficiently in a shared virtual environment.

In contrast, augmented reality adds a digital layer to the physical world, overlaying graphical information or contextual data in real-time. In the context of additive manufacturing, AR stands out by providing visual instructions directly in the workspace during the assembly process of 3D-printed products. Operators can benefit from precise and real-time visual guides, improving accuracy and reducing errors. Additionally, AR is used for real-time monitoring of 3D printers, displaying crucial data about the printing status, temperature, and other key parameters. This direct and contextual information facilitates informed decision-making and contributes to the early detection of potential issues.

The choice between virtual reality and augmented reality in additive manufacturing depends on specific objectives and the nature of the task at hand. While virtual reality offers total immersion in simulated environments, augmented reality enhances the physical environment

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with relevant digital information. The combination of both technologies, known as mixed reality, is also being explored to harness the best of both worlds. Collectively, these technologies are transforming how challenges are addressed and processes are optimized in additive manufacturing.

1.1. Virtual Reality (VR)

Virtual Reality (VR) plays a crucial role in additive manufacturing by providing an immersive environment that significantly enhances design, simulation, and operator training processes. Firstly, in the realm of design, VR enables engineers to visualize and manipulate 3D models in a three-dimensional space, facilitating the creation and optimization of designs for 3D printing. This virtual approach reduces the need for physical prototypes, speeding up the development cycle and saving costs.

Fig.1. Using Virtual Reality

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Secondly, VR is used for process simulation in additive manufacturing. Users can virtually experience each step of the process, from setting up the 3D printer to optimizing parameters, before carrying out the physical print. This helps identify potential issues and adjust variables efficiently, improving operational effectiveness and reducing material waste.

Thirdly, VR is employed in operator training. New operators can familiarize themselves with handling 3D printers and learn to troubleshoot potential problems in a virtual environment, expediting the training process and ensuring a consistent level of skills across the team.

In summary, virtual reality in additive manufacturing not only optimizes design and simulation but also transforms operator training by providing immersive learning experiences. These combined VR applications contribute to increased efficiency and accuracy in additive manufacturing, driving the adoption of advanced technologies in the manufacturing industry.

1.2. Augmented Reality (AR)

Augmented Reality (AR) plays a crucial role in the transformation of additive manufacturing, providing significant benefits in terms of efficiency and precision. Firstly, AR is used to enhance the assembly process of 3D-printed products by overlaying visual instructions directly in the operator's field of view. This not only simplifies and speeds up the assembly process but also reduces the possibility of errors by providing real-time visual guidance. AR thus contributes to the improvement of quality and productivity in the production chain.

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Fig.2. Example of Augmented Reality

Secondly, AR is employed for real-time monitoring of 3D printers. Operators can visualize crucial data, such as print progress, temperature, and other key parameters, directly on the printer. This facilitates early detection of potential issues, allowing for quick interventions and minimizing the risk of errors in the additive manufacturing process. Additionally, AR can provide information about the printer's status in an intuitive and accessible manner, enhancing decision-making.

Thirdly, AR is integrated into operator training in additive manufacturing. It enables the creation of immersive and practical training experiences, where operators can learn to interact with 3D printers and perform specific tasks in a virtual environment. This not only accelerates the training process but also improves knowledge retention by providing a more visual and hands-on learning experience.

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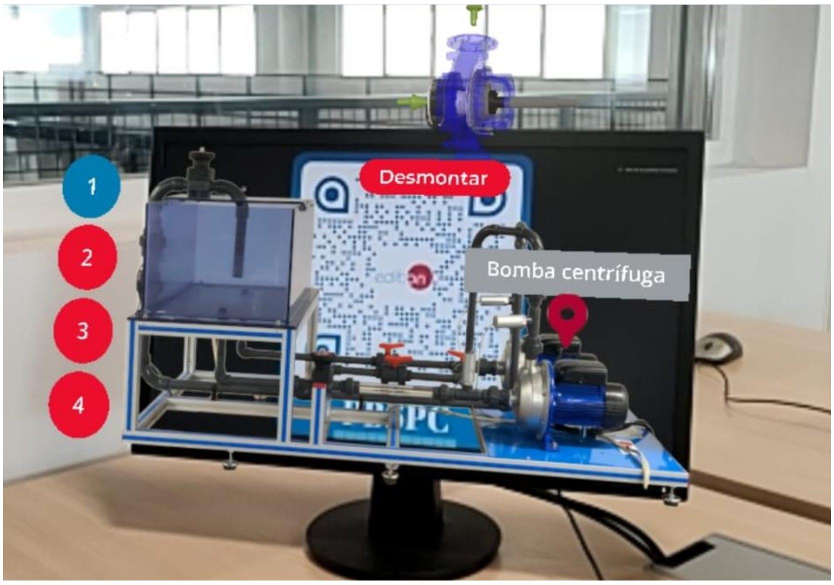

Fig.3. Example of Augmented Reality

In summary, augmented reality in additive manufacturing not only optimizes assembly and process monitoring but also revolutionizes operator training by providing more immersive learning experiences. These advancements contribute to more efficient and precise production in additive manufacturing, driving the adoption of cutting-edge technologies in the manufacturing industry.

2 Contextualization of the Importance of VR and AR in Additive Manufacturing

The integration of Virtual Reality (VR) and Augmented Reality (AR) in additive manufacturing represents a significant advancement that fundamentally transforms the way the manufacturing process is conceptualized, developed, and executed. This convergence of innovative technologies introduces a series of key benefits that positively impact the

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efficiency, precision, and flexibility of additive manufacturing. The contextualization of its importance can be understood through the following points:

a. Improvement in Visualization and Design: The combination of virtual reality (VR) and augmented reality (AR) has brought notable improvements in visualization and design across various industries, particularly standing out in the realm of manufacturing. Firstly, virtual reality allows designers to immerse themselves in three-dimensional environments, facilitating a deeper understanding of models and prototypes. This immersion enhances spatial perception and the detection of potential design issues, enabling adjustments and optimizations before production.

Fig.4. Concept of Augmented Reality

On the other hand, augmented reality offers an overlay of digital information in the real world, proving invaluable for visualization during the design phase. This technology enables engineers to view 3D models directly in the physical environment, facilitating the evaluation

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of sizes, proportions, and spatial relationships. Additionally, AR can be used to project real-time data about the production status, such as temperatures, speeds, and other parameters, contributing to more informed decision-making.

Together, VR and AR provide powerful tools to enhance visualization and design in manufacturing. From immersive prototyping to overlaying relevant information during production, these technologies are transforming how professionals interact with designs and optimize manufacturing processes. This innovative approach not only drives efficiency but also promotes more precise decision-making and continuous improvement in product quality.

b. Iterative Design and Rapid Prototyping: Virtual reality allows designers to create and modify models in an immersive three-dimensional environment. This facilitates rapid design iteration and the creation of virtual prototypes before physical production. Designers can visualize and evaluate the design from different perspectives to make precise adjustments.

Iterative design and rapid prototyping are key elements in the additive manufacturing process. Additive manufacturing, including technologies like 3D printing, enables the creation of three-dimensional objects layer by layer from digital data. Here is a description of how iterative design and rapid prototyping are integrated into the context of additive manufacturing:

c. Rapid Iteration: Additive manufacturing allows for rapid iterations in design. Designers can make changes to the digital model and then print an updated prototype in a short amount of time.

d. Design Optimization: The ability to manufacture objects layer by layer facilitates design optimization. Designers can adjust geometry to improve structural efficiency, reduce weight, or meet other specific requirements.

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e. Function-Based Design: Designers can focus on the performance and function of the object, as additive manufacturing allows the creation of structures and geometries that would be difficult or impossible to achieve with traditional manufacturing methods.

f. Fast Feedback: By easily and relatively inexpensively printing prototypes, quick feedback on designs is obtained. This facilitates the identification of issues and the implementation of improvements.

g. Cost and Time Reduction: Compared to traditional prototyping methods, additive manufacturing can significantly reduce costs and times associated with prototype creation. Determining the exact percentage of cost and time reduction when using virtual reality (VR) and augmented reality (AR) in additive manufacturing may depend on various factors, including the type of application, the complexity of the manufacturing process, and the effectiveness of the implementation of these technologies. However, in general, significant improvements in terms of efficiency and productivity can be expected. Here are some general estimates based on common use cases:

h. Design and Prototyping: The use of VR for design and prototype visualization can reduce development time and design iterations. Reductions of up to 30-40% in development time have been reported in some industries.

i. Collaboration and Communication: Real-time collaboration facilitated by VR and AR can decrease design review and approval times, contributing to cost reductions associated with decision-making delays.

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j. Process Simulation and Error Detection: Process simulation in VR can help identify and correct potential design errors before production, resulting in significant savings by avoiding defects and rework. Cost reductions in this area can exceed 20-30%.

k. Assembly Instructions and Training: The use of AR to provide assembly instructions and training can accelerate operators' learning curve and reduce the time needed to perform specific tasks. This can lead to cost reductions related to training and operational efficiency.

l. Inspection and Maintenance: AR used in virtual inspections can improve efficiency in the quality and maintenance process, reducing the time needed to assess and address issues. This can translate into time and maintenance cost savings.

It is important to note that these percentages are general estimates, and specific results may vary depending on the implementation and context. The successful adoption of VR and AR in additive manufacturing can not only reduce production costs and times but also improve product quality and customer satisfaction.

m. Design Validation: 3D-printed prototypes allow designers and engineers to validate the design before moving to large-scale production. Aspects such as shape, functionality, and ergonomics can be evaluated.

Design validation through the combination of virtual reality (VR) and augmented reality (AR) revolutionizes the product development process by giving designers and engineering teams the ability to immerse themselves in immersive virtual environments. In VR environments, three-dimensional models come to life, allowing for a thorough evaluation of every aspect of the design. This ability to interact and visualize in real-time facilitates the early identification

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of potential issues and the making of instant adjustments, drastically reducing the time needed for iterations and perfecting the design. Additionally, augmented reality adds a practical component to the process by overlaying virtual models on the real world, providing a tangible perspective of the design and allowing the assessment of key factors such as size and integration into the real environment.

The integration of VR and AR in design validation not only speeds up iterations but also fosters more efficient collaboration among multidisciplinary teams. The ability to collaborate in real-time in virtual environments enhances communication between designers, engineers, and other stakeholders, allowing for immediate feedback. This approach not only reduces the likelihood of design errors but also contributes to the overall efficiency of the product development process, enabling the creation of more innovative and competitive products in the market.

n. Error Detection: The rapid prototyping process facilitates early detection of design errors. By printing prototypes and evaluating their physical performance, problems can be identified and corrected before investing in expensive production tools.

o. Customization and Parametric Design: Additive manufacturing allows for the creation of customized prototypes and exploration of parametric designs, where model parameters can be easily adjusted to evaluate different configurations.

In summary, the combination of iterative design and rapid prototyping in additive manufacturing provides designers and engineers with a powerful tool to innovate, experiment, and refine their designs efficiently before scaling up to large-scale production. This approach helps accelerate the product development cycle and improve the quality and efficiency of the design process.

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3 Interactivity and Immersive Experience

Virtual reality environments offer an interactive and more immersive experience. Designers can manipulate 3D objects more naturally, enhancing spatial understanding and decision-making during the design process.

Fig.5. Example

Interactivity and immersive experience are fundamental elements in virtual reality (VR) and augmented reality (AR), transforming the way we interact with digital information and virtual objects. Here are some key aspects of how interactivity and immersive experience are applied in these environments:

Real-Time Interaction:

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- Direct Manipulation: The ability to interact directly with virtual objects using gestures, touch controls, or specialized input devices.
- Motion Recognition: VR and AR systems can track and recognize user movements to provide a more natural interaction experience.

Navigation and Exploration:
- Three-Dimensional Exploration: The ability to explore virtual environments or 3D information, allowing for a more immersive and detailed experience.
- Gesture-Based Navigation: Using gestures to navigate virtual environments or access information in augmented reality applications.

Simulation and Visualization:
- Interactive Simulations: Creating interactive simulations in VR for training, education, or prototyping.
- 3D Data Visualization: The ability to visualize complex data in three dimensions, facilitating understanding and analysis.

Remote Collaboration:
- Virtual Meetings: Facilitating meetings and collaboration among users located in different places through shared virtual reality environments.
- Project Collaboration: Collaborating in real-time on projects, designs, or presentations using VR or AR devices.

Training and Simulation:
- Immersive Training: Using virtual reality to train individuals in simulated environments, such as emergency situations or workplace practices.

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- Simulation of Complex Scenarios: Creating simulation environments that mimic realistic situations for training and skill development.

Interactive Education:

- Interactive Lessons: Developing educational content that allows students to interact with 3D models, explore concepts in three dimensions, and actively participate in learning.
- Virtual Experiments: Conducting virtual experiments or visualizing scientific phenomena interactively.

Personalization and User Experience:

- Environment Customization: Allowing users to customize their virtual environment, from appearance to the arrangement of elements.
- Intuitive User Interface: Designing intuitive and user-friendly interfaces that enhance the user experience in VR and AR environments.

Gamification:

- Game Elements: Integrating game elements and gamification to make experiences more engaging and motivating.
- Interactive Stories: Developing interactive narratives that engage the user and provide an immersive experience.

Interactivity and immersive experience are essential to fully harness the potential of virtual and augmented reality. These technologies are transforming various fields, from education and entertainment to industry and medicine, providing new ways to interact with the digital and physical world.

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4 Visualization in Detail

VR allows for detailed visualization of 3D models, even at a much larger scale than would be possible on a conventional screen. This is crucial for assessing the complexity and accuracy of models before production. Detailed visualization in virtual reality (VR) and augmented reality (AR) is essential for providing immersive and understandable experiences. Here are some key aspects of how detailed visualization is achieved in these environments:

Virtual Reality (VR):

Resolution and High-Quality Graphics:

- Use of high-resolution displays to provide sharp and detailed images.
- High-quality graphics to represent textures and details realistically.
- Motion and Position Tracking:

Precise tracking systems that allow exact correlation between user movements and real-time view in the virtual environment.

Position tracking technologies to enable movement in virtual space and detailed inspection. Realistic Lighting: modelling of realistic lighting to simulate shadows, reflections, and light effects contributing to detail perception.

Interactivity and Manipulation:

- Interactive tools that allow users to manipulate virtual objects and explore specific details through gestures and controls.

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- Detailed animations to represent processes or events realistically.
- Detailed simulations of phenomena, allowing real-time visualization.
- Complex 3D Environments:

Detailed representation of 3D environments with complex geometry and realistic textures. Detailed scenarios including landscapes, buildings, and objects with high fidelity.

Remote Collaboration:

VR platforms that enable real-time collaboration, facilitating visualization and discussion of details among users in different locations.

Augmented Reality (AR):

Anchoring in the Real World:

- Precise overlay of virtual elements in the user's physical environment.
- Correct alignment of virtual objects with their real context.
- Markers and Object Recognition:

Use of visual markers or object recognition to place virtual information contextually and in detail.

Integration of detailed information about products, buildings, or objects through visual recognition.

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Visualization of Contextual Data: presentation of contextual and detailed data about objects in real time, such as technical information, specifications, or related data.

Navigation Assistance: display of navigation cues in the user's field of vision to aid orientation and navigation.

Detailed information about points of interest and destinations in the environment.
Work Instructions and Maintenance:

Providing detailed and animated work or maintenance instructions on physical objects through AR.

Visualization of step-by-step guides for specific tasks.

5 Remote Collaboration, Information Sharing and Collaborative Design

The simulation of processes and environments through virtual reality (VR) and augmented reality (AR) technologies has transformed the way various industries visualize, understand, and make crucial decisions. Firstly, these technologies enable the optimization of industrial processes by allowing the virtual testing of different scenarios, identifying potential bottlenecks, or inefficiencies. This is particularly valuable in sectors such as manufacturing, where assembly lines and production flows can be simulated to improve operational efficiency.

Secondly, virtual simulations offer a safe and realistic environment for training, allowing professionals to practice and refine their skills in fields such as medicine, aviation, and

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manufacturing. Augmented reality, by overlaying digital information onto real-world scenarios, enhances training by providing context-specific guidance for each situation. Furthermore, these technologies are crucial for assessing the environmental impact of projects, visualizing how they could affect the surrounding environment, and supporting informed decisions in areas such as urban planning and sustainable architecture.

Thirdly, simulation in VR and AR is used to plan and rehearse responses to emergencies, from natural disasters to industrial accidents. This allows organizations and response teams to anticipate various situations, improving coordination and preparedness for real crises. Additionally, these technologies contribute to simulating the entire lifecycle of a product, from design and manufacturing to maintenance and final disposal, providing a comprehensive and sustainable view.

In conclusion, simulation in VR and AR not only provides valuable information for decision-making but also enhances operational efficiency, safety, and sustainability across a variety of sectors. From urban planning to workplace training, these technologies are revolutionizing how businesses and professionals approach everyday challenges, fostering more informed and collaborative decision-making.

6 Simulation of Industrial Processes

In the realm of Virtual Reality (VR), diverse applications revolutionize manufacturing, training, and collaborative design. Virtual Manufacturing Environments empower industries by creating digital replicas of manufacturing processes, allowing for comprehensive training and optimization before actual implementation. Assembly Simulation takes this a step further, enabling the visualization and virtual practice of complex assemblies, thereby enhancing operational efficiency and precision in real-world scenarios.

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Fig.6. Virtual Reality improves the ability to manipulate without using real items

Training and Education enter a new era with VR-based Training Simulators, offering immersive experiences for operators, pilots, and medical professionals. These simulators provide realistic scenarios, allowing professionals to hone their skills in handling complex or emergency situations within a safe and controlled virtual environment. The three-dimensional data visualization capabilities of VR extend to Data Analysis, where complex data sets are represented spatially, fostering a deeper understanding and facilitating analysis and decision-making processes.

In the planning and design domain, VR transforms the way spaces are conceptualized. Virtual Tours enable architects and planners to navigate and assess architectural spaces before construction, while Interior Visualization provides a realistic simulation of how building interiors or facilities will look. Project Collaboration experiences a paradigm shift with VR, facilitating Virtual Design Meetings in shared environments and enabling real-time collaborative editing of 3D models and simulations. This convergence of VR technologies

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across industries underscores their transformative impact on training, design, and collaborative processes.

The section discusses the applications of Augmented Reality (AR) across various domains, emphasizing its role in enhancing maintenance processes. In maintenance, AR proves valuable by overlaying maintenance instructions and visual guides directly onto equipment and machinery, simplifying the maintenance process. It also aids in problem detection by using AR to highlight issues or areas of interest in physical environments, contributing to swift issue resolution.

The text further delves into the visualization of contextual data using AR. It describes the overlay of contextual information on physical objects, offering insights into the integration of AR technologies to display real-time data on physical devices. AR is also employed for navigation and orientation, providing cues, routes, and virtual signs in the real world to facilitate navigation and decision-making, showcasing its practicality in diverse scenarios.

Moreover, the narrative introduces Augmented Prototyping and Augmented Parametric Design as applications of AR in rapid design and prototyping. These processes involve creating virtual prototypes on physical objects and adjusting designs in real-time through AR applications, demonstrating the efficiency and flexibility AR brings to design iterations. Lastly, the text touches upon the role of AR in remote collaboration and assistance, allowing experts to collaborate remotely and guide workers through complex tasks using visual overlays.

In a related context, the passage briefly mentions the advantages of simulation in Virtual Reality (VR) and AR across sectors, emphasizing their ongoing evolution to offer more immersive and functional experiences in complex processes and environments. It underscores

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the transformative impact of these technologies on efficiency, safety, and informed decision-making.

In a separate but related discussion, the use of Virtual Reality (VR) in training and orientation for designers and operators in handling additive manufacturing equipment is highlighted. Virtual simulators provide a safe and effective platform for practice before interacting with real equipment, contributing to improved skills and operational readiness. Additionally, immersive visualization in VR is credited with providing a deeper understanding of designs and manufacturing processes, thereby enhancing decision-making and reducing errors in additive manufacturing. The text underscores how VR has fundamentally changed professionals' approaches to creating and producing three-dimensional objects, offering tangible benefits in terms of efficiency, precision, and collaboration.

7 Immersion

Virtual Reality (VR) facilitates an immersive environment that allows designers and manufacturers to visualize 3D models in three dimensions before printing. This not only accelerates the design process but also enhances decision-making by providing a deeper understanding of the geometry and structure of the object to be printed.

Real-Time Process Simulation:

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Fig.8. Example of remote collaboration

VR enables real-time simulation of additive manufacturing processes. By allowing operators to interact with virtual environments, potential issues can be identified, and parameters can be optimized before physical printing takes place. This reduces costs associated with errors and material waste.

Operation Assistance:

Augmented Reality (AR) provides assistance in operating 3D printers by offering real-time information about the machine's status, assembly instructions, and other relevant data. This improves operational efficiency and reduces downtime.

Remote Collaboration and Access to Experts:

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The integration of VR and AR facilitates real-time remote collaboration. Experts can virtually assist in problem-solving, process optimization, and decision-making, regardless of their geographical location.

Value Chain Optimization:

The application of these technologies in the additive manufacturing value chain optimizes the flow from design conception to production. VR and AR become valuable tools that accelerate the product life cycle and improve overall efficiency.

Facilitation of Education and Training:
VR and AR offer virtual training environments, allowing manufacturing professionals to acquire skills and practical experience safely and effectively, contributing to the training of a highly skilled workforce.

The contextualization of the importance of VR and AR in additive manufacturing lies in their ability to optimize processes, improve decision-making, reduce costs, and open new possibilities for innovation in the realm of three-dimensional production. These technologies not only enhance operational efficiency but also drive the evolution of additive manufacturing toward a more advanced and adaptive future.

Augmented Reality

Augmented Reality (AR) has emerged as a key technology in additive manufacturing, offering advanced capabilities that enhance efficiency, precision, and interaction throughout the three-dimensional printing process. Here are the key aspects of applying AR in additive manufacturing:

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Assistance in 3D Printer Operation:

Augmented Reality (AR) provides real-time information about the status of 3D printers, allowing operators to effectively monitor machine operation. Data such as temperature, printing speed, and material level is displayed directly on the printer, improving supervision and facilitating decision-making.

Contextual Data Visualization:

AR offers contextual visualization of data related to additive manufacturing. Users can see relevant information, such as assembly instructions, printing parameters, and alerts, overlaid in the physical environment, simplifying understanding and task execution.

Real-time Inspection and Quality Control:

By overlaying visual information, AR facilitates real-time inspection and quality control during the additive manufacturing process. Operators can identify and correct potential defects immediately, reducing the likelihood of producing faulty parts.

Assembly and Maintenance Guides:

AR is used to provide step-by-step visual guides during the assembly and maintenance of 3D printers. This enhances efficiency and reduces errors by offering clear visual instructions directly on the parts to be assembled or maintained.

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Fig.9. Augmented Reality can allow to manipulate and observe mechanisms easily

Remote Collaboration and Technical Support:

AR enables remote collaboration by superimposing the image of experts in real-time on the operator's field of vision. This facilitates problem resolution and the provision of technical support, even when experts are in different geographic locations.

Visualization of Results Before Printing:

AR enables the visualization of virtual results before carrying out physical printing. Designers and operators can see how the final product will look in its real environment, facilitating decision-making before initiating the manufacturing process.

The effective application of AR in additive manufacturing improves operational accuracy, product quality, and collaboration among teams. From real-time assistance to visual inspection and assembly guidance, AR enhances the three-dimensional printing experience, supporting the continuous evolution of additive manufacturing.

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8 Mixed Reality: Discovering the Future of Immersive Technology

Mixed reality is an innovative technology that combines the physical and digital worlds, providing users with a new level of interaction and immersion.

It combines elements of virtual reality (VR) and augmented reality (AR) to create a seamless environment where users can interact with real and virtual objects in real-time. The virtuality continuum represents the spectrum between the entirely physical and entirely digital, with mixed reality positioned somewhere in between, allowing the coexistence of these two worlds.

Fig.10. Example of Mixed Reality

Advancements in computer vision, graphic processing, visualization technologies, input systems, and cloud computing have made mixed reality more accessible and versatile. This has

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led to the development of various mixed reality devices designed to meet different needs and experiences. The technology and design of these devices have evolved over time with the goal of providing a smooth and intuitive user experience across a wide range of applications.

Mixed reality has diverse applications, including entertainment, education, training, and business. From video games to product design and simulations, mixed reality allows users to immerse themselves in complex scenarios and explore new possibilities in a natural and engaging way. As technology continues to advance, the potential for real-world implementation and the development of mixed reality experiences increases, with developers constantly exploring innovative ways to merge the digital and physical worlds.

Key Points:
- Mixed reality merges the physical and digital worlds, providing users with enhanced interaction and immersion.
- Technological advancements have resulted in various mixed reality devices and applications.
- Mixed reality has potential for diverse real-world implementations, including entertainment, education, and business.

Mixed Reality Devices

In the world of mixed reality (MR), various devices allow users to experience a combination of real and virtual environments. This section covers some of the standout MR devices, including headsets, wearables, HMDs, Hololens, and consoles.

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Headsets

Headsets play a significant role in the mixed reality experience, enabling users to visualize the virtual environment merged with their real surroundings. A popular option is the Windows Mixed Reality headset, compatible with Windows 10 PCs. These devices consist of two main components: the headset itself and motion controllers for interaction with the virtual world. Many headsets also require a USB cable to connect to a PC.

Fig.11. Example of Headset

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Wearables

Wearables, such as smartphones and tablets, can also provide mixed reality experiences through the use of specialized applications and sensors. These devices often use cameras for tracking and projecting virtual objects onto the real world. While not as immersive as headsets, portable mixed reality devices offer greater flexibility and accessibility, as many users already own smartphones that can support these applications.

Fig.12. Example of Wearables

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HMD (Head Mounted Display)

A head-mounted display (HMD) is a type of wearable device that projects images and information into the user's field of vision. HMDs are commonly used in mixed reality experiences, with devices like Microsoft HoloLens providing both immersive visualizations and interactions with virtual content. HMDs often include integrated motion tracking and gesture recognition for more natural navigation and control within the mixed reality environment.

Fig.13. Example of HMD

Consoles

Mixed reality experiences can also be enjoyed through gaming consoles, such as Xbox or PlayStation systems. These consoles can be paired with various MR-compatible headsets and controllers to provide an immersive gaming experience. While not as common as PC-based mixed reality, console-compatible MR is growing in popularity with the increasing prominence of virtual and augmented reality technologies.

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Fig.14. Example of interaction with mixed reality

By understanding the different types of mixed reality devices available and their unique features, users can choose the best solution to meet their needs. From headsets and wearables to HMDs, and consoles, there are many options to explore and enjoy mixed reality environments.

9 Programming and Software in Virtual Reality and Augmented Reality

Programming and software are essential elements that drive the creation of immersive experiences in the field of Virtual Reality (VR) and Augmented Reality (AR). Both technologies, although distinct in their approaches, share the need for specific tools and programming skills to carry out successful projects.

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Virtual Reality (VR):

In the development of Virtual Reality applications, programmers rely on integrated development environments (IDEs) such as Unity or Unreal Engine. These platforms offer a robust set of visual tools and predefined components that simplify the creation of immersive three-dimensional environments. Commonly used programming languages include C# for Unity and C++ for Unreal Engine. Programming for VR involves managing interactivity, user navigation, and application logic, using concepts such as VR scripting to control the behavior of virtual objects. Additionally, VR programming often includes performance optimization to ensure a smooth and latency-free experience.

In addition to the programming component, software for VR encompasses design and 3D modeling tools. Software such as Blender or Autodesk Maya allows developers to create realistic three-dimensional models that will be an integral part of the virtual experience. Similarly, the VR development process involves audio integration and the implementation of intuitive user interfaces to enhance user immersion.

Augmented Reality (AR):

In the case of Augmented Reality, programming focuses on overlaying digital information onto the physical environment. Frameworks such as ARKit (for iOS devices) and ARCore (for Android devices) provide tools and APIs that facilitate the integration of virtual elements into the real world. Developers use languages such as Swift for iOS or Java/Kotlin for Android, adapting to specific platforms. AR programming involves a precise understanding of the device's real-time position and orientation, enabling the accurate placement of virtual objects in the physical environment.

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AR software also includes specific design tools that allow the creation and optimization of digital content to overlay onto the real world. AR design is a meticulous process that requires special considerations for scale, lighting, and interaction with real-world objects. The use of 3D modelling software, along with rendering engines, contributes to the creation of visually appealing and consistent AR experiences.

Collaboration and Agile Development:

In addition to programming and design, the VR and AR development process involves collaboration and project management. Source code management platforms, such as GitHub, are essential for facilitating collaboration among team members and enabling continuous integration in the development of these immersive applications. Agile software development methodologies align well with virtual and augmented reality projects, allowing for rapid iteration and effective response to changes and feedback during development.

Conclusion:

In summary, programming and software play crucial roles in creating engaging experiences in Virtual Reality and Augmented Reality. From choosing development environments to implementing realistic 3D designs and efficiently managing source code, a comprehensive approach ensures success in materializing projects that transform the way we interact with the digital and physical reality.

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10. Summary and comparison between technologies

Features	Augmented Reality	Virtual Reality
Definition	Overlays digital and visual information onto the real world.	Creates a completely new and artificial virtual environment.
Device used	Mainly mobile devices, screens, cameras, making it more accessible. AR can also be experienced through AR glasses.	Always requires devices such as VR glasses, VR headsets, motion tracking devices.
Interaction	Interaction with both the real world and virtual objects.	Interaction only with virtual objects in a virtual world.
Cost	Less expensive technology. Affordable solutions are available for any company and user.	Requires a much higher investment.
Applications	Advertising, marketing, gaming, education, navigation, medicine, construction, architecture, retail, industry, tourism, sports, events, culture, e-commerce, and more.	Video games, training simulation, entertainment experiences, design and prototyping, psychotherapy, occupational therapy, among others.
Visualization and Sharing	Allows sharing the same experience with other users in the same physical space.	Does not allow sharing the same experience with other users in the same physical space.

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Comfort	Can be worn for longer periods without causing visual fatigue or dizziness.	May cause visual fatigue or dizziness after short periods of use.
Limitations	Requires a well-lit environment to function properly.	Requires a spacious and well-lit space to avoid collisions with physical objects.
Level of immersion	Offers a partial level of immersion, meaning the experience feels like virtual objects are overlaid onto the real world.	Offers a total level of immersion, meaning the experience feels like the user is inside a completely new virtual world.
Learning	May be more intuitive for users, as it is based on real-world objects and overlays relevant information.	May have a steeper learning curve, as users need to learn to navigate and manipulate objects in a new virtual environment.
Accessibility	Much more accessible since nowadays everyone has a mobile phone to consume an AR experience.	Less accessible for all users as different specific devices are required.

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