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THE EFFECT OF BOWING TECHNIQUE ON VIOLIN SOUND

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Abstract: By the bowing of a violin especially by folk and gipsy bands a special bowing technique can be observed. Often a diagonal (not perpendicular to the string) bowing, resp. the bow slids onto the fingerboard. This study deals with the effect of this special bowing technique on the emitted sound of a violin and compares it with the classic detaché bowing technique on all four strings.

Keywords: *bowing technique, sound measurement, Total Harmonic Distortion, inharmonicity, frequency spectrum, sharpness, roughness*

1. INTRODUCTION, MOTIVATION

Watching folk bands play, it is obvious that the violin has a leading role in their playing. Therefore, the attention is directed to the violinist – let he/she be the lead or the soloist. There is a large amount of literature on correct bowing techniques. The main thing is, among other things, that the bow should run between the bridge and the fingerboard, perpendicular to the strings as shown in Figure 1, which was recorded at real performances.

Figure 1. *Analysing methods of fatigue behaviour*

Having listened to and observed several performances by folk bands and gypsy bands, the violinist and the viola players who played the accompanying parts, this method of conducting the bow was different. Mostly the location of the bow was not perpendicular or nearly perpendicular to the strings, but inclined and slid onto the fingerboard (sul tatso) as this can also be seen in Figure2.

Figure 2. *Bowing on the fingerboard (sul tasto)*

Perhaps it is not by chance that among the first fiddlers of a gipsy band who graduated from the College of Music or University, bowing was much more disciplined. These observations encouraged us to carry out the following tests, namely whether the oblique bowing or a possibly string sliding to the end of the fingerboard, causes a tonal difference.

In general, several other investigations were performed by other authors regarding to the classification of violin sound, among others the classification of bowing techniques too. Alar et al (Alar, Mamaril, Villegas, & Cabarrubias, 2021) investigated five types of bowing techniques, detaché, double stops, Ricochet, legato, spiccato and they introduced a model based on a convolutional neural network which determines the played sound and classifies it. The proposed model can help new violin players to understand each technique better.

Maestre et al (Maestre, Blaauw, Bonada, Guaus, & Perez, 2010) investigated bowing control techniques, how could they be applied to artificial violin sound synthesis. They included to the work different bowing parameters, like the temporal contour of bow velocity, bow pressing force, and bow-bridge distance. With the help of considering these parameters in the synthesis synthetic contours could be generated through a bow planning algorithm.

Su et al (Su, Lin, & Yang, 2014) studied several violins and collected 33 bowed single tone samples. They used new approach, instead of state-of the art time and frequency domain methods, they extracted from the magnitude spectra and phase

derivatives, including group delay function (GDF) and instantaneous frequency deviation (IFD). This approach led to significantly better performance of understanding bowing techniques.
Wang et al (Wang, Lostanlen, & Lagrange, 2023) studied also convolutional neural network in the time–frequency domain and investigated the classification of five comparable real-world playing techniques from 30 instruments spanning seven octaves. They found that relevant regions around the modulation rates of the playing techniques regardless of the pitch could be localized which are highly relevant to the technique.
We can state that the diagonal bowed technique was not investigated and compared with other ones until now, so this highlights also our intention for the investigations.

2. THE ROLE OF THE VIOLIN IN MUSIC

If we want to highlight the importance of the violin in one word, we can only say that it is indispensable, it should be featured as a solo instrument, e.g. J. S. Bach, N. Paganini, and its orchestral literature is endless. With this instrument you can express every feeling of life. It is no coincidence that a whole series of excellent violinists could be listed. The orchestral role of the instrument cannot be avoided, it has a prominent role, perhaps it is no coincidence that they are located on the left side of the conductor's heart.

3. DESIGN OF THE VIOLIN AND THE WAYS OF MAKING IT SOUND

The violin is the highest-tuned and smallest member of the violin family of stringed instruments, with strings pitched 4 fifths apart (G-D-A-E). The group also includes the bass violin, or more commonly known as the viola, the cello and the double bass The lowest string (which is the lowest note that can be played on the violin) is the minor G, followed by the single-line D, single-line A, or two-line E strings. Violin scores are written in treble clef (also known as G-clef). The structure and parts of the violin are shown in Figure 3.
The strings alone are not enough to hear the usual sound from the violin. A violin sound is obtained if the instrument has a designed body (cavity resonator), which amplifies the overtones and determines the direction of the radiation too. The string and body are usually rigidly connected but can also be air-coupled. The important part, the so called "soul", is not fixed by glue to the body of the violin it is only clamped inside between back and front side of the violin. Its placement is crucial for the timbre. If there would not be a soul inside, the violin will sound like a guitar when bowed.

In addition, the tailpiece performs the coupling between the vibration of the string and the vibration of the body. The purpose of the tailpiece is to take as much energy from the string and transfer it to the body so that the radiation remains uniform. But there should be enough energy left on the string so that with a constant bow, the constant vibration remains on it. In the best case, with a small violin, even with a little effort, you can play a sound equivalent to the volume of an entire orchestra! (This "small" energy investment means that with 1% efficiency, 99% is converted into heat; but to achieve the same volume, the opera singer does ten times as much work).

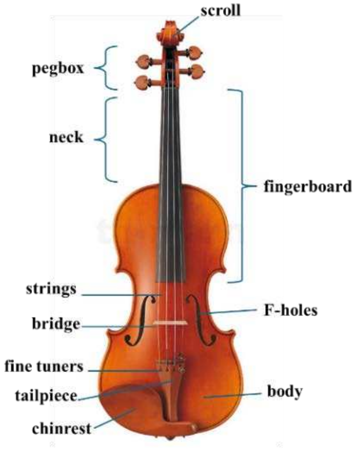


Figure 3. *Cantilever Beam*

With strings, it is difficult to control the timbre, which results from the sawtooth-like excitation of the string. By increasing the bowing speed, the vibration amplitude (and volume) of the string can be increased. By increasing the bowing force (bow pressure), only the timbre (vibration shape of the string) can be influenced, not the intensity. Pulling the string close to the foot also requires a larger bowing force. Under a minimum bowing force, no musical sound is produced. To bow a thicker string, more force (pressure) is required, therefore instruments with thicker strings have a shorter bow.
The bowing force changes the intensity distribution of the overtones, a higher force emphasizes higher overtones and suppresses lower ones - without changing the overall energy, so the musician may mistakenly perceive that he has (also) increased the intensity with the bowing force, but only he perceives this, the audience no longer.

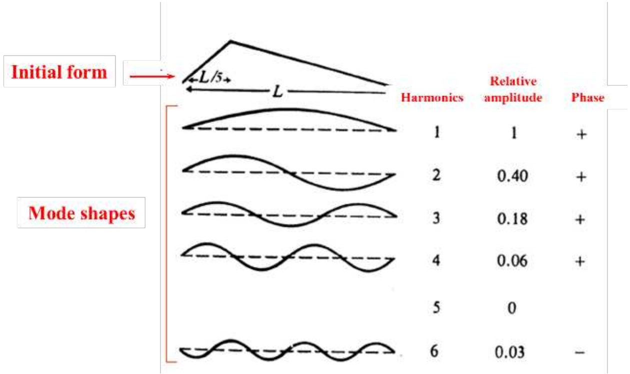
According to the Hornbostel-Sachs classification, the violin has the identification number 321.322-71. The first three numbers show that it belongs to the family of chordophones (3), compound chordophones (32) and lutes (321). Another three numbers refer to the construction of the violin, i.e. lute with handle (321.3), neck lute (321.32), or box-tie (321.322). The last two digits of the Hornbostel-Sachs classification refer to the method to cause the strings to vibrate: by bowing (321.322–7) and using bow (321.322–71).
From the point of view of the present study, these two latter are important, since our goal is to present the effect of a certain way of string bowing technique on the created acoustic experience. In accordance with these, the violin strings were bowed in several ways: with normal and high pressure, as well as by pulling the string diagonal (oblique).

4. THE PHYSICS OF VIOLIN SOUND

Being a chordophone (stringed) instrument, the basic tone of the violin is produced by making the strings to vibrate. Strings are elastic fibres that have negligible diameter compared to their length, clamped and stretched at both ends, and can vibrate in three ways: transversal, longitudinal and torsional. The main mode of vibration is transverse, and when excited, the string performs several different vibrations, the frequencies of which are given by Mersenne's law in Equation 1 (Beyer, 1999).

$$f = \frac{n}{2L}\sqrt{\frac{F}{Aq}} \qquad (1)$$

where n represents a series of integers (n=1,2,3 ...), L is the length of the string, F is the tension force, A is the cross-sectional area of the string and ρ is the density of the string material. The amplitude, starting phases and timbre of the individual natural vibrations are also determined by the initial state (shape and speed) of the string. Depending, for example, on where a string is bowed (between the two clamped ends at the halfway point, at the third, at the fifth), the given harmonics and their integer multiples may be missing from the spectrum (Figure 4).
Of course, the violin is typically not played by picking, however, the presence of individual harmonics in the spectrum is similar when playing with a bow. The aim of our study is therefore to be able to make a measurable difference between violin sounds played with different bowing techniques. For this, we perform measurements and evaluate the measurement results using different methods, and then select the method that seems most suitable for comparing the quality of violin sounds.



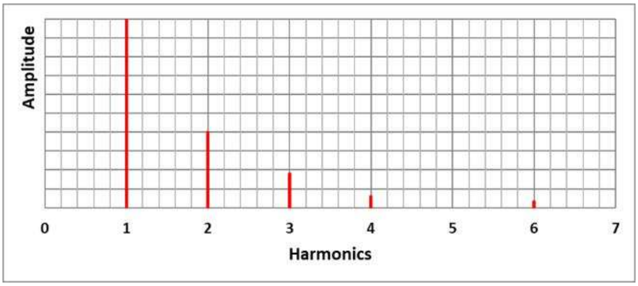


Figure 4. *Vibrations and theoretical spectrum of a string picked at the fifth of the length*

5. Structure and Execution of the Measurement

The string treatment methods can be compared in the simplest way if the violin strings (A, D, E, G) are bowed with the desired bowing technique, and the sounds emitted at that time are recorded, then the recorded sounds are subjected to acoustic analyses and the results are compared.

To make the recordings, we used a room that is free from disturbing reflections, and the external disturbing noises do not enter the room either. For this purpose, the (semi-) anechoic chamber of the Institute of Machine and Product Design of the University of Miskolc proved to be the most suitable. The four walls and the ceiling of the measuring room (except for the spy window) are covered with material that absorbs sound waves. The floor is covered with sheet steel. With this arrangement, e.g. we can also determine the sound power of machines and equipment based on the relevant standards (e.g. EN ISO 3741).

To record the sound, we placed 2 pieces B&K 4189 type free field microphones in 15 cm distance, approx. at 1 m distance from the violin, and 1.2 m distance from the floor. We did not consider it necessary to use a wind sponge, as there was no air circulation in the room. The data was recorded with a 4-channel B&K Photon+ data recorder. During the measurements, only the violinist was in the room (Figure 5), the person performing the measurements was in the adjacent observation room.

Figure 5. *The measurement setup in semi-anechoic chamber*

6. PRESENTATION AND ANALYSIS OF MEASUREMENT RESULTS

Time domain investigations

The duration of the measurements fell between 35 and 50 s, during which time we recorded 5 to 6 cycles (1 cycle = 1 pull and 1 tow phase of the bow) with the same bowing technique. These were repeated with all three investigated bowing techniques for all 4 violin strings. The time signals were processed with free audio editing software Audacity and GNU/Octave. Figure 6 shows the time signals related to the A-string as an example. It should be noted that the raw time signals were converted to *.wav format for further processing, so the real amplitude values (sound pressure) cannot be interpreted, they are lost. However, the relation of the individual amplitudes to each other remains.
The shapes of each cycle are visibly different, both in form and amplitude. The middle diagram of Figure 6 shows the sound of playing with the highest bow force. Its amplitude is expected to be the largest. We cannot determine much more than this from the shape of the time signals, so additional procedures and methods are needed. We will first examine some psychoacoustic metrics (Genuit, 2010) used to describe the nature and psychological effects of noise.

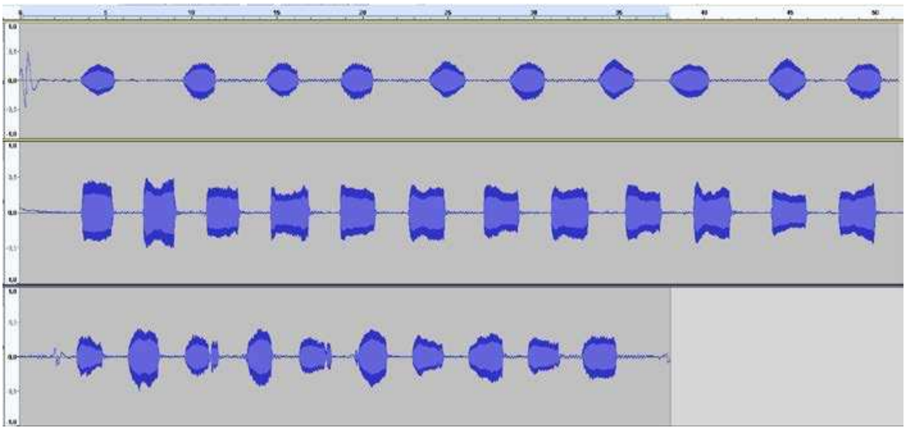


Figure 6. *The time signatures for the A string on the left channel (top: low force; middle: high force; bottom: transverse)*

The first is loudness, which is the subjective perception of sound pressure. The study of perceived loudness belongs to the field of psychoacoustics and uses the methods of psychophysics. According to Stevens' definition, 1 sone loudness corresponds to a loudness level of 40 phons (1 kHz sound at a sound pressure level of 40 dB) and is a quantity that characterizes the feeling of loudness.

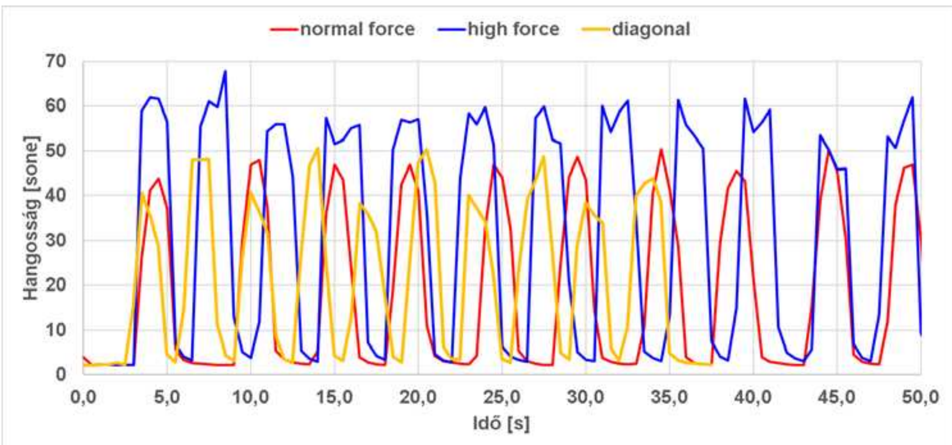


Figure 7. *Development of the loudness values (according to Zwicker) during the playing of the A string*

Figure 7 shows that the loudness of the A sound produced during the high force bow is indeed the highest, while in the other two cases their value is similar.

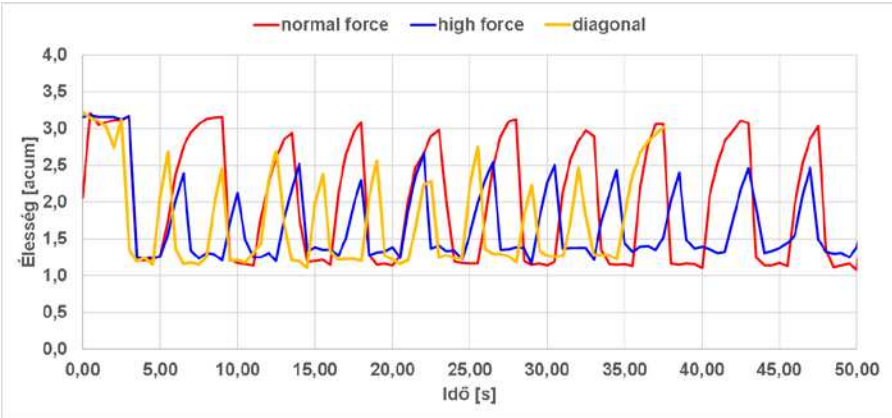


Figure 8. *Development of the sharpness values during the strumming of the A string*

Figure 8 shows that the acoustic sharpness during the three types of bows does not essentially differ from one another. In relation to the figure, it should be noted that, in contrast to the curves in Figure 7, the higher values are in the bow breaks, so the lower values must be taken into account.

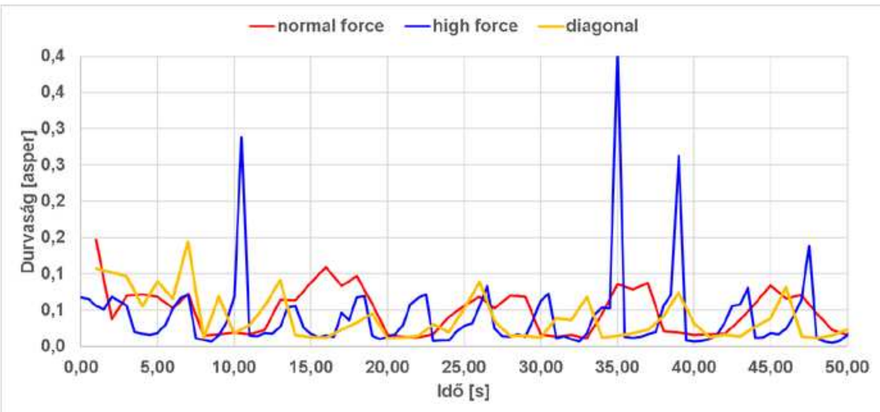


Figure 9. *Development of the sharpness values during the strumming of the A string*

Figure 9 shows that the acoustic roughness during the three types of sounding is essentially no different from each other, or their value is very low. Of course, this was to be expected due to the nature of the sound. In relation to the figure, it should be noted that, in contrast to the curves in Figure 7, the higher values are in the stroke breaks, so the lower values must be considered from the point of view of the analysis. In summary, it can be said that the analysis of psychoacoustic measures is only limited or not at all suitable for clearly distinguishing the bowing techniques.

Frequency domain investigations

For further processing, we cut out the relevant time periods from the time signals according to Figure 6 and converted them individually to the frequency domain using the FFT transformation (Fast Fourier Transformation). The average spectra obtained in this way are shown in Figure 10 on the example of the A-string. The display range is 200 – 20000 Hz. The diagrams clearly show the fundamental tone of the A string at 441 Hz and the large number of harmonics, which, together with the fundamental tone, result in the unique sound of the bowed violin. Of course, not only the string played contributes to the timbre of the sound, but also the design of the instrument body, the materials used, and the method of production. Also, we must not forget about the design of the bow, the materials used for it, or nor about bowing technique.
At first glance in Figure 10, there is not much difference between the spectra. In the range from 200 to 20000 Hz, we see many peaks. In all three cases, the individual peaks have roughly the same amplitude up to about 7000 Hz, although in the case of high force bowing, the fundamental harmonic has the highest value of all three. Above 7000 Hz, the peaks of the middle spectrum (the high force bowing) are higher compared to the other two spectra.
Another feature that can be noticed in the spectra is that some non-integer harmonics appear in the middle and lower spectra, i.e. the 1.5th, 4.5th, 7.5th, 10.5th, 13.5th harmonics. Comparing the amplitudes of these non-integer harmonics, we can see that they are approximately 25% higher in the case of diagonal bowing. Our task is therefore to quantify these differences for a more accurate analysis.
Electroacoustic devices can be characterized by specifying the value of total harmonic distortion (THD): the ratio of harmonics appearing at the output of amplifier relative to the fundamental harmonic. For such devices, it is desirable that the amplitude of the harmonics be small compared to the amplitude of the fundamental harmonic, since the amplifier's task is to transmit the input signal without converting it. The relevant literature considers a THD value above 1% undesirable for amplifiers.

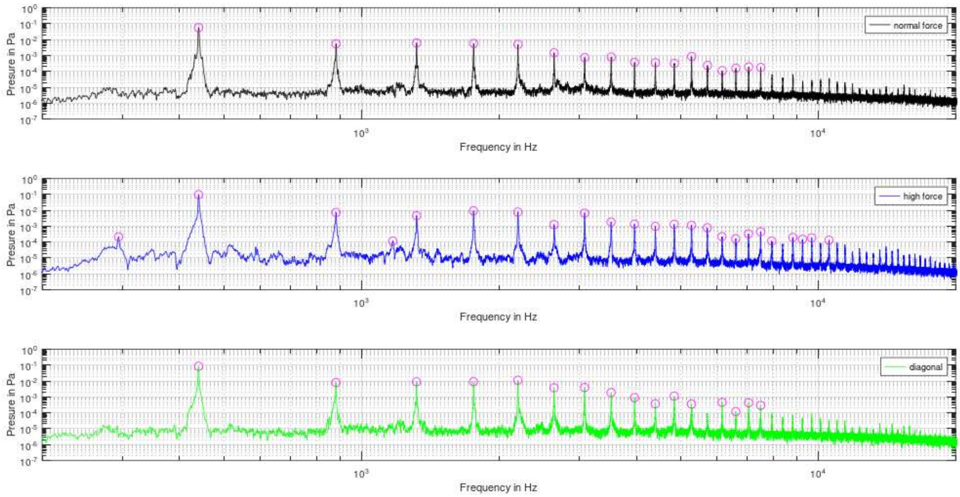


Figure 10. *Frequency spectra for the A string*
(top: low power; middle: high power; bottom: transverse)

In the case of a music instrument, of course, it is not desirable that only the fundamental harmonic emitted by the instrument should appear. Because of the presence of harmonics, we can distinguish between instrument sounds, so a kind of THD increase is necessary. THD can be used to quantify the difference between instrument tones using even number and odd number harmonics. THD can be calculated using the following equation:

$$THD = 100 \cdot \frac{\sqrt{p_2^2 + p_3^2 + \cdots p_n^2}}{p_1} \; [\%] \qquad (2)$$

where p denotes the amplitude of the sound pressure measured by the microphone in Pa.

To perform the THD calculations, we used the previously mentioned spectra as a basis (Figure 8), and to perform the operations, we created a GNU/Octave program. It reads the spectra as ASCII files, finds the peaks of the spectra (indicated by purple ◊'s on the peaks in Figure 8) and calculates the THD based on the peak values found. After completing the calculations, we get the following percentage values of THD for the A string

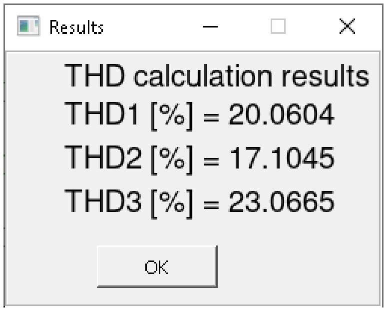
normal bow (THD1)	
high force bow (THD2)	
diagonal bow (THD3)	

Figure 11. *Results of the THD calculations*

It can be seen from the results that a clear difference can be established between the THD values of the bowing techniques. Taking the value of normal bowing as a reference value, bowing with high force means a decrease in THD value of about 15%, while diagonal bowing results in a 15% increase in THD. The former can be explained by the fact that the higher bowing force dampens some of the harmonics, and the latter by the appearance of additional harmonics. We have already described the latter in connection with odd number of harmonics.
Next, we examine the inharmonicity of the overtones. Musical inharmonicity shows the deviation of the components of a spectrum from the harmonic. Accordingly, the lines of the inharmonic spectrum are not equal, i.e. the frequencies of the overtones are not exactly integer multiples of the fundamental tone. The sound spectrum of ideal vibrating media (e.g. ideal vibrating string, ideal vibrating air column) serving as a model for some musical instruments is harmonic, but real instruments usually show inharmonicity (Murray, 2021). If the spectrum shows a small deviation from the harmonic (e.g. for piano, guitar and strings), then many listeners perceive it as close to harmonic, and inharmonicity affects the roughness of the sound. In other cases, the partial tones are scattered in the soundscape, not close to the frequencies corresponding to the harmonic, in which case, when a musical note is played, in some cases, the sensation of several separate sounds occurs at the same time (for example, percussion instruments with wooden or metal soundboards). In the extreme case, if the components are densely arranged in the inharmonic soundscape.
So, let us examine the magnitude of the inharmonicity for the case of the 3 types of string treatment. The results are shown in Table 1. The table's ref. column marked shows the theoretical base and harmonics of the 441 Hz sound A. The normal, high, and diagonal columns show the frequencies of the fundamental and harmonics of the tone A excited with three types of bowing.

Table 1
Comparison of inharmonicity in the case of different bowings techniques

	Ref	normal	Δf to ref	high	Δf to ref	diagonal	Δf to ref
Nr.	*Hz*	*Hz*	*Hz*	*Hz*	*Hz*	*Hz*	*Hz*
1.	**441**	**441**	*0*	**441**	*0*	**441**	*0*
2.	**882**	**881**	*-1*	**881**	*-1*	**881**	*-1*
3.	**1323**	**1322**	*-1*	**1322**	*-1*	**1321**	*-2*
4.	**1764**	**1762**	*-2*	**1761**	*-3*	**1761**	*-3*
5.	**2205**	**2203**	*-2*	**2201**	*-4*	**2202**	*-3*
6.	**2646**	**2643**	*-3*	**2642**	*-4*	**2642**	*-4*
7.	**3087**	**3083**	*-4*	**3081**	*-6*	**3082**	*-5*
8.	**3528**	**3524**	*-4*	**3522**	*-6*	**3522**	*-6*
9.	**3969**	**3965**	*-4*	**3962**	*-7*	**3962**	*-7*
10.	**4410**	**4405**	*-5*	**4402**	*-8*	**4400**	*-10*
11.	**4851**	**4846**	*-5*	**4842**	*-9*	**4842**	*-9*
12.	**5292**	**5286**	*-6*	**5282**	*-10*	**5282**	*-10*
13.	**5733**	**5726**	*-7*	**5722**	*-11*	**5722**	*-11*
14.	**6174**	**6166**	*-8*	**6159**	*-15*	**6163**	*-11*
15.	**6615**	**6607**	*-8*	**6601**	*-14*	**6603**	*-12*
16.	**7056**	**7047**	*-9*	**7041**	*-15*	**7043**	*-13*
17.	**7497**	**7488**	*-9*	**7482**	*-15*	**7482**	*-15*

The columns next to them show the deviations compared to the values in the reference column. An inharmonicity can be observed even in the case of the A note played with normal pulling force, which reaches 8-9 Hz in the case of higher frequency harmonics.

This difference is even higher than the other two sounding modes, reaching a value of 15 Hz. In these two latter cases, however, the differences are essentially the same. It can be concluded that the diagonal string treatment increases the inharmonicity, but compared to a strong string, this does not justify the unpleasant acoustic experience.

7. SUMMARY AND CONCLUSION

Our investigations showed that the finding of differences between the bowing techniques is a tough undertaking despite of the subjective clearly audible differences. Time and frequency domain methods were investigated and as a result we can state that the frequency domain method based on the THD is capable to describe the differences in form of quantitative and qualitative numerical values. The results are very similar for the other G, D, E strings too. Nevertheless, the extension of our investigations is planned to investigate other methods, such as autocorrelation, wavelet, Cepstrum, etc. to achieve more accurate distinguishing.

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INDUSTRY 5.0. PRESENT OR FUTURE?

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Abstract: Industry 5.0 represents a significant evolution in industrial development, building upon the technological foundations of Industry 4.0. Highlighting human-centric and sustainable approaches, Industry 5.0 aims to integrate human creativity and technology seamlessly. While previous industrial revolutions were marked by technological advancements –such as steam engines, electricity, and digital transformation– Industry 5.0 emphasizes the synergy between humans and machines. This collaboration is expected to drive production efficiency and ethical practices in industry, creating a more resilient and human-focused future. This paper investigates the need of education systems to prepare the students to i5.0.

Keywords: *Industry 5.0, Industry 4.0, sustainability, collaborative robots (cobots), AI, autonomous vehicles, human-machine interactions*

1. INTRODUCTION

The term Industry 5.0 was adopted by the European Commission in its white paper Industry 5.0 – Towards a sustainable, human-centric and resilient industry, published in January 2021.

According to the scientific approach, previous industrial revolutions were provoked by the introduction of one or more new technologies, each of which brought about a radical paradigm shift in industrial production. Accordingly, however, the described elements of industry 5.0 are based on the same core technologies as industry 4.0. Therefore, it should rather be seen as a complementary concept to Industry 4.0. The most significant distinction between Industry 5.0 and its predecessors is its emphasis on the human element.

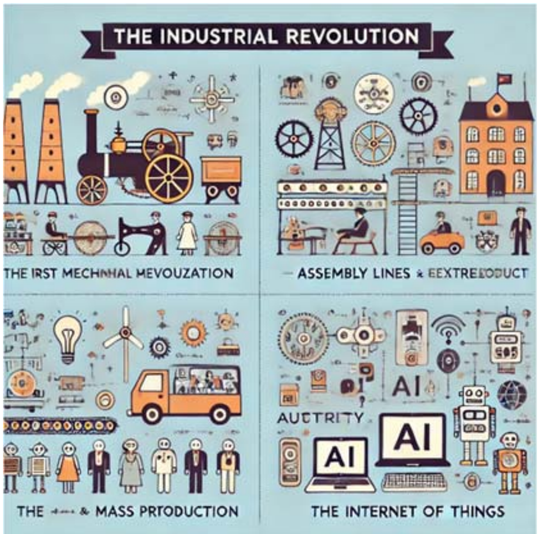

Figure 1. *The first four industrial revolutions*

The four industrial revolutions shown in Figure 1 can be described as follows:

- ***The first industrial revolution*** (late 18th century): Characterised by the appearance of steam engines and textile machinery. This era began with the transformation of manual production into machine production, with the steam engine at its heart. Agricultural societies became industrial societies.
- ***Second industrial revolution*** (late 19th century - early 20th century): Characterised by electricity and the spread of mass production. Assembly lines, electricity and new materials (e.g. steel) revolutionised manufacturing, enabling large-scale production.
- ***Third industrial revolution*** (mid to late 20th century): Created by the arrival of computers, automation and information technology. More and more processes in industry were automated and computer-controlled machines appeared, increasing efficiency.
- ***Fourth industrial revolution*** (21st century): Characterised by digital transformation, artificial intelligence (AI), robotics and the Internet of Things (IoT). Integration of smart technologies, automation at a higher level and acceleration of industrial production's entry into the digital world.

These industrial revolutions led to significant social and economic changes.

Industry 5.0 is a new stage of development that follows the digital revolution of Industry 4.0. While Industry 4.0 is based on automation, robotics and the Internet of Things (IoT), Industry 5.0 aims to create harmony between people and technology, emphasising human creativity and value. Human-machine collaboration will take production to a new level, bringing technology and ethics to the forefront (Breque, De Nul, & Petridis, 2021).

2. KEY FEATURES OF INDUSTRY 5.0

- ***Human-machine collaboration:*** Industry 5.0 aims to take human-robot collaboration to a higher level, where machines support, but do not replace humans. The focus is on the creativity and problem-solving abilities of humans, while machines perform repetitive, monotonous tasks.
- ***Custom production:*** in the era of Industry 5.0, the focus will be on the production of individual, customised products.
- ***Sustainability:*** The focus of technology is on reducing environmental pressures and using resources more efficiently.
- ***People-centric:*** People are at the centre, not only as employees but also as individuals who contribute to the production process based on their personal values and skills.

Industry 5.0 therefore envisions a future where technology does not replace people, but supports them, enhancing innovation and sustainability. The theory of Industry 5.0 is already being manifested in practical applications. Some examples are presented in relation to the four main characteristics.

Human-machine interaction

- Cobots: Companies such as Universal Robots and Kassow Robots are developing collaborative robots (cobots) that work directly with humans on production lines. These robots can safely manage complex tasks in close proximity to humans, such as precision assembly.
- BMW production lines: cobots are used in BMW car factories to carry out heavy lifting and repetitive tasks, while human workers concentrate on more sophisticated, highly demanding jobs (Schillmoeller, 2024).

Customized production

- Nike and Adidas - custom shoe production: Nike and Adidas have introduced systems that allow customers to design custom shoes, which the companies quickly produce to order. Automated systems help to provide the flexibility of mass production while tailoring products to individual needs (Condliffe, 2017).
- 3D printing: General Electric is using 3D printing in the aerospace industry to produce custom parts, reducing production time and costs. 3D printing allows for customized solutions in manufacturing.

Sustainability

- Siemens - smart energy systems: Siemens has developed smart grid solutions that optimise energy production and distribution, enabling sustainable energy management in factories. Smart systems help to improve the energy efficiency of manufacturing processes and reduce emissions.
- Tesla Giga Factory: the Tesla Giga Factory is fully based on renewable energy sources, and the batteries produced there will help the uptake of electric vehicles, which will reduce the use of fossil fuels in the long term (Peters, 2019).

Human centricity

- Toyota - Lean Manufacturing Philosophy: Toyota's manufacturing system, which is based on the development of human workforce and continuous improvement (Kaizen), can be seen as a forerunner of Industry 5.0. Here, workers play a major role in optimising production processes and the company places a strong emphasis on the use of human capabilities.
- Ericsson - developing human capabilities: some of Ericsson's industrial projects in the telecommunications sector focus on developing human creativity and problem-solving capabilities, particularly in innovative approaches to the development and use of technology.

These industrial examples show that the Industry 5.0 process is already here, supporting the human-centred development of technology alongside sustainability and customisation. Autonomous vehicles are a typical manifestation of Industry 5.0.

Here, the human instructs, but the machine, car, on the basis of current measurement data and Internet sources, chooses the direction and achieves the desired destination (Torok, Derenda, Zanne, & Zoldy, 2018), (Beza, Maghrour Zefreh, & Torok, 2022), (Alatawneh & Torok, Potential autonomous vehicle ownership growth in Hungary using the Gompertz model, 2023), (Alatawneh & Torok, 2023).
Another increasingly used area of Industry 5.0 is the additive manufacturing technology, which can produce any kind of geometric shape, even bionic or organic, through generative design supported by artificial intelligence (Takács & Albert, 2024), (Takács & Aghakhani, 2023). With this manufacturing technology, even in an office environment, we can produce one-at-a-time customised parts without designing and manufacturing tools. This is a perfect example of customised, sustainable manufacturing, while maintaining the human-machine relationship, where humans are assigned higher-level design and production planning tasks. In such tasks, for example, production parameters and settings can have a significant influence on the final result, on the product (Dömötör, 2023), (stratasys, 2024).

3. THE EXPECTED ADVANTAGES AND DISADVANTAGES OF IMPLEMENTING INDUSTRY 5.0

Implementing Industry 5.0 can be beneficial in many ways, but it also brings challenges and difficulties.

Advantages

- Harnessing human creativity: one of the key benefits of Industry 5.0 is that it highlights the creativity and problem-solving skills of the human workforce, while machines take over repetitive tasks. This increases job satisfaction by allowing workers to focus on more valuable, innovative tasks.
- Tailored production: Consumers are increasingly demanding personalised products. Industry 5.0 makes manufacturing processes flexible, allowing for customised production while maintaining the efficiency of mass production. This can increase competitiveness and market share.
- Sustainability and green technologies: Sustainability is at the heart of Industry 5.0. Smart energy use, green technologies and resource optimisation can reduce environmental impact. This will make industrial processes not only more economically efficient, but also more environmentally friendly.

- Increased competitive advantage: Collaboration between machines and people, integration of digital technologies and automation will increase productivity. Companies can respond more quickly and efficiently to changing market conditions, while introducing new, innovative products and services.
- Better working environment: A human-centred approach can improve the working environment and make people feel safer. Cobots can help perform accident-prone or tiring tasks, reducing workplace stress and improving employee well-being.

Disadvantages and difficulties

- High start-up costs: implementing Industry 5.0 can require significant investment, especially for new technologies such as robotics, artificial intelligence, IoT and the deployment of digital systems. This can be a challenge for smaller companies, as initial capital requirements can be high.
- Reskilling the workforce: Industry 5.0 requires new skills, particularly in digital technologies and automation. Workers need to be retrained to interact with robots and use new systems. This is not only time-consuming and costly but can also create resistance among workers.
- Technology dependency: Industry's heavy reliance on 5.0 technology also brings with it the risk of system disruption. If automated systems malfunction or fail, it can cause severe production downtime, impacting productivity and company revenues.
- Data protection and cybersecurity: the increasing use of digital technologies also brings cybersecurity risks. Data protection compliance and the protection of sensitive data will be critical, especially for IoT and AI systems. Addressing cybersecurity challenges can add cost and complexity.
- Social and labour market impacts: Although Industry 5.0 relies on the interaction between human labour and technology, automation may lead to job losses. This may particularly affect low-skilled workers, who risk being excluded from the labour market.

Industry 5.0 offers many advantages, especially in terms of customised production, sustainability and leveraging human creativity. However, high deployment costs, technological dependency and retraining of the workforce can pose challenges.

Nevertheless, this direction of industrial development is likely to be essential for future competitiveness and sustainability.

It should be noted that most of the disadvantages listed here are already present in the implementation of Industry 4.0, so they would not pose additional difficulties and challenges in moving on from it.

4. INDUSTRY 5.0 IMPLEMENTATION REQUIREMENTS

The introduction of Industry 5.0 requires extensive preparation by industrial companies and society. A number of technological, economic and human factors are prerequisites without which the effective implementation of Industry 5.0 cannot be achieved.

Prerequisites:

- Advanced technology infrastructure:

Artificial intelligence (AI) and machine learning: in Industry 5.0, machines not only perform automatic processes, but can also learn from databases. Advanced AI systems are therefore needed to support the optimisation of manufacturing processes and collaboration with robots.

IoT (Internet of Things): Stable, fast data connections are needed to link production lines, sensors, robots and other systems.

5G network: A high-speed, low latency 5G network is essential for real-time data processing and communication between devices connected to the network. 5G will ensure continuous connectivity of production systems and fast data transfer.

Cloud-based systems and computing: Cloud computing enables companies to access data quickly, optimising production and inventory management.

- Reskilling and upskilling of human resources:

To implement Industry 5.0, workers need new skills, particularly in digital technologies, robotics and data processing. Companies need to invest in ***reskilling*** their employees to enable people to work effectively with collaborative robots (cobots) and other intelligent systems.

Soft skills: Industry 5.0 requires a creative, problem-solving mindset and a willingness to innovate. Educating people is not only necessary for technical skills, but also for teamwork, creative thinking and adapting to change.

- Organizational change:

In order to ensure the successful implementation of Industry 5.0, it is essential that companies ***adapt*** their ***approach*** to align with the key principles of collaboration

between people and machines, flexibility and innovation. This necessitates a transformation of corporate hierarchies and the adoption of novel technologies.
Agile operations: Industry 5.0 implies a dynamic and fast-changing environment, so companies need to be able to react quickly to market changes, new technologies and customised production needs. Agile operating models facilitate adaptability.

– Commitment to sustainability:

Industry 5.0 emphasises ***environmental sustainability***. Companies should invest in technologies and solutions that reduce energy consumption, minimise waste and enable more efficient use of resources.
Circular economy: production is based on the principles of the circular economy, with a focus on recycling of raw materials, energy saving and environmental protection. The pursuit of sustainability is a fundamental expectation in the era of Industry 5.0.

– Data security and cybersecurity:

With the rise of data-driven manufacturing systems, data protection and ***cyber security*** are becoming increasingly important. Companies need to establish strict data protection policies and implement strong security systems to protect their systems from cyber-attacks (NIS2).
Data protection: the proper handling and protection of the huge amount of data generated during production is essential, especially for sensitive business or customer data.

– Economic and government support:

The implementation of Industry 5.0 will require significant ***investment***, so it is important that companies have access to government subsidies, incentive programmes and access to credit facilities. Governments have a key role to play in promoting technological progress.
Regulatory environment: The right legislative and regulatory framework is needed to ensure that technological developments can be smoothly introduced. This includes digital legislation, data protection regulations and cybersecurity protocols.

In summary, the implementation of Industry 5.0 requires advanced technology systems, a skilled workforce, organisational culture change and cybersecurity measures. The pursuit of a harmonic interaction between man and machine, as well as sustainability and innovation, is essential for the successful deployment of this new era of industry.

Since the application of AI has already appeared in the field of Industry 4.0 and is also a pillar of industry 5.0, it is important to mention its applicability and legal background. Currently, this is a grey area, there are regulatory initiatives, but at global level the legal standards for the application and adoption of AI are not clear. The AI Act, which entered into force on 1 August 2024, would help to address this, but would only regulate its applicability in the EU. While this is useful in many cases (life protection, health decisions, etc.), it also involves serious risks. However, the result of a ban in critical areas could in some cases be a significant competitive disadvantage (Zákányi, 2024).

5. CHANGES IN VOCATIONAL EDUCATION AND HIGHER EDUCATION AS A RESULT OF INDUSTRY 5.0

Industry 5.0 brings new challenges and opportunities for vocational education and universities, as the needs of the job market are dramatically changing due to technological developments. The education system needs to adapt to this, so that the workers of the future can take advantage of the opportunities for human-machine interaction and meet the demands for sustainability, innovation and creativity.

Interdisciplinary and flexible education programmes

- Industry 5.0 requires employees to be multidisciplinary. Educational institutions need to place greater emphasis on developing interdisciplinary courses that combine engineering, IT, management and human skills.
- Integrating engineering, IT and robotics with creative thinking or sustainability skills will be key (Fait, Hofrichterová, Mašek, & Čermák, 2023), (Mašek, Fait, & Čermák, 2023).

Develop digital skills

- Digital technologies such as AI, IoT, robotics, and data management are essential elements of Industry 5.0, so it is important for both vocational training and higher education to provide comprehensive digital literacy education.
- The education of programming, data processing, AI development and cybersecurity will play a key role in the education structure of Industry 5.0.

- The introduction of AI-based systems and the Internet of Things (IoT) in automotive and engineering systems requires engineers to be able to connect and code the different components of these systems.
- Self-driving cars and predictive maintenance require AI technologies that enable engineers to optimise the performance of vehicles and the efficiency of manufacturing systems (Fait, Mašek, & Čermák, 2022).

Developing soft skills and creativity

- One of the key elements of Industry 5.0 is the focus on human creativity and innovation. Therefore, education systems need to put more emphasis on the development of soft skills (e.g. creative thinking, problem solving, teamwork, communication) as they play a key role in the collaboration between humans and robots.
- Training methods such as project-based learning, real-world problem solving and creative design (e.g. design thinking) will be an important part of the future education.

Supporting lifelong learning

- The rapid technological changes in Industry 5.0 mean that employees are constantly having to learn new skills, making Lifelong Learning essential. Vocational and higher education institutions must offer flexible, modular learning opportunities that employees can use at any point in their careers.
- The introduction of online training, micro-credentialing programmes, courses and reskilling programmes will make it easier for experts to learn new technologies.

Collaborative robots and robotics education

- Cobots (collaborative robots) are a key element of Industry 5.0, so both vocational and higher education are focusing on teaching how to work with robotics. The new generation of experts will need to know how to use cobots, how to program them and how to integrate them into production processes.
- For example, robotics, automation and maintenance of industrial systems, as well as artificial intelligence programming, are areas that will be essential in the future of the job market.

Sustainability and environmental skills

- Environmental sustainability and efficiency is a key requirement of Industry 5.0, so training should focus on teaching sustainable technologies and production processes. Knowledge that supports resource-efficient production and the principles of a circular economy will be needed, taking into account environmental impacts.
- Educational institutions should work closely with industrial partners to integrate sustainable methods and technologies into industrial practices.

Promoting creative and innovative thinking

Education should support the development of innovation skills and entrepreneurship, as Industry 5.0 builds on human values and creativity. Therefore, entrepreneurial skills, learning about start-up culture and focusing on creative thinking will help individuals to adapt to the changing industrial environment.

Stronger links with the job market and industry

- The impact of Industry 5.0 will bring even closer cooperation between educational institutions and the labour market. Joint industry-education projects, internships and close cooperation with industry partners will give students the opportunity to meet real industrial problems and gain practical knowledge.
- Training programmes developed with industrial partners help to ensure that education responds directly to the needs of the job market.

In the era of Industry 5.0, mechanical and automotive engineers will need new competences and mindsets in addition to traditional engineering skills.

With the emergence of Industry 5.0, digital skills, knowledge of automated systems and AI technologies, and creative, sustainability-oriented thinking are essential for newly qualified mechanical and automotive engineers. A systemic approach, open-mindedness to human-machine collaboration and a commitment to lifelong learning will ensure that engineers successfully respond to the new industrial requirements.

Newly qualified engineers need a broader knowledge base and a more analytical mindset to successfully implement Industry 5.0. Industry 5.0 will build on a combination of digitalisation, artificial intelligence and personalised production processes, requiring a high level of multidisciplinary knowledge and flexible thinking.

Therefore, education and vocational training should also focus on these areas to ensure that future engineers are prepared for the challenges of Industry 5.0.

6. INDUSTRY 5.0 OR INDUSTRY 4.2

According to some experts, Industry 5.0 is not so different from another technological revolution, but a new way of thinking, focusing on the sustainable use of people and technology, with the help of digital twins and augmented reality (AR) (Myat, 2024), (Fait, Masek, & Cermak, 2022).
The perception of Industry 5.0 as an industrial revolution in its own right or as an extension of the fourth industrial revolution (Industry 4.0) is often debated. Some features of Industry 5.0 overlap with Industry 4.0, but there are also clear differences. The arguments for both perspectives are presented below:

Industry 5.0 as a separate industrial revolution

- People-centric: A key feature of Industry 5.0 is the emphasis on the human role alongside technological systems. While Industry 4.0 focuses on full automation and the development of machine intelligence, Industry 5.0 aims to optimise human-machine interaction. Collaborative robots (cobots), for example, work together with humans, bringing a new dimension to manufacturing and production (Krynke & Mazur, 2024), (Ágoston & Madleňák, 2020).
- Sustainability and social responsibility: Industry 5.0 will focus on sustainability and social responsibility issues, which were less in focus in Industry 4.0. Energy efficiency, the circular economy and the integration of green technologies are key elements that will set a new direction for industrial development (David, Kļaviņš, Olei, & Midan, 2024), (David, 2024).
- Customization and tailor-made production: Industry 5.0 emphasizes customized products and services, while Industry 4.0 focuses on automated, high-volume, standardized production. New technologies (such as 3D printing) allow for greater flexibility and rapid adaptation to customer needs.
- Technology-human balance: Industry 5.0 aims to find a balance between smart technologies (e.g. artificial intelligence, robotics) and human creativity and responsiveness. This differs from the goal of Industry 4.0, which sought to minimise human intervention through automation (Škorupa, Bulková, Gašparík, & Kendra, 2023).

Industry 5.0 as an extension of Industry 4.0 (e.g. Industry 4.2)

- Technological continuity: The technological basis of Industry 5.0 (automation, artificial intelligence, IoT) is closely linked to the achievements of Industry 4.0. In fact, Industry 5.0 is essentially an evolution of Industry 4.0, where new goals and values are set, building on technological progress, but the starting point and the toolbox are the same.
- Common technological base: Both eras are built on technologies such as AI, Big Data, automation, and IoT. The difference mainly in the ways they are used, not in the new technological foundations. Therefore, many believe that Industry 5.0 is just another evolutionary phase in Industry 4.0.
- The human factor is also present in Industry 4.0: Although Industry 5.0 explicitly emphasises human-machine collaboration, Industry 4.0 already includes the role of human intervention in the monitoring and control of intelligent systems. Thus, many believe that Industry 5.0 is not a new industrial revolution, but a refinement and humanisation of Industry 4.0.
- Focus on flexibility and customisation: The possibility of customised production, which Industry 5.0 highlights, can also be realised with Industry 4.0 technologies. For example, 3D printing and mass customisation were also present during Industry 4.0.

7. SUMMARY

Industry 5.0 can partly be seen as an extension of Industry 4.0, as the technological foundations are largely the same. However, the human-centred approach, the focus on sustainability and the emphasis on personalised production methods lead many to see Industry 5.0 as a new industrial revolution. Depending on whether you look at the technological or the social aspects, Industry 5.0 could be a continuation of Industry 4.0 or a new chapter in the history of manufacturing.

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MECHANICAL DESIGN OF A CARTESIAN ROBOT

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Abstract: This paper investigates the assembling options of a cartesian type robot, which can be used for material handling or 3D printing purposes. The structure has three ball screw driven linear units, which will be controlled by a microcontroller. The requirements of the structure to use as a 3D printer are defined. The solution selection matrix is constructed in order to choose the appropriate configuration of the system.

Keywords: *Cartesian robot, 3D printer, Solution selection matrix*

1. INTRODUCTION

Nowadays 3D printing is a widely used technique to achieve cost effective prototypes. A cartesian type robot containing three prismatic joints to construct the kinematic chain of the system can be suitable for this purpose. Cartesian robots can be used not only as 3D printers, but also in industry for various workpiece moving and positioning tasks. Its kinematic description is the simplest among the different common kinematic arrangements (Spong, Hutchinson, & Vidyasagar, 2006).
There are papers which deal with the design and use of cartesian robots. Paper (Civelek & Fuhrmann, 2023) presents the control of a Cartesian robot with mixed reality interface containing virtual buttons and virtual gloves. A gantry type Cartesian robot was developed for automation purposes at the University of Udine in the beginning of the 2000's (Gasparetto & Rosati, 2002). Cartesian 3D printers are common in additive manufacturing with Fused Filament Fabrication (FFF) technique. A 3D printer with crossed gantry design is investigated in (Wolf, Werkle, & Möhring, 2024) to analyse the printing performance with stepper and servo motors. In this article, two motor types were compared according to several aspects, e.g., dimensional accuracy, printing speed, vibration etc., servo motors are clearly more advantageous.

The main aim of the paper is to develop a linear robot, which is capable to serve 3D printing and material handling options. Three linear actuators and servo motors with its controllers are used to build the robot. These elements shown in Figure 1 are provided by Power Belt Ltd.
Section 2 deals with feasible assembling options for robotic structure. Furthermore, the section contains the requirements of the unit and the evaluation method of the feasible solutions. The mechanical, electrical development of the robot and the programming task will be performed soon, some information related to the mechatronic design is described in Section 3.

Figure 1. *The linear units (3. – 5.) and one of the motors, motor drivers (1., 2.)*

2. EXAMINATION OF ASSEMBLING OPTIONS

The 3 linear actuators of different sizes and load capacities can be assembled in various ways. This Section introduces briefly these solutions.
Since it is a mechatronic system, it is worth using one of the important parts of methodical machine design, the creation of structural variants, to build such a system (Jakab, 2013). This method is mainly used in the case of machine tools. In the course of the formation of the structures, it can be determined based on the elementary movements of the actuator chains, how many ways the mechatronic system can be built. A specific structure includes the division of movements and which of these subunits is built on what.
This includes the fact that the number of actuator units performing elementary movements determines the exact degree of complexity of the planned mechatronic system. This is characterized by the number of subunits performing elementary movements, with the letter D (Dimension) next to it (Szabó, 2024). Since three

compact units perform elementary movements, it is a 3D machine. When creating the structure versions, it must be taken into account that the tool (s) or the workpiece (m) is moved by the given compact units (Szabó, 2024). The extruder can be considered a tool here.
Based on these, the number of first-degree assembling options can be calculated as follows:

$$m_1 = 2^D = 8. \quad (1)$$

If all movements are built on each other, there is no division of movements for the given structure. If there is a movement that is not based on another movement, then it is a movement division.
Furthermore, it is an important aspect where the unit operating in a specific direction is in the construction line. This is given by the order of the given movement, i.e., the orderliness (Szabó, 2024). The orderliness specifies how many subunits move either the tool or the workpiece.

Table 1
Possible structures

No.	Without movement division	No.	With movement division
1.	X(s,1), Y(s,2), Z(s,3)	13.	X(m,1), Y(s,1), Z(s,2)
2.	X(s,1), Y(s,3), Z(s,2)	14.	X(m,1), Y(s,2), Z(s,1)
3.	X(s,2), Y(s,1), Z(s,3)	15.	X(s,1), Y(m,1), Z(s,2)
4.	X(s,3), Y(s,1), Z(s,2)	16.	X(s,2), Y(m,1), Z(s,1)
5.	X(s,3), Y(s,2), Z(s,1)	17.	X(s,1), Y(s,2), Z(m,1)
6.	X(s,2), Y(s,3), Z(s,1)	18.	X(s,2), Y(s,1), Z(m,1)
7.	X(m,1), Y(m,2), Z(m,3)	19.	X(s,1), Y(m,1), Z(m,2)
8.	X(m,1), Y(m,3), Z(m,2)	20.	X(s,1), Y(m,2), Z(m,1)
9.	X(m,2), Y(m,1), Z(m,3)	21.	X(m,1), Y(s,1), Z(m,2)
10.	X(m,3), Y(m,1), Z(m,2)	22.	X(m,2), Y(s,1), Z(m,1)
11.	X(m,3), Y(m,2), Z(m,1)	23.	X(m,1), Y(m,2), Z(s,1)
12.	X(m,2), Y(m,3), Z(m,1)	24.	X(m,2), Y(m,1), Z(s,1)

Since movement division and orderliness are also considered, it can be stated that second-degree structures are created. The number of structures is given by the following formula:

$$m_2 = (3D + 1)! = 24. \quad (2)$$

This means that 24 different structures can be formed with 3 subunits. The codes of the structures are illustrated in Table 1. The structure code contains the direction of the elementary movements (X, Y or Z), element to be moved (s: tool or m: workpiece), and orderliness. Three assembling options are shown in Figure 2 and Figure 3.

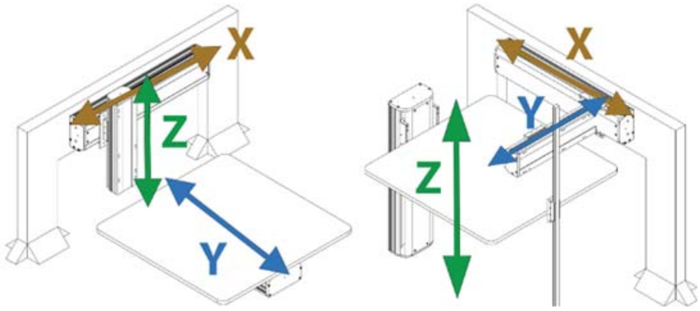

Figure 2. *Examples for parallel division of movements: X(s,1), Y(m,1), Z(s,2); X(s,1), Y(s,2), Z(m,1)*

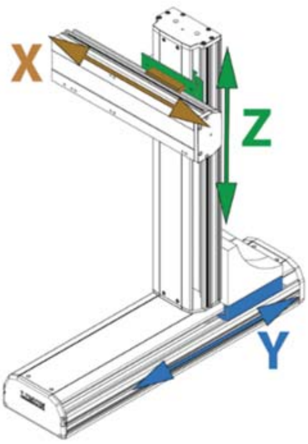

Figure 3. *An example for X(s,3), Y(s,1), Z(s,2) construction*

Requirements of the structure

Among the construction options, the most suitable one must be selected, which helps the robot to perform its task. For this, it is worth comparing the solutions with each other, taking into account different aspects, for which it is advisable to use the comparison of the feasible solution variants.
A total of 5 aspects were defined in relation to the system, these are:

- A: Load capacity,
- B: Installability,
- C: Size of the workspace,
- D: Nature of worksplace,
- E: Incurred costs.

The nature of workspace describes that in which workspace can more widely used workpieces be made. The most important aspects are the Load capacity and Installability. The size of the workspace is also important, but the differences between the concepts can be considered minimal.

Evaluation of solutions

The assembling options will be evaluated by using the so-called solution selection matrix. The interval of points that can be given for each solution with respect to each criterion is 1-20. According to subsection 2.1., there are five criteria. The most appropriate solution will be the one for which the sum of the points given for the criteria turns out to be the smallest. The result of the solution selection matrix can be seen in Table 2.

Table 2
The solution selection matrix

	A	**B**	**C**	**D**	**E**	**SUM**
3.	13	7	20	1	7	48
4.	14	1	9	7	1	32
6.	19	3	10	11	3	46
10.	16	4	19	6	2	47
13.	2	10	1	3	12	28
14.	4	11	8	9	14	46
15.	1	9	3	2	11	26
16.	3	12	4	4	13	36

In advance, the assembling options were analysed, and only viable structure variants are included in the table. Based on the matrix, the best solution is the fifteenth, which has the following code X(s,1), Y(m,1), Z(s,2), and it can be seen on the left side of Figure 2.

3. FUTURE PLANS

Based on the selected structure, the mechanical design of the workspace of the robot began. A frame was designed for the robot (see Figure 4), on which the compact units and the electronic devices that will be used and selected in the future can be attached.

For the proper functioning of the robot, it will be essential to carry out electronic design and electrical connections. Since the controllers belonging to the servomotors are able to receive STEP and DIR signals, a microcontroller-based panel will be necessary that will be able to produce these signals in the knowledge of the appropriate movement instruction. The block scheme of the desired system is shown in Figure 5. The control system must be able to interpret the G code generated after slicing the 3D model.

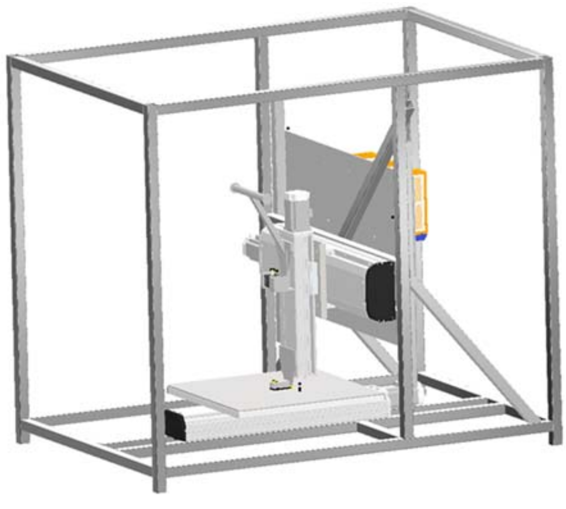

Figure 4. *Model of the system to be implemented and its frame*

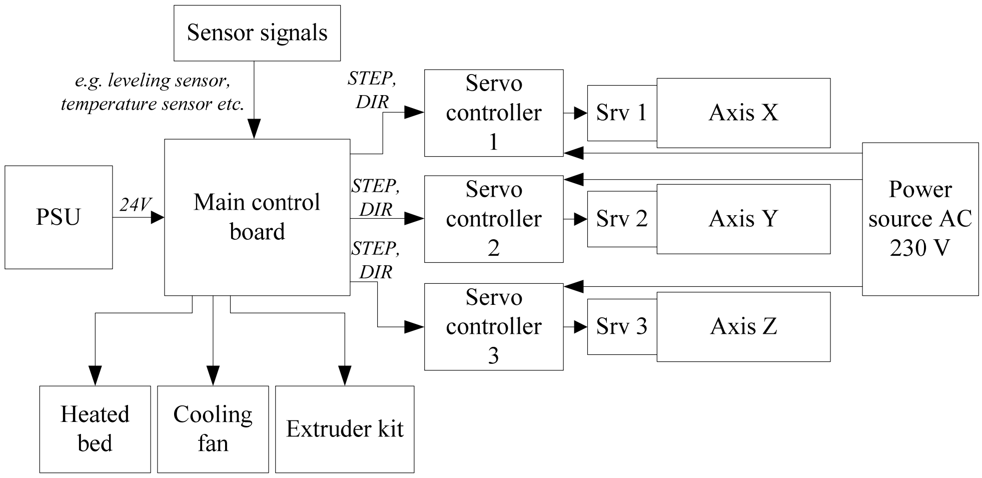

Figure 5. *The block scheme of the control*

4. SUMMARY

The article dealt with the exploration of the structural variants of a Cartesian robot suitable for 3D printing. Out of the 24 structural variants, the 8 viable constructions were compared according to 5 criteria using the solution selection matrix.
Mechanical design of the best version has already begun and will continue in the future. Furthermore, the control and connections belonging to the system are also expected in the near future. After the construction of the system, it will be necessary to complete tests, which will cover, e.g., for positioning accuracy and measuring the size of the workpiece.

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DESIGN CONCEPTION OF A FOOD DEHYDRATOR

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Abstract: Nowadays, the household is unimaginable without the three main pillars of the technical field, which are mechanical engineering, electrical engineering and IT. The paper deals with the design conception of a food dehydrator unit. These types of devices are capable of drying fruits and mushrooms. The article covers the design conception of a specific version, and then by building a test system, it becomes possible to check the correctness of the control program code belonging to the system.

Keywords: *Food dehydrator, Arduino development platform, fritzing*

1. INTRODUCTION

Before the invention of machines, mankind dried fruits, vegetables, mushrooms and herbs directly with the help of the sun, and indirectly, e.g., in the attic, because this is one of the ways which can preserve the taste of fruits. The other method, preservation with salt, is also quite an old and proven method. Salt, as well as the warm flowing air during drying, extracts moisture from the fruit in order to terminate the survival conditions of bacteria and mould. During drying, the fruits were laid on a net or pulled over a wire and dried in the sun, which has the disadvantage of a long drying time and weather dependence (Haq & Khan, 2019).

Through the development of IT over the past 50 years, even this process can be made simpler and more efficient, thanks to the availability of programmable drying equipment with which the drying time and temperature can be adjusted.

An energy efficient food dehydrator using electrical heat generation has been designed with PID controller. In this configuration an Arduino Uno, temperature control module and an intel fan were installed, and the temperature range was from 45°C to 55°C. There were published the design calculations and three-dimensional model of the dehydrator (Madhankumar, Muthukkhumaran, Navaneeth, Padmanabhan, & Shriram, 2021). Another research dealt with development of a uniform dehydrator which can dry up to 50 kg vegetable on uniform temperature (Perera, 2022). The improvement of efficiency and environmental impact of a low-cost food dehydrator was analysed by Timothy J. Bowser and his colleges (J. Bowser, 2011). It was declared that coefficient of performance (COP) of the dehydrator increased 39 % when a ventilation waste heat recovery (VHR) system was implemented, carbon emissions equivalent was reduced by 35 % and product drying time was also reduced increasing the amount of production time available (J. Bowser, 2011).

The main goal of the article is the design of a drying device, which contains the 3D model of the unit and programming a test system to check the correctness of the control program (Czigler, 2023).

Section 2 describes the types of drying devices which are common in households. Then it deals with the requirements of a food dehydrator. Section 3 shows the 3D model of the system and its size. The self-devised program code of a test system is detailed in Section 4.

2. FOOD DEHYDRATOR STRUCTURES

In most households, two types of drying solutions have spread, as shown in Figure 1. The main parts of the units are the following: 1 – base; 2 – fan; 3 – heater unit; 4 – trays; 5 – ventilation cover; 6 – door; 7 – protective grid. In the cylindrical version, the heater and the fan are located on the base. Fan ensures adequate air movement in the equipment. The heating element is a resistance wire with a high melting point, through which an electric current flows, thereby producing heat. Sliced fruits, vegetables, mushrooms or herbs must be placed on the trays. The ventilation cover is located on the top of the device in the cylindrical version, and in the grooves behind the door in the cuboid version, plays a role in removing moist air. The door is visible in the case of the cuboid version, where the drying process can be easily followed through the glass, and by opening the door, the products can be rotated for even drying. The grid protects the operator of the equipment from the hot heater and the rotating fan blades.

In the following, the requirements for the unit to be designed will be determined (Czigler, 2023), which are formulated during the study of several commercially available units. The design conception of the unit will be detailed in Section 3.

The advantage of plastic cylindrical drying equipment is that the number of trays can be expanded. In this way, even more elements can be stacked on top of each other than the number given by the manufacturer upon delivery. This advantage is more likely to apply only to higher-performance equipment, since, in addition to the low heating power, the drying is less efficient in the parts further away from the heating element. Compared to stackable plastic trays, the stainless-steel housing is a fixed size. A big advantage of dryers with metal housing is the position of the heater, which is located on the side in the middle of the dryer, therefore all trays heat up evenly, it is not necessary to change their order from time to time.

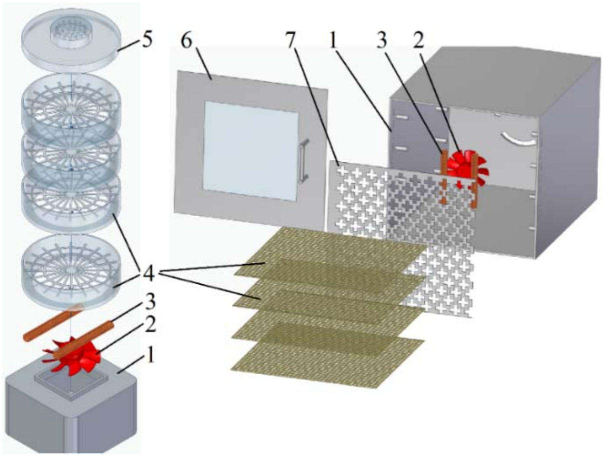

Figure 1. *The main parts of different dryer designs*

Assuming the floorspace, the cuboid type dryer structure can hold more fruit, therefore it proves to be better in terms of space utilization compared to the cylindrical version.

The material quality of the drying unit is an important parameter. The decomposition time of plastics can be hundreds of years, depending on the type used, which means a large environmental burden, for this reason they are increasingly trying to favour environmentally friendly plastics. The advantage of using metal lies in the fact that customers associate it with better quality and a longer service life. Therefore, sheet metals will be used to construct the casing of the unit.

The important requirements for the design of the drying equipment are included in the following list:

- Size of each drying tray: 450x540,
- Number of the trays: 5,
- Material of the cover and trays: stainless steel,
- The self-devised controller unit should be performing temperature control, timer function,
- HMI function will be provided by a touchscreen.

3. DESIGN CONCEPTION OF THE SYSTEM

The designed trays provide a drying surface of 0.24 m^2 each, five trays 1.2 m^2, which can be used to dry 8-12 kg of fruit or mushrooms, depending on the size characteristics of the product. There is 25-40 mm between the trays of commercially available fruit and mushroom drying equipment, depending on the type. The model contains a 100 mm gap between the trays, which can be seen in Figure 2.
Axial fan is used to ventilate the air. With its help, the heat generated from the resistance wire is evenly distributed in the dryer, and the steam generated from fruits and mushrooms flows more easily from near the surface of the product, thus increasing the drying speed.

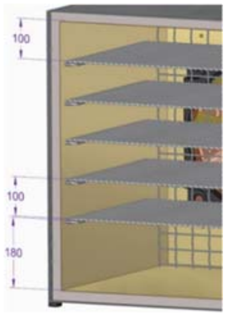

Figure 2. *3D model of drying equipment*

The model of the food dehydrator is shown in Figure 3. On the right side of the unit there is a compartment designed for the control unit. The height of the equipment: 752 mm, width: 727 mm, depth: 660.5 mm.

Figure 3. *3D model of drying equipment*

4. DESIGN OF THE CONTROL, PERFORMING TESTS

The following elements are used to build a test system: a desktop computer case, a computer fan, the heating element of a sandwich oven and the corresponding heat transfer plate, a temperature sensor and a temperature and humidity sensor, a cover for touch protection, under which the cables, buttons, relays, microcontroller, test panel, display are located. The microcontroller and various inputs are connected to a test panel. The connection of these elements is illustrated in Figure 6.
The breadboard wiring diagram of the control system for testing is shown in Figure 4. The Arduino Nano development platform is responsible for controlling the system. The program code was developed in the Arduino IDE software.

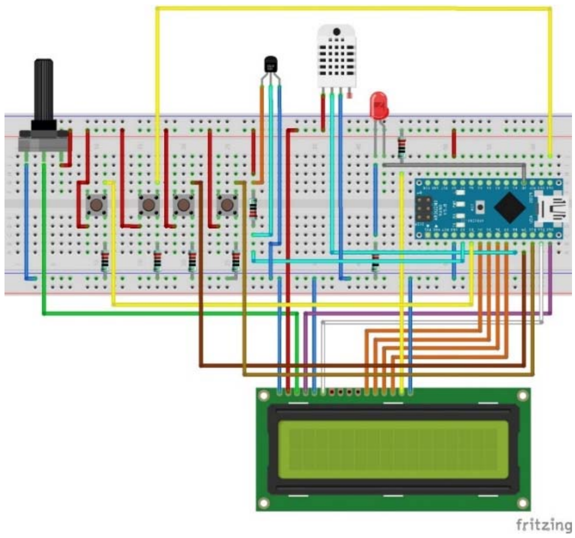

Figure 4. *The breadboard scheme of the control circuit*

The first step is to define the necessary variables, outputs and inputs. In the main program, if the value of the set temperature is not zero and is below the value of the upper hysteresis during the heating phase, the heating element is switched on by the system. If the temperature exceeds the set value, the heating stops.
There are 3 operating modes on the test display, which can be used to set the desired values in a user-friendly way. In addition, the values required for the user are also displayed.
The first mode provides information about the current state of the unit. The display shows the current temperature, humidity and remaining time. The temperature can

be adjusted in the second mode. This can be achieved by pressing the mode button, the temperature can be adjusted from 25°C to 75°C. By pressing the plus (+) button the temperature can be increased by five, while by pressing the minus (-) button, it can be decreased by five. The desired temperature can be set by pressing the set button.

The third mode is responsible for setting the timer. The counter can be set from 0 to 24 hours, the program allows adjustment every half hour. The flowchart of the program is shown in Figure 5.

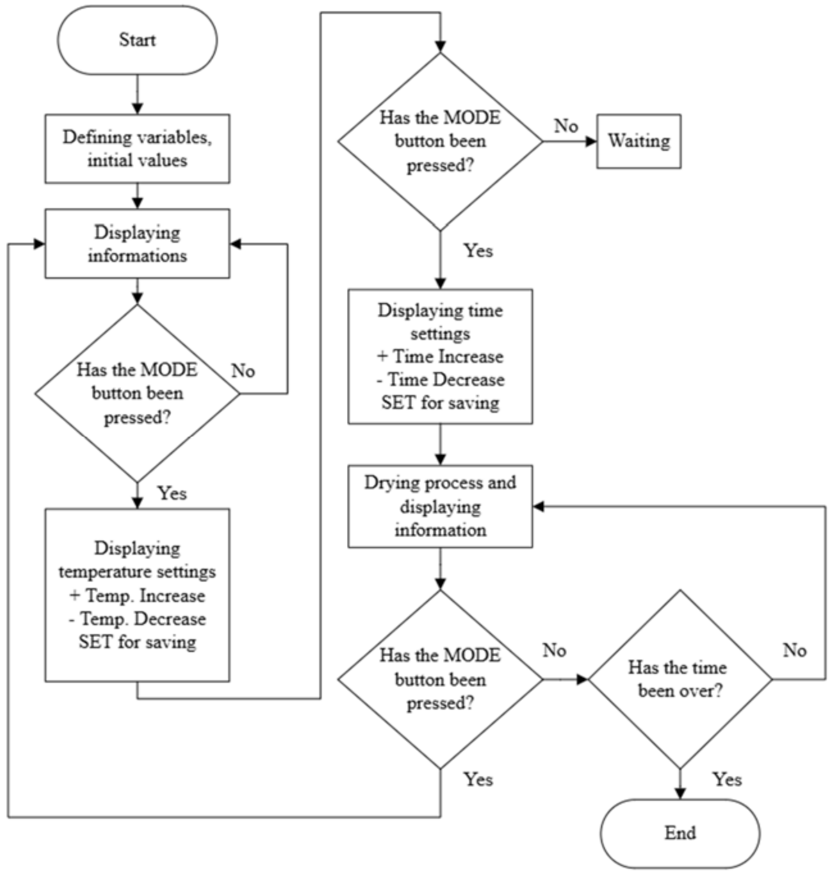

Figure 5. *The flowchart of the control program*

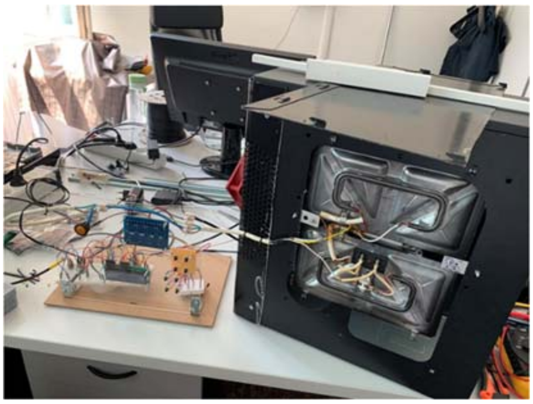

Figure 6. *The picture of the test unit*

5. SUMMARY

The article dealt with the design conception of a food dryer system and its programming. The correctness of the control program was checked by a test system. The system was built from a desktop computer case and a sandwich heater. In the future the case of the system will be manufactured, and then the control unit will be attached to it.

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ADVANCING PLANT CELL WALL MODELLING: PARAMETRIC FINITE ELEMENT APPROACH

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Abstract: The study utilized genetic algorithms to optimize the mechanical properties of wheat stems, focusing on axial stress, shear stress, bending stress, and critical buckling force. The results indicated that the optimized stem design could withstand applied forces with adequate safety margins, enhancing lodging resistance. Future work will include advanced optimization techniques and validation to further improve wheat stem structural integrity.

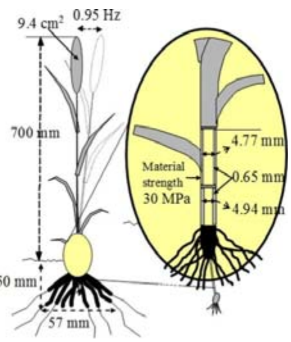
Keywords: *wheat, plant cell wall, modelling, parametric finite element approach*

1. Importance of Studying Wheat Stalk Mechanics

Wheat is a staple crop that plays a crucial role in the global food supply. (Valluru, Reynolds, & Lafarge, 2015) Stalk lodging (mechanical failure of plant stems during windstorms) leads to global yield losses in cereal crops estimated to range from 5% to 25% annually. Classical genetic and breeding methods, far broader international cooperation than was experienced in earlier periods, and improvements in agronomic techniques have led to previously unimaginable developments in the utilization of wheat for human consumption. (Reynolds, et al., 2009), (Oduntan, Stubbs, & Robertson, 2022), (Stubbs, Oduntan, Keep, Noble, & Robertson, 2020), (Kong, et al., 2013), (Khobra, et al., 2019), (Stubbs, et al., 2022), (Zhang, et al., 2016) Understanding and optimizing the mechanical properties of wheat stalks is vital for several reasons:

1. Lodging Resistance: Lodging, or the bending and breaking of stalks, is a significant problem in wheat production. It can lead to substantial yield losses, reduced grain quality, and increased harvesting difficulties. By studying the mechanical properties of wheat stalks, researchers can develop varieties that are more resistant to lodging, ensuring more stable and higher yields.

2. Yield Improvement: Improving the structural integrity of wheat stalks allows plants to support more grain weight without collapsing. This can directly translate to increased yield per hectare, which is essential for meeting the growing food demand driven by global population growth.
3. Environmental Stress Adaptation: Wheat crops are subjected to various environmental stresses, such as wind, rain, and hail. Understanding how these stresses affect the mechanical properties of stalks can help in breeding programs aimed at developing varieties that are more resilient to adverse weather conditions.



1. Figure. *Dimensions of a lodging-proof wheat plant. [2]*

4. Agricultural Efficiency: Stronger and more resilient wheat stalks can lead to more efficient agricultural practices. Reduced lodging means less need for mechanical support and chemical treatments, leading to lower production costs and a reduced environmental footprint.
5. Resource Utilization: Optimizing stalk mechanics can contribute to better resource utilization. Healthier, more robust plants require fewer inputs in terms of water, fertilizers, and pesticides, promoting sustainable farming practices.
6. Economic Benefits: Minimizing yield losses due to lodging and improving overall crop resilience can have significant economic benefits for farmers. Higher yields and better grain quality translate to increased profitability and economic stability in the agricultural sector.
7. Food Security: Enhancing the mechanical properties of wheat stalks is a step towards ensuring global food security. By reducing crop losses and improving yield reliability, we can better meet the nutritional needs of a growing population.

The study of wheat stalk mechanics is not just a scientific pursuit but a practical necessity for modern agriculture. By leveraging advanced computational tools, optimization algorithms, and data-driven insights, researchers can develop wheat varieties that are more robust, resilient, and productive. This, in turn, supports sustainable farming practices, economic stability for farmers, and food security on a global scale. (Shah, et al., 2019), (Crook & Ennos, 1994), (Berry, Spink, Sterling, & Pickett, 2003), (Borbás & Ficzere, 1970), (Dömötör, 2014), (Bedö & Láng, 2001)

2. The Analysis of Wheat Stalk

The study and optimization of wheat stalk mechanical properties are crucial for improving agricultural yields. Wheat stalk lodging, caused by a combination of external factors (like wind) and internal factors (such as the plant's own weight), can lead to significant crop losses. By understanding and enhancing the structural characteristics of wheat stalks, we can develop more resilient crops, ensuring better stability and higher productivity.

Purpose of the Program

The objective of the program is to study the mechanical properties and resistance of wheat stems under different geometric and material properties. The aim is to optimize the stem geometry to withstand various loads, such as the combined effect of wind and rain, while minimizing the risk of failure.

Used Data and Input Data

The program uses various mechanical and geometric data to simulate the wheat stem model. These data include the stem length, which is 700 mm, the root plate spread of 57 mm, and the wall width of the bottom internode, which varies. The diameters range from 5.86 mm to 4.00 mm. The program operates with a wind load of 19.3 m/s (Liang & Guo, 2009) and considers a maximum material strength of 54.6 MPa. The weight of the wheat head is 3.89 g. (Valluru, Reynolds, & Lafarge, 2015) These inputs help the program to calculate and optimize the mechanical properties of the stem.

Program Operation

The program's blocks include reading input data, checking and preprocessing the data, calculating mechanical properties, applying the genetic algorithm, and displaying the results. After reading the input data, the program checks and prepares the data for calculations. Using the genetic algorithm, the program optimizes the stem geometry, generating and evaluating different alternatives. When displaying results, the program ranks the alternatives, identifies weak points, and evaluates them.

3. Wheat Stem Optimization Using Genetic Algorithms: Results and Interpretations

Genetic Algorithm Optimization

Objective: The primary aim of this analysis was to determine the optimal mechanical properties and structural design of a wheat stem using genetic algorithms. This process involved simulating various internal and external stressors to understand how a wheat stem can best resist these forces while maintaining structural integrity.

Input Data Collection	**Initialize Genetic Algorithm**	**Genetic Algorithm Execution**	**Fitness Evaluation**	**Convergence Check**	**Output Results**
Stem properties Environmental factors Mechanical properties	Population initialization Define fitness function	Selection Crossover Mutation	Calculate stress Evaluate failure points	Check if stopping criteria are met	Optimal stem properties Stress analysis Failure points

2. Figure. *The block diagram summarizing the workflow of the program*

Table 1

The new alternatives morphological traits and biomechanical properties

	Weak point height (mm)	**Diameters (mm)**	**Wall thicknesses (mm)**	**Maximum stress (MPa)**	**Critical load (N)**	**Bending moment (Nmm)**
0.	45 - 25	2.96 - 3.63	0.43 - 0.83	13.39 - 16.25	60 - 150	118.69
A1	50	5.86	1.34 - 0.69	8.40	1100	78.49
A2	60	5.50	1.26 - 0.65	10.00	1300	118.69
A3	70	5.00	1.14 - 0.59	12.00	1500	139.80
A4	80	4.50	1.03 - 0.53	15.00	1700	176.76
A5	90	4.00	0.92 - 0.48	18.00	1900	284.86

4. Analysis of Results

The analysis indicates that the optimized alternatives, generated by the genetic algorithm, show improved resistance to mechanical stresses compared to the original stem. Each alternative maintains the material strength and geometric constraints provided. The bending strength and bending rigidity have been adjusted to ensure optimal performance under dynamic loading conditions, such as wind and rain.
The genetic algorithm proved effective in identifying the most suitable stem configurations, enhancing the overall stability and resistance of the wheat stalks. The results suggest that focusing on the geometric properties, such as diameter and wall thickness, can significantly improve the mechanical performance of wheat stalks.

Benefits and Drawbacks of the Program

Benefits:

1. Optimization of Wheat Stalk Properties:
   - The program uses a genetic algorithm to optimize the geometric and mechanical properties of wheat stalks, leading to increased resistance against environmental stresses like wind and rain.
   - By identifying the optimal stem configurations, the program helps in reducing lodging incidents, which is crucial for maintaining high crop yields and minimizing losses.
2. Detailed Analysis and Insights:
   - The program provides a detailed analysis of the mechanical stresses and failure points of the wheat stalks, offering valuable insights into the structural integrity of different stem configurations.
   - This information can guide plant breeders in selecting and developing more robust wheat varieties.
3. Customization and Flexibility:
   - The program allows for the input of various mechanical and geometric properties, making it adaptable to different wheat varieties and environmental conditions.
   - The ability to specify constraints and parameters ensures that the optimization process aligns with specific breeding goals and agricultural practices.
4. Integration of Environmental Factors:
   - The program considers dynamic environmental factors, such as wind and rain, in its calculations.

Future Development Opportunities

To further enhance the functionality and accuracy of the wheat stalk mechanical analysis program, several advanced algorithms and techniques can be integrated. Here are some potential areas for future development:

1. Advanced Optimization Techniques:

 – Machine Learning Integration:

Predictive Models: Use machine learning models to predict failure points and optimize stem properties more efficiently.

Real-time Adaptation: Implement algorithms that adapt to new data, improving prediction accuracy over time.

 – Enhanced Genetic Algorithms:

Multi-Objective Optimization: Incorporate multi-objective genetic algorithms to balance between different conflicting objectives, such as stem strength and yield.

Hybrid Approaches: Combine genetic algorithms with other optimization techniques like simulated annealing or particle swarm optimization for better performance.

2. Improved Environmental Modelling:

 – Dynamic Environmental Factors:

Weather Simulation: Include more detailed weather simulations that account for changing conditions over time, such as varying wind speeds and rain intensities.

Soil Interaction: Model the interaction between the stem and soil to better understand the anchorage system's contribution to overall stability.

 – Stress and Load Modelling:

Complex Loading Conditions: Incorporate more complex loading conditions, such as combined effects of wind, rain, and mechanical handling during harvesting.

Fatigue Analysis: Extend the analysis to include fatigue and long-term wear and tear on the stem under cyclic loading conditions.

By incorporating these advanced techniques and expanding the program's capabilities, it can provide even more valuable insights and practical solutions for enhancing crop resilience and yield.

5. SUMMARY

This study demonstrates the potential of using genetic algorithms to optimize the structural properties of wheat stalks, thereby improving their resistance to environmental stresses. By fine-tuning the geometric parameters, it is possible to develop wheat varieties that are less prone to lodging, ultimately leading to higher yield stability and reduced crop losses.

The results demonstrate the effectiveness of computational optimization in improving stalk mechanics, offering potential pathways for breeding more resilient wheat varieties.

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EXAMINATION OF CONDITION OF ROLLING BEARINGS

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Abstract: Bearings operating properties impact the function of the whole machine therefore their investigation is an important topic. Early detection of failure of bearings allows for the replacement of them during planned maintenance, thus avoiding sudden downtime or unexpected accidents. There are several methods for monitoring the operating conditions of bearings, which help determine the residual lifetime of the bearings. This paper focuses on a test procedure which can be used to determine the condition of rolling element bearings.

Keywords: *condition monitoring, rolling bearings, vibration diagnostic*

1. INTRODUCTION

According to environment-conscious approach of our days the purpose primarily is the more efficient extraction of the reusable raw material during the annihilation of industrial products. At the same time the certain number of extracted materials during the recycling processes could be recycled on higher preparation level. Voltage regulators and generators, starters, bearings disassembled from the cars and other industrial products are counted in this class, which can be even built into a new product if it has well defined and sufficient remanent lifetime (Patkó, et al., 2010). Research group of the Department of Machine Tools at the University of Miskolc gained extensive experiences in development of special precise machine details and producing machines (Takács, Patkó, Csáki, Szilágyi, & Hegedűs, 2006). One of the preliminary works in this field was the cooperative project of the University of Miskolc with the Hungarian Roller Bearings Works (MGM) in framework of which a cooperative linear motion guide developer and analyser laboratory was operated and a new precise linear motion roller guide family was worked out.

2. Vibration analysis

There are many different techniques for condition monitoring of rotating machinery, most of the bearing testing methods are based on vibration measurement. The current state and features of a bearing, and its deterioration can be assessed by vibration analysis. During the condition monitoring of equipment units and components, two important conditions are usually observed: one is the detection of possible defects, and the other is the frequency of defect occurrence, which also informs us about the service life of the component (Tóth, 2022). This latter aspect is especially important in the case of components that operate in continuous mode for a certain period. The balls and rollers rotating inside the bearing generate broadband noise and vibration, which is increased by poor lubrication of the bearing, overloading (for example, misalignment), or by damage to the raceways or rolling element surfaces. Since the noise and vibration generated by the bearings (which are otherwise high-frequency) are broadband, it is difficult for instruments measuring the effective value to define any specific frequency or narrow frequency band with which the condition of the bearing can be characterized (Szilágyi, Takács, Kiss, & Tóth, 2016). This is also impossible because the specific bearing failure frequencies depend, among other things, on the bearing type and the current speed of the machine. In practice, the method that has proven successful is to determine the value characteristic of the bearing condition based on the effective value of the vibration acceleration measured in the frequency range between 2 kHz and 20 kHz. The frequency domain techniques involve analysing or display of vibration data based on the frequency. One advantage of the method is that the repetitive nature of the vibration signals is exactly displayed as peaks in the frequency spectrum at the frequency where the repetition takes place. Time domain vibration signals are processed into the frequency domain by the adaptation of Fourier transform, typically in the shape of fast Fourier transform (FFT) algorithm. FFT is an algorithm to calculate the discrete Fourier transform and its inverse (Tóth, Szilágyi, & Takács, 2014). In a frequency spectrum the horizontal axis is generally the frequency, and the vertical axis is the amplitude of displacement, velocity or acceleration. Figure 1 shows a spectrum from a late stage in the life of a ball bearing. It is striking that the acceleration values have increased around 1000 Hz.

Time-frequency domain analysis can evince the signal frequency components, identifies their time variant features. These techniques have facility to handle both, non-stationary and stationary vibration signals (Tóth, 2016). These methods for instance the short time Fourier transform, the Wavelet transform and the Wigner-Ville distribution. One of the most widely used time-frequency techniques is the short time Fourier transform (STFT). STFT distributes the original signal into segments with short-time window and then apply the Fourier transform to each time segment to ascertain the frequencies that existed in that segment. The Wavelet transform (WT) is a favoured method to diagnosis bearing faults. One advantage of WT over the STFT is that it can achieve high frequency resolutions with sharper time resolutions (Tóth, Szilágyi, & Takács, 2018).

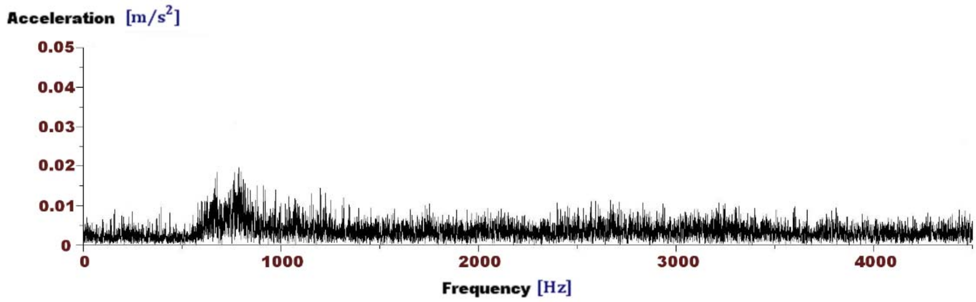

Figure 1. *Frequency spectrum of a ball bearing*

3. CONDITION MONITORING OF BEARINGS

It is advisable to estimate the residual life of a used bearing as result of a comparative experiment. In this case, the condition of the used bearing is compared with the condition of a specified number of journal bearings of the same type as the used bearing but subjected to specified operating conditions. Specified operating conditions can be achieved, for example, during a bearing fatigue test. In this case, a used bearing of the same type as the bearing to be tested is fatigued under predetermined conditions. The fatigue is continued until the nominal life determined from the specified conditions. A bearing test equipment is used to perform the bearing fatigue and measurement investigations. Figure 2 shows this equipment, which is located at University of Miskolc, Department of Machine Tools.
The above-mentioned bearing test device used to examine ball bearings (type: 6303). During the experiments, the vibration patterns measure from bearing using piezoelectric vibration accelerometer (Kistler 8632C). During bearing fatigue tests the left, fatigue shaft works at the given rotational speed, while the hydraulic cylinder exerts artificial load (6 kN) for the bearing. The fixed-term fatigue cycles on average 4 hours long. After the fixed-term fatigue cycles, the bearing is put over to the right, measuring axis. During the measurements the shaft works at the given rotational speed, while the hydraulic cylinder exerts artificial load (1 kN) for the examined bearing. 5 vibration samples and 16 384 element samples were taken within each

cycle. The spindles are driven by a Siemens frequency converter controlled electric motor. During fatigue tests and measurements always set on rotational speed 1500 min^{-1}, which corresponds to a frequency of 25 Hz. Consequently, the tested bearing has a lifetime of nearly 150 hours with described data. Typical failure frequencies of 6303 bearings are summarized in the Table 1, considering that the inner ring rotates.

Figure 2. *Bearing test rig in measurement position*

Table 1
Typical failure frequencies

Name	**Abridgment**	**Value [Hz]**
Inner ring frequency	BFSI	≈ 110,62
Outer ring frequency	BFSO	≈ 64,37
Rolling element frequency	BSF	≈ 44
Cage frequency	FTF	≈ 9,12

Fast Fourier transform was used to represent the recorded vibration patterns in spectrum form. The program code (see Figure 3) written in symbolic language, used both Maple and Matlab mathematical softwares.

```
with(Matlab)
a := readdata("1.txt")
V := convert(a, list)
num := 16384
Time := [seq(1/9600 (h), h = 1 ..num)]
ft := Matlab[fft](V)
setvar("FT", ft)
setvar("n", num)
evalM("result=FT.*conj(FT)/n")
pwr := getvar("result")
pwrlist := convert(pwr/num, list);
pwrlist1 := [seq(2·sqrt(pwrlist_w), w = 1 ..num)];
pwr_points := [seq([(h − 1)/Time_num, pwrlist1_h], h = 1 .. num/2)]

plots[pointplot](pwr_points, style = line, view = [0 ..4500, 0 ..0.05])
```

Figure 3. *Program code for fast Fourier transform*

During the tests, more and more failure frequencies appear as time progresses, and their values increase exponentially. The largest changes were in the harmonics of error frequency of the cage and the outer ring. Figure 4 shows the evolution of failure frequencies of cage.

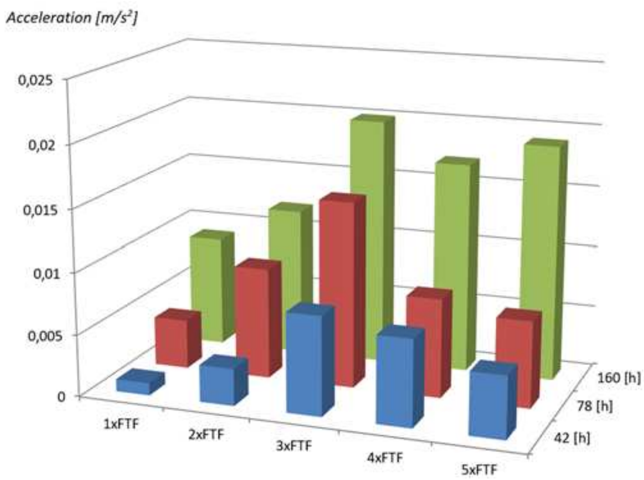

Figure 4. *Evolution of failure frequency of cage*

At the limit of the previously calculated lifetime, the fault frequency peaks in the vibration spectrum have become clearly visible. Figure 5 shows the temporal evolution of the fault frequency harmonics of the outer ring.

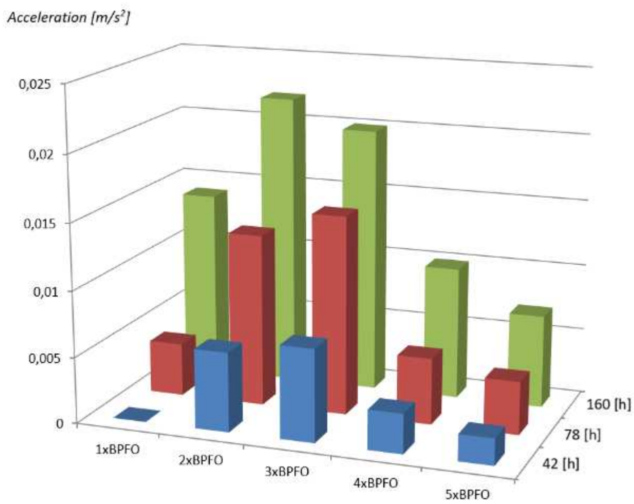

Figure 5. *Change of failure frequency of outer ring*

After the results of the frequency domain analysis indicated and the bearing noise increased, the bearing was taken apart to pieces. As predicted the frequency domain analysis after 161 fatigue hours the bearing indeed had a defect. The main reason of bearing failure was the failure of cage (see Figure 6).

Figure 6. *Failure of cage*

As expected from the results of the spectral analyses, it can be concluded that the main cause of the failure of the tested bearing is damage of the cage structure. The high load force certainly contributed to the development of the defect.

4. SUMMARY

Accurate and trustworthy measuring methods and devices are necessary for rotary and bearing condition monitoring. The investigation of vibration signals is an important technique for monitoring the condition of machine components. The present paper shows that the frequency domain techniques can be effectively used in condition monitoring and fault diagnosis of ball bearings. These methods are reliable tools, and they make fast data processing possible.

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COMPARING THE MARKET HISTORY OF MOBILE PHONES AND ELECTRIC CARS BY USING SIGMOID CURVES

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Abstract: The time curves of market history for mobile phones and for electric cars is compared by sigmoid curves. Creating the approximate sigmoid curves of the curves showing the real data of products sold in function of the time, it is possible to find similarities and differences of the time history of the market of mobile phones and electric cars. One of the most important decisions during this investigation is to decide, which curve describes better the product investigated: Logistic curve (Pearl-Reed curve) or Growth curve (Bertalanffy)? On the basis of many characteristics of these curves, in the second step of the study it is possible to characterise the market of the products, and the comparison can give important points of view for the understanding the present situation of the markets and to try to forecast their possible future.

Keywords: *market of mobile phones, market of electric cars, comparison, sigmoid curves*

1. INTRODUCTION

Sigmoid curves are very useful to describe several phenomena of our life. If we have the equation and the diagram of the sigmoid curve, it is possible to find very useful and interesting characteristics of the investigated phenomenon. Investigating as many cases as possible can give new points of view for the study of a concrete case: the sigmoid curve has all its characteristics in every case, but it is necessary to "translate" or reinvent or reconsider what could be the actual meaning of a given property of the curve. This reinvention can lead to a new conclusion on the investigated phenomenon, it can give a new point of view for the studies, which was not investigated before. In this way it is possible to "learn" new information from the investigation of several different phenomena.

The author of this paper until today performed the investigation of the following cases:

- Iteration history curve of optimisation algorithms (Szabó, 2018), (Szabó, 2023);
- 100 years history of sport world records (long jump, women and men, world and Hungarian, javelin throw, man and women, world and Hungarian) (Szabó, 2011);
- Comparison and characterisation of different student groups by using the EBSYQ system (Evolutionary Based System for Qualification of Group Achievement), writing the same test (Szabó, 2017);
- Forecasting the possible future of the plastic waste quantity of the world seas and oceans (Szabó, 2019);
- Investigating the wear curve of machining tools (Szabó, 2021);
- Application of sigmoid curves in product development (Szabó, 2022), (Szabó, 2021);
- Study of the market of electric cars (Szabó, 2023);
- Time history of the COVID-19 disease in Hungary from March 2020 until June 2023 (Szabó, 2020), (Szabó, 2022);
- Possibility for decreasing the time necessary for experiments (Szabó, 2024).

During the investigation these different phenomena it was possible to derive many useful conclusions which can be used for the forecasting and characterising some other or newer phenomena (Bihari & Sarka, 2018). The EBSYQ system can give the possibility to compare sigmoid curves of cases very accurately and detailly, giving numerical differences of several points of view of the comparison. This accurate comparison shows the existing differences between phenomena even in case when they are very similar to each another or the shape of the curves are very close to each another. This could help us during the qualification of the cases and to decide which one is “better” or “quicker”, etc.

2. TYPES OF SIGMOID CURVES

Two important forms of the sigmoid curves can be identified in the literature:

- Pearl-Reed (logistic) curve, they used it for the analysis of the population of the United States in 1920 (Pearl & Reed, 1920).
- Bertalanffy (growth) curve, he used this curve for measurements of agricultural products in 1960 (Von Bertalanffy, 1960).

The most important difference between these two curves is the derivative curve, which is monotone decreasing in case of Bertalanffy curve, but the derivative of the Pearl-Reed curve has an increasing part, too. Other important difference is that the Pearl-Reed curve in the beginning part has an exponential increasing shape and only after the inflexion point will have the saturation growth part. Table 1 shows the shape of the curves, the derivatives and the integrals. The equations of the curves:

Pearl and Reed (logistic) curve:

equation of the curve: $y(x) = \frac{K}{1+ce^{-rx}}$, first derivative: $\frac{dy(x)}{dx} = \frac{Kcre^{-rx}}{(1+ce^{-rx})^2}$, integral:

$$\int y(x)dx = -\frac{K}{r}\ln(e^{-rx}) + \frac{K}{r}\ln(1 + ce^{-rx}) \tag{1}$$

Bertalanffy (growth) curve:

equation of the curve: $y(x) = K(1 - ce^{-rx})$, first derivative: $\frac{dy(x)}{dx} = Krce^{-rx}$, integral:

$$\int y(x)dx = Kx + \frac{Kc}{r}e^{-rx} \tag{2}$$

For the approximation of the curves the least squares approximation technique (Szabó, 2022) is used, but before this approximation it will be always necessary to transform the exponential functions into linear function. For this step the Fisher-Pry transformation (Fisher & Pry, 1971) is applied.

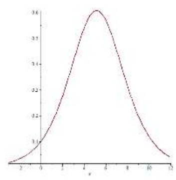
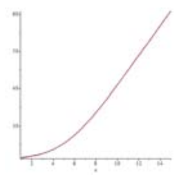
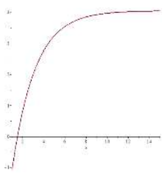
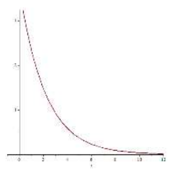
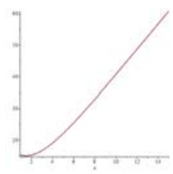
When using the method of least squares, it is necessary to approach the given discrete values $(xi, yi),\ i = 1, 2, 3, \dots, n$, by a function $y^* = f(x)$, while the parameters of the curve should give the minimum possible value of the sum of the squares of the differences. This means that regarding the approximating function values $f(xi) = y_i^*$, we have to find:

$$H = \sum_{i=1}^{n}(y_i - y_i^*)^2 = min \tag{3}$$

Equation (3) describes an optimisation problem. For the numerical solution this optimisation problem Nelder-Mead (Nelder & Mead, 1965) optimisation algorithm is used, searching the minimum of the H function (3).

Table 1

Two important sigmoid curve types

Pearl- Reed (logistic curve)		
The curve	**Derivative**	**Integral**
		
Bertalanffy (Growth curve)		
The curve	**Derivative**	**Integral**
		

Calculating the regression coefficient of the linear regression R_{lin}, it is possible to decide, which type of the sigmoid function gives the best approximation to the investigated phenomenon: If the value of the regression coefficient is closer to 1, that type of curve is better for further approximation or forecasting.
The regression coefficient can be calculated as:

$$R_{lin} = \frac{A_{xy} - \frac{B_{xy}}{n}}{\sqrt{\left(C_x - \frac{D_x}{n}\right)\left(C_y - \frac{D_y}{n}\right)}} \qquad (4)$$

where:
$A_{xy} = \sum_{i=1}^{n} x_i y_i$, $B_{xy} = \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i$, $C_x = \sum_{i=1}^{n} x_i^2$, $D_x = (\sum_{i=1}^{n} x_i)^2$,
$C_y = \sum_{i=1}^{n} y_i^2$, $D_y = (\sum_{i=1}^{n} y_i)^2$.

In equation (4) it is possible to calculate the linear regression coefficient of the y* transformed function determined in equation (3), but it is simpler return to the y notation.

3. MARKET OF MOBILE PHONES

It can be seen in Figure 1, that the number of smart phones sold to end users worldwide from 2007 until 2023 shows the classical Pearl-Reed curve (logistic curve) form. From the shape of the curve, it can be evidently decided, that the logistic curve will be the best to approximate it, because the Bertalanffy curve cannot follow its exponential growth part in the beginning of the curve. After 2020 it is possible to detect a little decrease of the market, but it is possible also to discover some effects of innovations or developments in 2021 and 2022. This means that the real shape of the curve could be a multi-logistic curve with two waves.

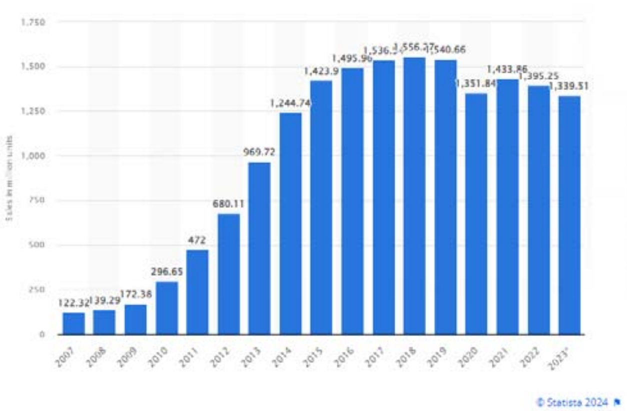


Figure 1. *Mobile phones sold from 2007 until 2023*
https://www.statista.com/statistics/271496/global-market-share-held-by-smartphone-vendors-since-4th-quarter-2009/

Figure 2 shows the number of mobile network subscriptions sold worldwide from 2016 and forecasted until 2028. The shape of this curve does not show in its beginning part the exponential growth shape, so in this case the Bertalanffy curve will be the best to approximate.

Comparison of the curves shown in Figure 1 and Figure 2 shows that the market of the mobile phones follows the classical form of product life curve. The market of the mobile network subscriptions follows the Bertalanffy growth curve. This means that the number of mobile networks sold is always growing monotone, not needing any development or innovation, but the number of mobile phones can show a saturation part, with decreasing market, so it will need in the future more intensive developments and innovations. If the market is already saturated, the efficiency of the developments and innovations will be slower and slower.

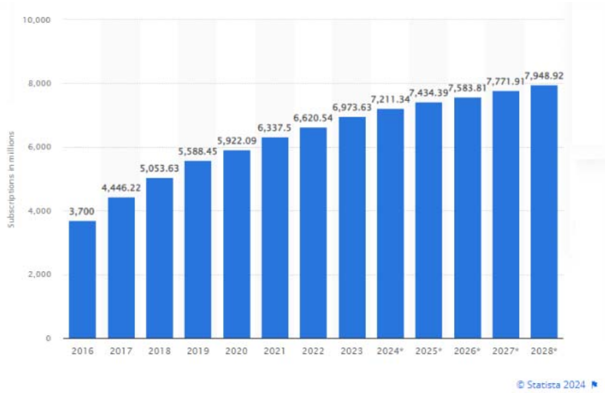


Figure 2. *Mobile network subscriptions from 2016 and forecasting until 2028.*
https://www.statista.com/statistics/271496/global-market-share-held-by-smartphone-vendors-since-4th-quarter-2009/

4. MARKET OF ELECTRIC CARS

The electric cars selling in percents of the total number of new cars sold is shown in Figure 3, for Europe, China and USA. The figure shows that all three curves are sigmoid curves, with several decreasing parts and renewal of the market, which means that this segment of the market can be described by multi wave logistic curves. The presence of the newer and newer increasing parts shows the effects of significant innovation works, developments and several forms of government grants.

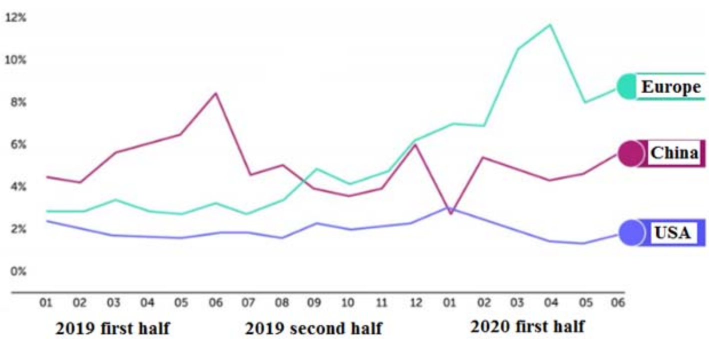


Figure 3. *Market of electric cars by the new cars selling in percents, regarding USA, China, Europe*
https://theicct.org/

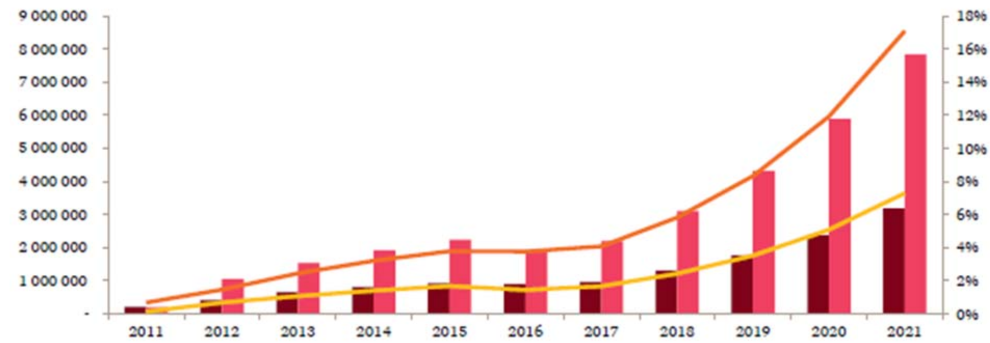


Figure 4. *Number of electric cars manufactured in the world and in Europe*
www.pwc.com/hu

Figure 4 shows the number of the manufactured electric cars in the world and in Europe from 2011 until 2021. Both these curves show that between 2016-2017 there was a saturation in the manufacturing of electric cars, but after this period it was renewed, and it is growing monotonous also in our time. This new part of increasing could be the result of several innovations and/or developments.
The number of electric cars in Hungary (Figure 5) shows a very similar shape, the only difference is that the saturation part of the curve is between 2019-2020, a little bit later than in the World or in Europe. The EU 90 g/100 km rule also has an effect to this curve.

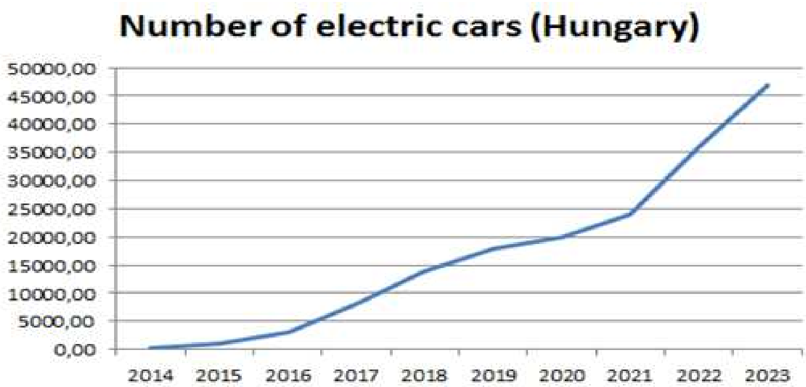


Figure 5. *The number of electric cars in Hungary, from 2014 until 2023*
www.pwc.com/hu

Figure 3, 4 and 5 show the situation of the manufacturing of electric cars. These curves are very optimistic regarding the possible future. However, in the end of 2024 latest news say that because of a worldwide decrease in the demand for electric cars, several electric car manufacturers and manufacturers of parts for electric cars close some parts of their factories, provoking the termination of employment of several thousands of workers, so possibly the increasing tendency of the electric car manufacturing will slack in the future. In this dim and equivocal situation, it would be hazardous to build any forecasts for the future, in particular long-term prognosis.

5. SUMMARY

In this paper the market of the mobile phones is studied by the sigmoid curves of the number of mobile phones sold worldwide between 2007 and 2023 and by the sigmoid curve of the mobile network subscription sold from 2016 and forecasted until 2028. The analysis of the sigmoid curves shows that the mobile phones market shows the shape of the classical product life curve, even with decreasing market in 2020. In order to increase this market, the experts and managers will need to do important innovations or developments. The number of mobile network subscription describes a monotonous growth shape, so in this case no need to do innovations or developments, the growth will continue in the future without any problem. Comparison of the number of waves of the curves, it can be concluded that the market of electric cars regarding the percentage in new cars selling shows more waves than market of mobile phones. This means that the market of the electric cars needs high amount of innovations, developments and governmental grants in order to compete with other car types. Regarding the curve of the number of electric cars in Hungary, it is very similar to the curve of the World or of Europe, but the difference is that the saturation period of the Hungarian curve is later, than it is in case of the world or Europe. Comparing the sigmoid curves of mobile phones and electric cars, it is very interesting that from 2017 until 2020, a strong saturation period can be found in the curves. This shows a significant decrease of the market in case of mobile phones and in case of electric cars, too. In this kind of situations an innovation or some developments could be necessary to increase the market again. In case of the electric cars the experts and managements performed these innovations or developments and maybe there are government grants too; therefore, it can be seen a remarkable increase in the amount of the market. In case of the mobile phones this increase is smaller, which means that the innovations or developments are not enough to improve the market. In future work it would be very interesting to investigate the reasons of the saturation of the markets in 2017 and to find, what could be the reason for this saturation presents a little bit later in Hungarian electric car market.

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MANUFACTURING ISSUES WITH 3D-PRINTED GEARS MECHANICAL PROPERTIES – A LITERATURE SURVEY

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Abstract: Additive manufacturing, often known as 3D printing, is substantially revolutionizing the industrial environment by turning new ideas into tangible items. This technology promotes innovation in various industries, like healthcare, aerospace and automotive, by allowing for the development of sophisticated, one-of-a-kind designs while reducing waste and expenses. Prompting improvements in production, additive manufacturing demonstrates a great deal of design variation while also being very efficient. This technology reforms traditional production techniques and makes solutions that were previously impossible. This research delves into the mechanical properties and production challenges of additively manufactured 3D-printed gears. The evaluation of gear performance focuses on the influence of essential characteristics, including the analysis of printing orientation and infill patterns, among other factors. Mechanical properties such as tensile and bending strength rise in a horizontal direction; conversely, in a vertical structure, the reverse is true. Concentric, grid-like infill patterns improve materials like PLA and PLA+ in strength and surface quality. This study examines significant challenges, such as thermal expansion and air gaps that affect gear reliability. Effective solutions require refining gear designs, enhancing heat dissipation, and optimizing material properties. The research findings improve comprehension of how 3D-printing parameters affect gear performance, offering valuable insights for the design and manufacture of durable, high-performance 3D-printed gears in industrial applications.

Keywords: *printed gear, additive manufacturing, printing orientation, infill patterns*

1. INTRODUCTION

Additive manufacturing (AM), sometimes referred to as 3D printing, is a process used to construct three-dimensional solid items using 3D computer-aided design (CAD) model data, typically in a layer-by-layer manner, in contrast to conventional subtractive manufacturing techniques. This technology may replace several traditional manufacturing processes and enable the emergence of novel business models, goods, and supply networks (Markiz, Horváth, & Ficzere, 2020). The primary advantages of selecting additive manufacturing are design flexibility, cost-effective prototyping, material efficiency, customization, supply chain simplicity, and energy efficiency (Gupta, 2018), besides, AM is used in various applications in the medical-, defence-, aircraft-, and automobile industries, etc.

In mechanical power transmission systems, gears play a crucial role. They are suitable for both large rotating machines and small wristwatches because of their size variation. They are often composed of several metallic and non-metallic materials (Karupaiah, et al., 2024). Polymer gears have become favoured in moderate and heavy-duty tasks mainly to their cost-effectiveness and lower noise levels in comparison to metal gears. These polymer gears have several benefits, including cost-effectiveness, reduced weight, better efficiency, almost noiseless operation if the lubrication is in the right quantity, and in most cases the absence of a need for external lubrication, however, it is needed for specific cases. These characteristics make them especially appropriate for applications in automotive, aeronautical and medical engineering (Pujari, Manoj, Gaddikeri, Shetty, & Khot, 2024).

The mechanical properties of a 3D-printed gear can be negatively influenced by thermal expansion and material softening when the surface temperature of its teeth rises as a result of load and friction. This may result in excessive wear, deformation, and possible breaking of the gear teeth. Utilizing materials with great thermal stability, refining the gear design for increased heat dissipation, and ensuring considerable lubrications to lower friction are vital for reducing these defects. Additionally, any thermal issues can be quickly identified and addressed with thorough testing and careful observation of the operational conditions of the gear (Yilmaz, Yilmaz, & Gungor, 2024).

Among all parameters, those affecting the mechanical properties of the gear, printing orientation and infill pattern have their share of influencing the gear performance and need to be demonstrated properly.

Loads act on the gear tooth, and these loads create a bending moment somewhere on the tooth root, which can damage the tooth and break it somehow (rigid or fatigued). So, the aim is to investigate and know which printing direction is good since the helical gear starts horizontally and goes up at an angle, as shown below in Figure 1. Consequently, the best printing direction reduces the damage to the tooth.

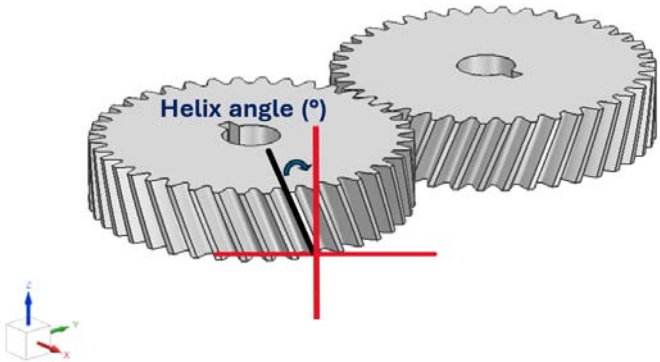

Figure 1. *Helix Angle direction of two meshed gears*

And need to experience which type of infill pattern can endure and withstand the loads (pressure and bending moment), as explained in Figure 2. The line of action is signed with blue line in the figure, for the two meshed gears. The normal tooth force is (red) acting on the centre point of the flank, in the direction of the line of action, the letter "n" indicates the direction of the rotation speed (black), while the bending moment loads the cross-section of the root of the tooth (green), with the possibility of using different types of patterns simultaneously.

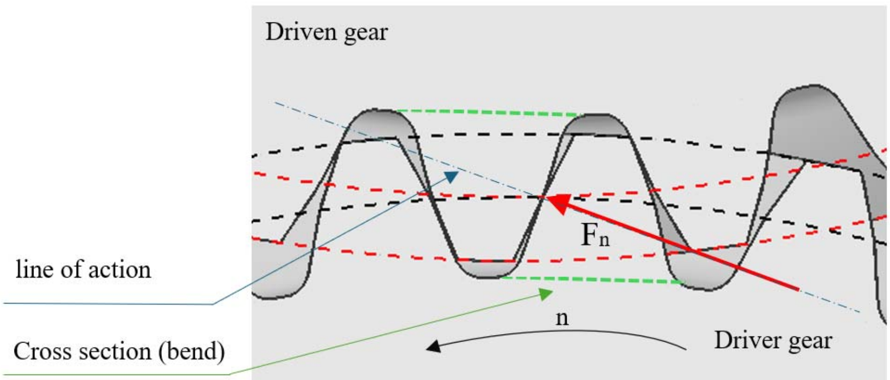

Figure 2. *A simple schematic diagram showing the (force and the bending moment) acting on the teeth*

2. THE INFLUENCE OF PRINTING ORIENTATION ON THE STRENGTH OF THE COMPONENTS

As mentioned earlier, many factors can influence the strength of the printed part. Among these factors -as an additive manufacturing technology- printing orientation shows up with a pivotal effect, as it significantly impacts the behaviour of the printed part by determining how much the printed part can endure for a long time of working cycles without a breakage.

Horizontal orientations along the XY (flat) and YZ (on-edge) offer the best tensile and impact strength in comparison to vertical orientations along the ZX (which are often poorer in terms of strength and stiffness) (Mohd Khairul Nizam, Ismail, & Yap, 2022), as illustrated in Figure 3. Moreover, to investigate the impact of printing orientation (horizontal/vertical) and printing continuity on the strength of the printed components, printing with a pause for a specified duration and resuming afterwards does not considerably affect ultimate tensile strength for the horizontal direction, in contrast, the vertical direction resulted in reduced ultimate tensile strength (Alzyod & Ficzere, 2022). Optimal orientation selection, such as horizontal alignment, is best for gears used in load-bearing applications.

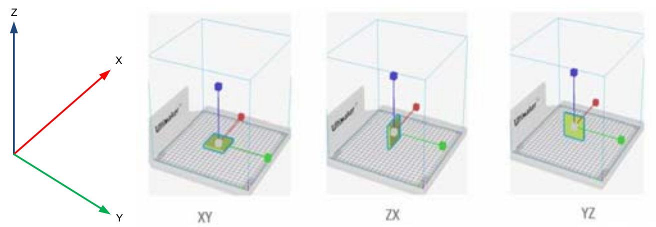

Figure 3. *Printing Orientation*
(Mohd Khairul Nizam, Ismail, & Yap, 2022)

For all orientations (upright, on-edge, and flat), increased feed rates resulted in reduced strength and stiffness properties, contributing to more brittle behaviour. Conversely, increased layer thickness in various printing orientations enhanced tensile and bending strengths; however, this also resulted in a heavier specimen, extended printing duration, and lowered ductility (Chacón, Caminero, García-Plaza, & Núñez, 2017). Three orientations (X, Y, Z) and three cooling settings (cooling within the printer, in an oven, and at room temperature) were examined to assess the impact of printing direction and post-printing cooling conditions on the fatigue bending properties. The results indicated that specimens in the X and Y directions showed similar mechanical performance when cooled in the printer or oven;

conversely, samples cooled at room temperature exhibited weaker performance, with Z-direction samples demonstrating the poorest bending ability. For industrial applications, oven cooling may be superior to in-printer cooling (Glaskova-Kuzmina, et al., 2023).
Upon investigating the influence of angle on mechanical properties, a sample printed along the x-axis at various angles (0°, 30°, 60°, 90°), as illustrated in Figure 4, revealed no correlation between the orientation of the specimen on the printing bed and the direction of the fracture surface, which is perpendicular to the applied testing force (Cojocaru, Frunzaverde, Nedelcu, Miclosina, & Marginean, 2021).

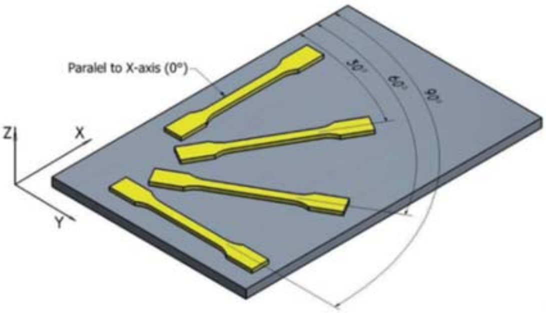

Figure 4. *Printing orientation angle*
(Cojocaru, Frunzaverde, Nedelcu, Miclosina, & Marginean, 2021)

Oppositely, ultimate tensile strength is at its highest at a 90° printing angle and reduces as the angle lowers when the samples are printed vertically, as the layers are aligned with the direction of the applied force (Yao, Deng, Zhang, & Li, 2019), as briefly shown below in Figure 5.

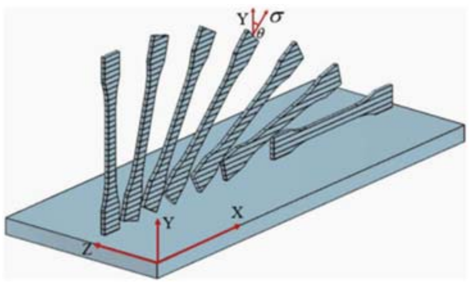

Figure 5. *The printing positions and angles of 3D printing specimens*
(Yao, Deng, Zhang, & Li, 2019)

3. THE INFLUENCE OF THE INFILL PATTERNS ON THE MECHANICAL PROPERTIES OF THE COMPONENTS

As a part made by additive manufacturing, so-called 3D printing, which totally differs from the conventional manufacturing methods (i.e. injection moulding, CNC, hobbing, etc.), the infill pattern plays a crucial role in defining and determining the mechanical properties and lifetime of a product.

The selection of various materials and infill patterns significantly affects the mechanical properties of the printed component. Various densities (20% - 100%) for diverse filling patterns, as seen in Figure 6, indicate that the concentric and grid patterns yield superior surface quality and tensile strength for Polylactic Acid (PLA). Conversely, triangle and zigzag designs have the least desirable properties (Lalegani Dezaki, et al., 2021). Moreover, increasing the infill density enhances strength but increases weight.

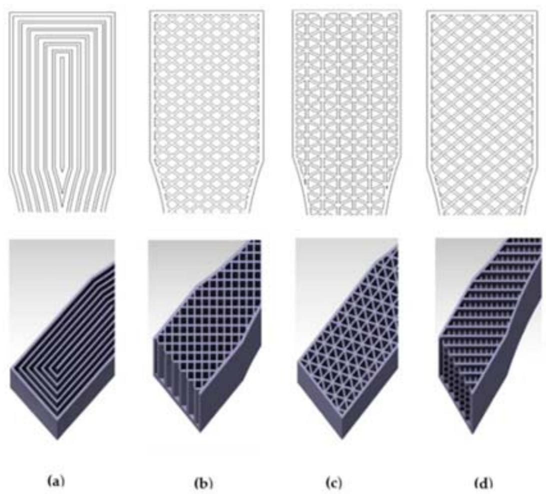

Figure 6. *(a) concentric pattern, (b) grid pattern, (c) triangle pattern and (d) zigzag pattern (Lalegani Dezaki, et al., 2021)*

For enhanced PLA (PLA+/tough PLA), which offers greater resistance against damage than the normal PLA, the concentric pattern offers optimal strength and surface quality, whereas the gyroid and quarter-cubic, Figure 7, patterns for Polyethylene Terephthalate Glycol (PETG) provide superior smoothness and high tensile strength (Kadhum, Al-Zubaidi, & Abdulkareem, 2023).

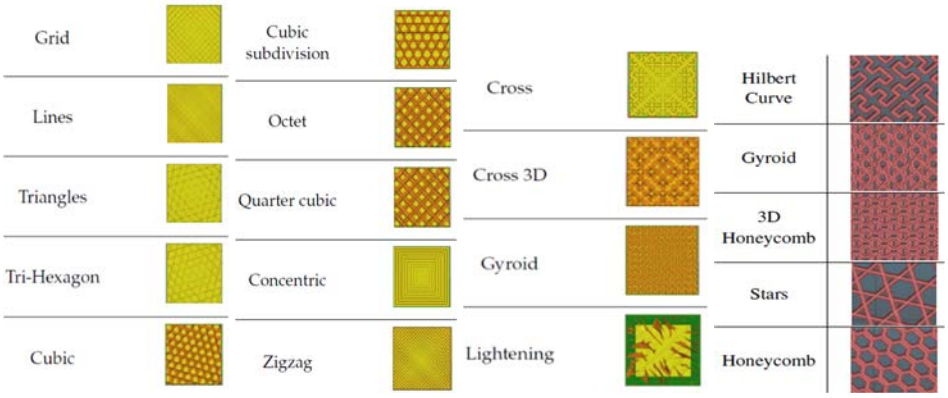

Figure 7. *Different infill patterns*
(Kadhum, Al-Zubaidi, & Abdulkareem, 2023)

Whereas the influence of raster angle greatly enhances the strength for specific raster angles (0° - 90°). The 0°, 90° raster angle exhibits greater resistance to deformation, whereas -45°, +45° enhances elongation and toughness (taking into consideration the part design and shape). Taking care of the air gaps -space between two tool paths- is also important to ensure better properties; however, as the air gaps decrease, as shown in Figure 8, tensile strength increases (Akhouri, Karmakar, Banerjee, & Mishra, 2021). The best pattern in this concern is the honeycomb and the hexagonal, which leave small air gaps, while The Hilbert tends to have the weakest properties because of the large air gaps (Eryildiz, 2021).

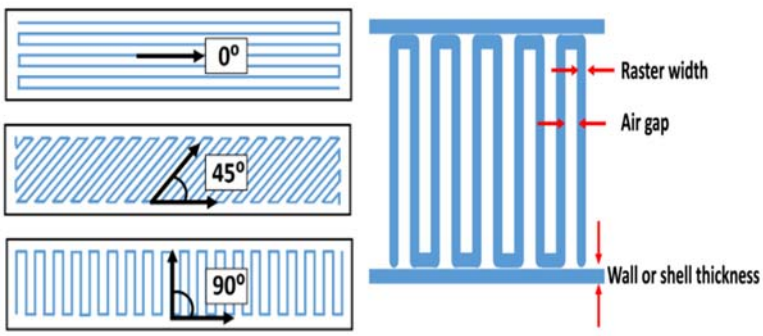

Figure 8. *Air gap and raster properties (angle, width)*
(Gordelier, Thies, Turner, & Johanning, 2019)

4. Conclusion

The examination of manufacturing challenges in 3D-printed gears underscores the considerable impact of printing orientation, infill patterns, and material characteristics on their mechanical performance. The best printing orientation, especially when aligned horizontally (in the XY and YZ planes), significantly improves tensile and bending strength, which is perfect for applications that bear loads. On the other hand, vertical orientations typically demonstrate weakened strength and stiffness.

Infill patterns are crucial, with designs like concentric and grid patterns providing enhanced strength and surface quality for materials such as PLA and PLA+ (tough). Increasing infill density improves mechanical properties; however, this comes with the cost of added weight and longer printing durations. Furthermore, the impact of raster angles and air gaps highlights the necessity for careful design to enhance strength and elongation characteristics. Dealing with issues like thermal expansion, wear, and deformation demands meticulous material selection and operational modifications, including enhanced heat dissipation and lubrication methods. The findings establish a basis for enhancing the durability and efficiency of 3D-printed gears, facilitating their wider use in mechanical systems across multiple industries.

Future research should focus on advanced materials selection and hybrid infill patterns to further enhance the performance of these components. It should also address the possible damages that could happen to 3D-printed gears and distinguish them from other traditional gear manufacturing technologies.

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