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EDITORIAL



I am delighted to welcome you to the inaugural issue of the International Journal Polytechnic, an international, peer-reviewed, open-access journal published by the Academy of Applied Studies Polytechnic in Belgrade.

A new journal begins with a commitment rather than a reputation. Ours is to publish research in the technical and technological sciences that is methodologically sound, relevant to practice and openly available to all. Academies of applied studies work at the point where scientific knowledge meets industry, agriculture and public services, and much valuable research emerges from that position. The International Journal Polytechnic was founded to give such research a home, and to incubate, influence and inspire work in technological development.

From the outset, the journal has been conceived as international. Its editorial board brings together researchers from Serbia, Bulgaria, Slovenia, North Macedonia and Vietnam, and we intend to build the same diversity among authors and reviewers. The journal is published twice a year, in June and December, and every manuscript undergoes peer review in line with recognised standards of publication ethics.

This first issue reflects the breadth of the journal's scope. Three papers in biotechnology and agriculture address maize and millet intercropping for biomass production, customs protection of agricultural production in Serbia, and flower bud differentiation in strawberry. They are complemented by a multifractal comparison of an original painting and AI-generated images, and by two review articles in mechanical engineering, on aircraft flight control actuators and on a digital-twin-enabled architecture for metal cutting.

I sincerely thank the authors who entrusted their work to a new journal, the reviewers whose expertise safeguards its quality, the members of the editorial and advisory boards, and the management of the Academy of Applied Studies Polytechnic, whose support made this first issue possible.

The credibility of a journal is earned issue by issue. I invite researchers and practitioners from Serbia, the region and beyond to take part in building it, as authors, reviewers and readers.

Marina Stamenović, PhD, professor of applied studies,
Academy of Applied Studies Polytechnic, Belgrade, Serbia
Editor-in-Chief

EDITORIAL



It is my pleasure, as Deputy Editor-in-Chief, to introduce the scientific scope of the International Journal Polytechnic. The journal is built around four areas of the technical and technological sciences that are increasingly interconnected in research and in practice.

Biotechnology, agriculture and food technologies cover sustainable production, plant and food biotechnology, and food quality and safety. Electrical engineering, electronics and telecommunications include energy efficiency, embedded systems and communication networks. Information technology and industrial software encompass data analysis, artificial intelligence, cyber security and industrial automation. Mechanical and production engineering address manufacturing technologies, materials, mechatronics and quality management.

The connections between these areas are as important to us as the areas themselves. Precision agriculture relies on sensors and software, modern manufacturing on data and automation, and food safety on digital traceability. We therefore particularly welcome interdisciplinary research, as well as applied studies grounded in industrial practice that meet the standards of scientific rigour.

I thank our co-editors, whose expertise makes this broad scope possible, and I encourage researchers and engineers in all these fields to help shape the profile of the journal from its very first volume.

Aleksandar Stevanović, PhD, professor of applied studies,
Academy of Applied Studies Polytechnic, Belgrade, Serbia
Deputy Editor-in-Chief

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Original research article

INTERCROPPING OF MAIZE AND MILLET FOR ECONOMICAL BIOMASS PRODUCTION

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Abstract

Maize (Zea mays L.) and millet (Panicum miliaceum L.) are very important cereals with excellent grain quality. Due to their low input requirements and small production losses, millets are among the best crops for agricultural sustainability. Maize is strategically one of the most important plant species in the world, as it is the most widely distributed agricultural plant in Serbia and ranks third globally (with 143 million ha), behind rice (151 million ha) and wheat (215 million ha). The goal of sustainable agriculture is to provide nutrients and high-quality food with as little negative environmental impact as possible. One of the most effective strategies for producing biomass with high nutritional value is to combine crops. This study assessed the productivity of two crops produced as a sole crop and as an intercrop. The following crop combinations were tested: sole millet, sole maize, and alternating rows of maize and millet (C-M). The plants' morphological characteristics were determined, and the aboveground biomass was gathered. The C-M combination produced the highest biomass yield in mixed crops. Intercropping is therefore the most promising method for producing large amounts of biomass yield.

Keywords: *Maize, millet, intercropping, morphological traits, chernozem.*

1. INTRODUCTION

Millet (Panicum miliaceum L.; Poaceae) is a plant species cultivated 10,000 years ago in China. It achieves high biomass and grain yields. The grain is rich in proteins, oils, minerals, and vitamins and is an important source of energy (Popović et al., 2025). The convenience of consuming millet is due to its easy digestibility and the fact that the grain does not contain gluten, which makes it an ideal food for gluten-intolerant people. It contains calcium, iron, potassium, magnesium, phosphorus, zinc, dietary fiber, polyphenols, and proteins (about 12%). In 2023, millet was sown globally on 31.33 million ha, while the average world

production was 31.59 million t. According to FAO (2025) data, the most important world producers of millet are Africa (63%) and Asia (34%). The average world yield of millet was 100.800 kg ha-1. In Serbia, millet was sown on 112.0 ha; the total production was 107.1 t, while the average yields were slightly higher than the average world yields (Božović et al., 2020; 2022; Popović et al., 2025). In Europe, yields were significantly higher than the average world yields and amounted to 1.79 t ha-1. Production amounted to 661,707.80 t from harvested areas (368,612.00 ha). For successful production, it is necessary to select several genotypes suitable for the planned growing region. The genotype is only one of many, but also the most important production factor (Popović et al., 2025). The stability and adaptability of genotypes are best evaluated by testing varieties in different environments and ecological areas (Glamočlija et al., 2015).

Maize (Zea mays L.) is one of the most abundant plant species in the world. Strategically, it is an important agricultural species that ranks third in distribution in the world (143 million hectares), after wheat (215 million hectares) and rice (151 million hectares), and in Serbia it is in first place. In the last few years, the area under maize in Serbia has averaged around 1 million hectares and has been experiencing fluctuations. The hybrid is only one of many, but also the most important production factor, the effect of which, fortunately, can be controlled. For successful production, it is necessary to select several hybrids, the most suitable for a specific agroecological area (Pavićević, 1984; Živanović et al., 2017; Babić et al., 2026; Mladenović Drinić et al., 2024; Popović, 2010; 2015). The average yield of maize in the world is 5.6 t ha-1 (Maksimović et al., 2018). In dry years, in order to ensure successful production of maize, it is necessary to apply irrigation to the crop (Pavićević, 1984; Munćan et al., 2018; Popović et al., 2024). Sustainable agriculture implies high-yield production of high-quality food and nutrients with minimal harmful impact on the environment. By combining crops, biomass of high nutritional value is obtained. Because millets can be cultivated in challenging settings with minimal output losses, they are among the best crops for maintaining agriculture. Another benefit of this crop is that it can be grown on marginal land and in low-input agricultural circumstances. Because millet can adapt to a wide range of agro-ecological situations, it becomes a significant cereal for intercropping (Habiyaremy et al., 2017). Millet is one of the earliest crops to be cultivated. It is more valuable than other cereals because it contains high-quality proteins, which is why its increased use is justified (Kalinová, 2007).

High inputs are required to generate high yields in intensive agriculture systems, which are frequently focused on productivity and profitability. According to Malézieux et al. (2009), these systems have a detrimental effect on the ecosystem in terms of soil and water, increasing chemical contamination and reducing biodiversity. Sustainable agriculture is an economically viable form of farming that respects the environment. Efficient resource utilization that enhances food and feed security and stability is the goal of sustainable agriculture (Mousavi & Eskandari, 2011). Intercropping, crop rotations, cover crops, and other techniques are suggested to adhere to the principles of this type of agro-ecology (Duchene et al., 2017). One of the most effective methods for producing nutrient-rich biomass for animal feed is intercropping (Iqbal et al., 2018).

The success of intercropping depends on the spatial arrangement of crops and the plant species selected. When compared to a single crop, the performance of one crop grown as an intercrop can differ dramatically (Nelson and Robichaux, 1997; Esmaeili et al., 2011). Due to their better use of resources, cereals and legumes are known to be a good combination for intercropping (Duchene et al., 2017). Furthermore, legumes are N-fixing plants and a significant source of N (protein) for both people and animals (Amanullah et al., 2016). Conversely, because of their low cost and high dry matter output, grains are often used as a starchy component in cattle feed despite having a low protein content. Combining these

cereals can provide a solid foundation for producing high-quality fodder that is profitable. Productivity, soil fertility, fodder quality, and less damage from pests, diseases, and weeds are examples of potential benefits, according to Eskandari et al. (2009).

Recent findings from rainfed maize production further emphasize the importance of diversified cropping strategies for improving crop productivity and resource-use efficiency. In particular, the use of pea–oat cover crops was associated with improvements in maize ear leaf area, grain yield, and nitrogen use efficiency under residual nitrogen fertilization (Vasileva et al., 2026). These findings support the broader concept that combining maize with complementary crop species may contribute to more efficient use of available resources and more sustainable production systems. However, the potential of maize–millet intercropping specifically for biomass production requires further evaluation.

Recent research has also demonstrated the potential of maize–millet intercropping for biomass production under field conditions, with the combined crop showing a high biomass production compared with the respective sole crops (Popovic et al., 2026). Nevertheless, further evaluation of maize–millet intercropping under different agroecological and management conditions is needed to better understand its effects on the morphological and productive characteristics of the component crops.

The aim of this study was to determine the optimal cultivation technology for growing maize and millet as intercrops. Furthermore, it sought to integrate alternative gluten-free grains into traditional maize production systems to enhance environmental sustainability and public health. This approach aligns with the sustainable management of natural resources and aims to reduce the use of agrochemicals in the food production process.

2. MATERIALS AND METHODS

Experimental trials with maize and millet were carried out in Bački Petrovac, at the experimental field of the Institute of Field and Vegetable Crops, Novi Sad, in 2025. In this study, the following cropping systems were investigated: alternating rows of maize and millet (C-M), a sole crop of maize (C), and a sole crop of millet (M). The subjects of the research were: 1) Maize genotype 'Kn 435', which was selected at the Maize Research Institute in Kneža, Bulgaria; and 2) Millet genotype 'Biserka', which was selected at the Institute of Field and Vegetable Crops, Novi Sad, Serbia.

Aboveground biomass was collected from all plots. The experimental plots consisted of four rows with a total area of 10 m² (2 × 5 m), with an inter-row distance of 50 cm and an intra-row distance between plants of 5 cm for both millet and maize. The preceding crop was buckwheat. Sowing was performed during the optimal period, in the middle of April (April 22, 2025). During the growing season, mechanical agrotechnical practices were applied. Harvesting was conducted at technological maturity, at the end of August. Following the harvest, samples of ten plants each were taken from each experimental plot for the investigated parameters: plant height (cm), panicle weight (g), panicle length (cm), grain weight per panicle (g), grain weight per plant (g), and total plant weight (g).

The millet variety 'Biserka' was characterized by a short vegetative period, which made it suitable for cultivation in late sowing, a short stem, which provided excellent tolerance to lodging, and a high yield potential. The tested variety developed light green, upright stalks that occasionally branched at the base, and it produced white grains. The experiments were laid out in a randomized complete block design (RCBD) with three replicates, with a randomized arrangement of variants. During the experiment, standard cultivation technology was applied for common millet (Berenji, 1993; Hunt et al., 2011; Santra, 2013; Popović et al.,

2025) and maize (Pavićević, 1984; Popović et al., 2024, 2025). The breeders of the Institute of Field and Vegetable Crops created this variety of millet. The genetic potential of the variety exceeded 4 t ha^{-1} of seeds; it featured a short vegetative period of about 110 days, and it possessed short stems, which made it resistant to lodging and suitable for later sowing. On a dry matter basis, the ground seeds contained 16% protein, 72% starch, 2–3% mineral matter, and 2–4% fat (Popović et al., 2019, 2025).

2.1. Statistical analysis

Based on these measurements, the average values of the tested parameters per plot were calculated. The obtained results were statistically processed using the software package Statistica 12 for Windows. The statistical significance of the differences between the obtained mean values was determined by applying the analysis of variance (ANOVA) model, based on the F-test at significance levels of $p < 0.05$ and $p < 0.01$.

2.2. Soil conditions

The experiment was carried out on a Chernozem soil type. The soil samples taken for analysis, at a depth of 30 cm, had a slightly alkaline soil reaction; pH in H2O was 8.08, pH in KCl was 7.40, Total nitrogen was 0.18%, humus content 2.43%, carbonate content was 2.42% (CaCO3), while the content of readily available Al - K2O and P2O5 was 23.45 mg/100g and 26.82 mg/100g of soil. The Republic of Serbia is characterized by variable climatic conditions in terms of precipitation and air temperature. The limiting factor of agricultural production is precipitation. Therefore, irrigation is recommended in dry years (Popović, 2010, 2015, Popović et al., 2020). The optimal amount and favorable distribution of rainfall are prerequisites for a higher yield (Pavićević, 1984). The meteorological data used in the work were taken from the meteorological station in Bački Petrovac. The average monthly temperature was 22.1°C, while the total precipitation during the growing season was 283 mm.

3. RESULTS

The maize hybrid achieved good results in 2025. The average plant height in the control was 231.0 cm, height up to the first ear 114.0 cm, root length 17.1 cm, stem thickness 2.3 mm, plant mass 613.0 g, ear mass 192.0 g, mass of 1000 grains 50.7 g, number of grains per plant 560, while grain yield per plant was 173.0 g (Table 1).

Table 1. Morphological and productive traits of maize and millet in the control and intercropping systems, 2025

Genotype	Maize Kn 435	Millet Biserka	Intercropping Maize-Millet	Maize Std. Dev.	Millet Std. Dev.
Plant biomass, g	613.0	14.1	545.0+13.0	48.08	0.78
Plant height, cm	231.0	125.7	227.0+121.0	2.83	3.32
Plant height up to 1st ear/panicle, cm	114.0	104.0	98.0+92.0	11.31	8.49
Mass of ear/panicle, g	192.0	7.6	106.0+4.7	60.81	2.05
Number of grains per ear/panicle	479.0	937.0	307.0+809.0	121.62	90.51
Number of grains per plant	560.0	937.0	548.0+809.0	8.49	90.51
Mass of 1000 grains per plant, g	50.7	0.6	42.0+0.5	6.15	0.07
Yield (mass) of grains per plant, g	173.0	4.9	155.0+4.1	12.73	0.57

Source: Authors' calculations

The average height of the plant in the maize intercrop was 227.0 cm, height up to the first ear 98.0 cm, root length 17.0 cm, stem thickness 2.2 mm, plant mass 545.0 g, ear mass 106.0 g, mass of 1000 grains 42.0 g, number of grains per ear 307, number of grains per plant 548, while grain yield per plant was 155.0 g. The maize hybrid achieved better average results for all parameters compared to the variant with intercropped maize and millet.



a.



b.



c.

Figure 1. Maize crops (a), millet crops (b), and maize + millet crops (c), Bački Petrovac, 2025. Source: Authors

The high-yielding millet variety achieved excellent results in 2025. The average plant height in the control was 125.7 cm, height up to the first panicle 104.0 cm, plant biomass 14.1 g, root length 12.0 cm, stem thickness 0.6 mm, panicle mass 7.6 g, mass of 1000 grains 0.6 g, number of grains per panicle 937, while grain yield per plant was 4.9 g. The average height of the plant in the intercrop was 121.0 cm, height up to the first panicle 92.0 cm, root length 11.9 cm, stem thickness 0.5 mm, plant mass 13.0 g, panicle mass 4.7 g, mass of 1000 grains 0.6 g, number of grains per panicle 809, while grain yield per plant was 4.1 g. The Novi Sad millet variety Biserka achieved better average results for all parameters in the control (Table 1).

4. DISCUSSION

The grain yield of cultivated plants depends on their plant density, i.e., the shape and size of the vegetation area. By reducing the density of the crop, the yield is reduced. The reduction in yield caused by insufficent seeding cannot be compensated for by other agronomic practices. Furthermore, increasing crop density above the optimum has a negative effect on crop yield. The advantages of intercropping become more recognizable when two or more different types of plants are planted on the same land at the same time. Therefore, there is a need to understand the influence of the biological components of plants. By growing combined crops, due to the increase in the number of plants on the same surface, competitive relations are expressed within one species (intra-species) and between different species (inter-species). Competitive relations are especially pronounced in combined crops according to the system of additive series when one crop (maize) of optimal density is added to another crop (soybean, millet, buckwheat, or another crop) at different densities (Dolijanović, 2007; Popović et al., 2025; Popovic et al., 2026).

Cultivation of mixed crops is attractive for ecologists because of the diversification of agroecosystems and attempts to imitate the structure and stability of natural ecosystems, for economists because of increased productivity and income, and for sociologists because of finding a stable balance in nature. Solving this problem is carried out by determining the optimal volume and structure of production, where it is possible to achieve the maximum result under the conditions of the given limiting factors (area, mechanization, workforce, market). The procedure for determining the optimal production structure is based on the previously determined gross margin per unit of production capacity for each line. Preference is given to those lines whose representation will be the most economically efficient use of capacities and workforce (Dolijanović et al., 2007; 2020).

More recent research has mainly been related to the examination of the importance of intercropping in the strategy of nitrogen management in the soil. Intercropping can reduce nitrogen losses from agricultural systems by reducing nitrate leaching and ammonia and nitrous oxide volatilization into the atmosphere. It has been proven that combined crops affect weed control, reduce the occurrence of pests, nematodes, and various soil pathogens, and improve soil quality by increasing the content of organic matter and the availability of nutrients (Oljača et al., 2013).

Cultivation of combined crops, regardless of the great influence of meteorological conditions, is economically more profitable than conventional production. The advantages of this method of growing crops are especially evident in years when yields are significantly below average (Popovic et al., 2026).

The results obtained in the present study are consistent with recent findings emphasizing the agronomic potential of maize–millet intercropping. Author et al. (2026) reported that the maize–millet combination produced high biomass under field conditions and highlighted intercropping as a promising approach for increasing biomass production. In the present study, the combined crop likewise demonstrated advantages in terms of total plant biomass, supporting the potential of maize–millet intercropping as a strategy for efficient biomass production.

5. CONCLUSION

Based on the analysis of the obtained results, the following preliminary conclusions can be drawn:

The maize hybrid Kn 435 and the Biserka millet variety achieved good results in the examined year across both treatments, both in the control and in the intercrop. Millet is adaptable to climate change, with the potential for higher economic returns under marginal conditions compared to other cereals. It is used in food due to its positive effect on human health. The variety Biserka achieved a statistically significantly higher average value of all parameters in the control compared to the intercrop. The maize hybrid achieved better average results for all parameters in the control compared to the variant with intercropped maize + millet. The average yield of grains per plant in the control was higher by 11.62% compared to the intercrop of maize and millet, while the average weight of millet grains per plant in the intercrop was lower by 19.52%. The total mass of plants and the mass of maize and millet grains were higher in the intercrop. Therefore, it is recommended to sow in a mixed crop.

Maize and millet have an excellent perspective for cultivation in Serbia and can be alternative crops for cultivation and for ensuring food security in arid regions. They achieved excellent results in the intercrop. Intercropping is desirable in production because it provides, on average, a higher biomass of plants on the same surface area.

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Original research article

NET EFFECTIVE CUSTOMS PROTECTION OF AGRICULTURAL PRODUCTION IN SERBIA UNDER TRADE LIBERALIZATION

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Abstract

International trade flows are of great importance for the development of national economies and the wider environment.Contemporary international trade dynamics raise questions about the role of government intervention in protecting domestic production. Agriculture is a strategic production branch in the Republic of Serbia that directly and indirectly employs a large number of agricultural producers. Fiscal policy therefore plays an important role in protecting agricultural producers and maintaining their comptetitiveness. This paper aims to investigate the impact of non- customs protection on the production of agricultural products in the Republic of Serbia: wheat, corn, pigs, cattle, and meat products in the period 2021-2025. The analysis of theoretical frameworks, legal provisions, and empirical data describes the role of customs protection as a fiscal, protective, and regulatory instrument. Special attention is paid to the mechanisms for implementing protective measures and the effects on the agricultural sector. An analytical model considering the volume of production, customs tariffs, and the dinar exchange rate is used to examine how economic policy affects production conditions. In this regard, the policy of the national dinar exchange rate should play an important role as a factor in the concept of state interventionism.

Keywords: *Agricultural production, trade, effective customs protection, net effective customs protection, state interventionism.*

1. INTRODUCTION

This study examines the role of trade protection in the international trade of agricultural products and the inputs used in their production. In this sense, the international movement of production factors is understood as the migration of labor and the transfer of capital through international borrowing and lending as an integral part of the development process of transnational corporations (Balšić, 2014). Trade enables the exchange of goods and thus makes goods more widely available. On the other hand, trade in inputs has the same impact

on the demand for factors of production as on technical changes in those factors. It is often noted that the size of trade flows between countries is too small to lead to the observed changes. For many industrial countries, the ratio of trade to GDP (Gross Domestic Product) is on average 8.8%. To better compare trade with total production, goods should be measured in the numerator and denominator - i.e., compare trade in goods with value added.

Various pieces of evidence show that intermediate goods are playing an increasingly important role in trade. In a widely cited paper, Lawrence and Slaughter (1993) showed that price movements in different industries are inversely related to movements in relative wages. However, if we accept that industries import intermediate inputs, then this suggests a different way of looking at price data. Instead of comparing prices across industries, depending on their intensity and skills, it now makes sense to compare import and export domestic prices within each industry. The types of goods imported within each industry (e.g., feed ingredients) are not the same as those sold on the domestic market (e.g., feed). Based on this logic, there is no "contradiction" between price movements and relative wages (Grubišić, 2012). International trade flows are of great importance from the point of view of the development of the domestic economy and the wider environment. Economic growth depends partly on access to international markets for goods and financial resources. A country's trade balance can, in turn, influence its growth and broader macroeconomic performance (Clark, 2018). Thus, the import of certain products and services into a country has a negative impact on the foreign trade balance, which then requires the engagement of financial resources to cover it, causes debt growth, affects the movement of the exchange rate, and, through the prices of imported products, causes inflation in the country. Conversely, the export of products and services increases the level of resource employment in the country, provides financial resources without increasing indebtedness, along with a number of other benefits that subsequently arise within the domestic economy (Balšić, 2014). Opportunities for performing quantitative analyses of trade flows and their implications for other economic variables can be found within certain multivariate statistical tools. International trade in goods represents the most significant segment of international trade, accounting for over 80% of total world trade.

The role and importance of foreign trade (Krugman et al., 2019):

- It enables the placement of surplus products on foreign markets and the purchase of deficits;
- It enables the achievement of more favorable prices compared to sales being made only on the domestic market;
- It supplements the range of products and services and enables better satisfaction of human needs;
- It directs manufacturers to apply global criteria and standards for evaluating production and the most modern technological processes;
- It enables constant communication with the world, which has a positive impact on personnel training, as well as on expanding knowledge and learning about the cultures and customs of other people.

International trade is part of the entire trade, and represents the exchange of products and services between business partners from two or more countries, or two or more customs territories. Its basic function is to procure products and services for the needs of citizens and the economy and to place products and services on foreign markets. The reasons and motives for entering a foreign market are different.

The application of technologies with market globalization creates opportunities for intensive specialization, diversification, and the use of economies of scale (Kruger, 2009). When crossing the customs border, the selling country exports, and the country whose territory the

object of purchase and sale enters imports (Blanchard, 2006). It is very important to consider what the determinants of imports and exports are. Imports are part of the domestic demand that relates to foreign goods. Therefore, it is clear that imports depend on domestic income, so higher domestic income leads to higher domestic demand for total goods, and thus also for imports. Imports also depend on the real exchange rate, which represents the price of domestic goods in units of foreign goods. The more expensive domestic goods are in relation to foreign goods, the greater the domestic demand for foreign goods, and therefore a higher real exchange rate leads to higher imports (Aburesidze et al., 2022). Imports are therefore determined and positively correlated with domestic income and the real exchange rate. In contrast to imports, exports are part of foreign demand for domestic goods. Higher foreign income means higher demand for total goods, and thus for those exported from a particular country. Exports depend on the real exchange rate, because the higher the price of domestic goods in units of foreign goods, the lower the foreign demand for domestic goods. In other words, a higher real exchange rate means lower exports. Exports are determined and positively correlated with domestic income and negatively correlated with the real exchange rate (Blanchard, 2006). Customs duties are one of the oldest forms of taxation and are paid on all goods that are imported. The purpose of tariffs is primarily to protect domestic production by making imported goods more expensive and thus encouraging domestic production (De Lange et al. 2024). Another function of tariffs is fiscal, i.e., they constitute one of the budget revenues. While the goal of other taxes is to collect as much revenue as possible, customs duties play a primary role in a country's foreign trade policy, which is reflected in the protection of the domestic market. Customs duties are essentially a tax on imported goods. The price of imported goods increases by the amount of the customs duty.

This reduces consumption, increases production, and reduces imports. The introduction of customs duties increases the difference in prices in different markets; i.e., customs duties increase prices in the domestic market and lower prices in the foreign market. Therefore, it can be said that the main function of customs duties is the protection of domestic production. It is expressed at nominal rates according to the existing customs tariff on the value of imported goods. In addition to the fact that customs duties can be imposed on imports of goods in order to protect domestic production, the state can also impose customs duties on exports of goods that are introduced for the same reason (Steinfatt, 2020). Effective customs protection refers to the added value of production, which is the difference between the total value of production of a sector and the value of reproduction consumption of that sector, and is levied at a legally determined rate. The effective protection rate is the percentage increase in value added per unit of production of a sector that is conditioned by the tariff structure of protection compared to the situation without protection (Sorwar, 2023). Therefore, the effective customs protection rate depends on the nominal tariff rate on the final product of that sector, the tariff rate on imported intermediate products (inputs) of that sector, and the share of intermediate consumption in the value of the final production of that sector. The level of nominal customs protection is important primarily for consumers because it shows how much the price of the finished product increases due to the introduction of tariffs, unlike effective customs protection, which is interesting primarily for domestic producers. The view of net effective customs protection includes in its scope protection policy changes in the exchange rate of the domestic currency (real appreciation and real depreciation) and means an expansion of the concept of effective protection. Taking into account the change in the exchange rate, the effective protection of an individual sector also changes. Real exchange rate appreciation will be equivalent to import subsidies, or an export tax on domestic exports, while real depreciation of the domestic currency will have effects consistent with the introduction of a tariff on all imported products and export subsidies (Heakal, 2025). Conceptually, the net effective protection rate can be represented as Net effective tariff protection: ej (-, +) real appreciation (↓); depreciation (↑) of the domestic currency.

Accordingly, it is possible to define four concepts when a sector is protected (Babić & Babić, 2006):

- A sector is protected when the nominal protection rate on imports of finished products of that sector is positive. Nominal protection is relevant for the analysis of consumption effects, not production effects;
- A sector is protected if its effective protection is positive. This would be the case when domestic product prices are given, and the exchange rate has no influence, and each sector with positive protection attracts resources from domestic sectors;
- If the effect of the exchange rate, appreciation or depreciation, is taken into account, a sector will be protected only if its net effective protection rate is positive;
- An economic sector is protected if protection in all elements leads to an increase in the added value of that sector. This is the concept of total protection.

Agricultural production can be viewed through two prisms: the first, as the principle of subsistence through agriculture, i.e., the production of enough food to satisfy the needs of the agricultural producer himself and his family, and the second, as commercial agricultural production, which consists of obtaining financial profit through cultivating the land. For developing economies, including the Republic of Serbia, the agricultural sector is extremely important because it lays the foundation for sustainable economic growth:

- The development of agricultural production, in addition to the agricultural sector itself (crop farming, livestock farming, fruit growing, viticulture, etc.), stimulates growth in other sectors, which results in increased employment and improved living standards;
- Agriculture in rural areas is of exceptional importance because it effectively uses available arable land;
- Rural development policy must ensure an integrated approach to problems and offer appropriate solutions to the issues and needs of the development of the agricultural sector in rural areas.

Caring for rural areas as a whole is reflected in innovation, modernization, and investment, from strengthening local producer associations to improving the marketing of agricultural products, short supply chains, i.e., village markets, and simplifying procedures for the sale of products by producers. Such measures will come from all stakeholders and should, on the one hand, contribute to greater competitiveness of farmers, while on the other hand, raise the level of food security.

For the Republic of Serbia, rural development policy is very important, given that almost 40% of the population lives in rural areas, compared to the EU average of 24%. At the same time, the ratio of the population over 60 and under 20 years of age in rural areas is less favorable than in urban areas. In addition to natural mortality and migration of young people to cities, the lack of professional opportunities is worsening the demographic, economic, and development picture of rural areas. In addition to the negative consequences of the war, a particular problem in the countries of the former Yugoslavia is the gap between very small and difficult-to-sustain agricultural holdings and large agricultural producers.

Against this background, the study examines the structure of tariff protection for raw materials, intermediate goods and finished agricultural products in Serbia, with particular emphasis on net effective customs protection. This issues is especially relevant given Serbia's EU accession process and the economic challenges facing its agricultural sector.

2. MATERIALS AND METHODS

The calculation of net effective customs protection involves analysing nominal and effective protection rates, estimating protection levels for agricultural inputs, and examining how tariff structures and the real exchange rate interact to influence trade flows and competitiveness. As a member of the World Trade Organization (WTO), Serbia has easier access to world markets. Over 80% of total foreign trade exchange takes place under the auspices of free trade. Quantitative and qualitative data were collected for a period of 5 years, as follows:

- Data on the level of customs tariffs for agricultural raw materials, semi-finished products, and finished products. Data source: Customs Administration of the Republic of Serbia;
- Data on import and export of pigs, cattle, mineral fertilizers, wheat, maize (corn). Source: Republic Statistical Office (hereinafter referred to as SORS- Statistical Office of the Republic of Serbia) and Ministry of Agriculture;
- Data on the movement of the real effective exchange rate of the dinar. Source: National Bank of Serbia.

The collected data were analysed by calculating customs protection rates and descriptive analysis to interpret the results. The data in Table 1 shows the range of basic customs rates for the import of goods, according to the degree of processing. The categories analyzed are: raw materials, semi-finished products, and finished products. The range of customs rates ranges from 0% for raw materials to 30% for meat products.

Table 1. Summary of heading levels and formatting

Product Category	Range of Basic Customs Rates, %	Products
Agricultural Raw Materials	0 – 5	Livestock for breeding, raw cotton, mineral fertilizers, unprocessed tobacco, seed goods.
Semi-finished / Intermediate Products	5 – 15	Vegetable oils, chilled meat, wheat flour, whole milk powder.
Finished Products	15 – 30	Meat products, cheeses, confectionery, alcoholic and non-alcoholic beverages.

Source: Customs Administration of the Republic of Serbia

The data in Table 2 show that in all analyzed categories, Serbia has a surplus in international trade (high for corn and wheat, and mild for cattle and meat products), except in the livestock sector, where it has a critical deficit of 43,000 tons.

Table 2. Trade in goods table for the period 2021 - 2025

Product	Average annual Exports, tons	Average annual Imports, tons	Balance (Surplus/Deficit)
Maize	1.800.000	20.000	+ Surplus (High)
Wheat	1.200.000	15.000	+ Surplus (High)
Pigs / Pork	< 2.000	45.000	- Deficit (Critical)
Cattle / Beef	15.000	10.000	+ Slight surplus
Meat products	18.000	15.000	+ Slight surplus

Source: Rep. Statistical Office (hereinafter referred to as RSO) and Ministry of Agriculture

The data from Table 3 show that the share of raw material inputs in the final value of the product ranges from 32% to 60%, while the average gross value added ranges from 25% to 45% depending on the sector.

Table 3. Synthetic table of technical coefficients (asij) for calculating effective protection

Product (Final Output)	Main Raw Material Input	Raw Material Share in Final Value (asij), %	Average Gross Value Added (BDV), %
Maize / Wheat	Fertilizers, Protection, Seed	32 – 35	40 – 45
Pigs (Livestock)	Feed (Maize / Soybean)	48 – 52	28 – 35
Cattle (Livestock)	Feed and Roughage	45 – 50	30 – 35
Meat Products	Fresh/Frozen Pork and Beef	55 – 60	25 – 30

Source: RZS

The data in Table 4 show that the dinar exchange rate is overvalued, that is, that in the past five-year period, a cumulative real appreciation of the dinar of 13% was achieved. This means that imported goods become 13% cheaper on the domestic market solely due to the exchange rate of the national currency.

Table 4. Real effective exchange rate of the dinar in the period 2021 - 2025

Year	Rise + /fall, %	Trend of the dinar exchange rate
2021	+0.5 to 1.2	Stabilization phase
2022	+3.5 to 4.2	Strong real appreciation
2023	+5.0 to 6.1	Strong real appreciation
2024	+1.2 to 1.5	Slowing of appreciation
2025	+12 to 14	Strong appreciation

Source: National Bank of Serbia

Further in the paper, the standard model of effective protection (g) according to the Corden formula will be used, and the coefficients (asij) will be used with nominal customs rates (tj for the final product and ti for the raw material) according to the formula:

$$g_j = \frac{t_j - \sum (as_{ij} \cdot t_i)}{1 - as_{ij}}$$

qj = Effective customs protection

tj = nominal customs rate on the final agricultural product

ti = nominal customs rate on the raw material (input)

asij = technical coefficient (share of raw material in the value of the final product excluding customs duties)

The classic qj does not take into account the overvaluation or undervaluation of the domestic currency. To obtain net effective protection, the formula is corrected for the percentage deviation of the real exchange rate from its equilibrium level (d):

$$NetoERP = \frac{g_j + 1}{1 + d} - 1$$

Working hypotheses:

H1: The effective protection of the agricultural sector in Serbia is higher than the real one due to lower tariffs on raw materials.

H2: The real overvaluation of the domestic exchange rate neutralizes the positive effects of tariff protection and WTO (World Trade Organization) concessions.

The results presented in the paper will show the effects of net tariff protection of the agricultural sector in the Republic of Serbia.

3. RESULTS

Based on the data from the tables and using the working methods, the data for effective customs protection were calculated. The data are presented in Figure 1.

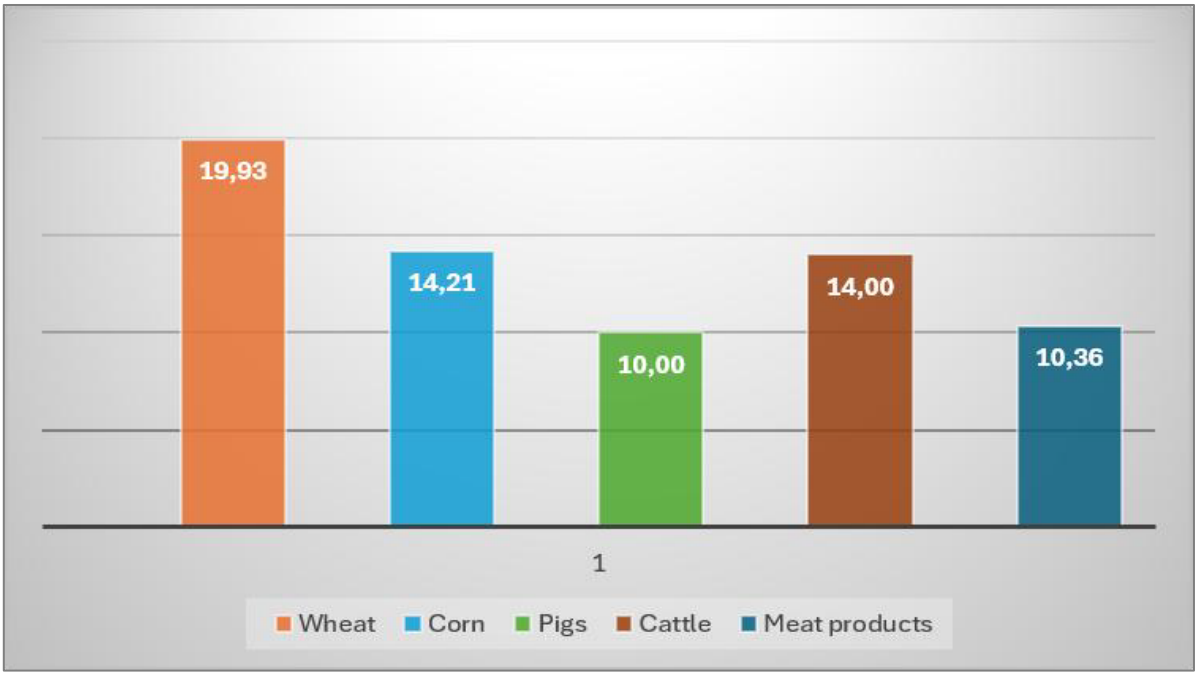


Fig. 1. Effective customs protection for the production of grain, maize (corn), pigs, cattle and meat products in the period 2021–2025

The data in the Figure 1 show the following:

- Wheat production enjoys the highest level of effective tariff protection, 19.93%.This rate indicates that tariff protection increases value added in domestic wheat production by approximately 20% relative to the unprotected scenario.

- Maize production also records a high level of effective tariff protection, 14.21%. This means that maize producers have a significant economic advantage and room for higher operating costs in the domestic market compared to imported alternatives.
- Cattle production has an effective tariff protection rate of approximately 14%. This means that domestic producers are protected by state policy measures that enable them to have more stable production and competitiveness.
- Meat production achieves an effective tariff protection of 10.36%. This means that the protection of final products is lower compared to the raw material base (cattle), but higher than the long raw material base (pigs); this means that these products are "threatened" by import competition.
- Pig production has the lowest effective protection rate of 10.00%; this means that domestic pig producers are exposed to greater pressure from foreign competition compared to the above-mentioned production sectors.

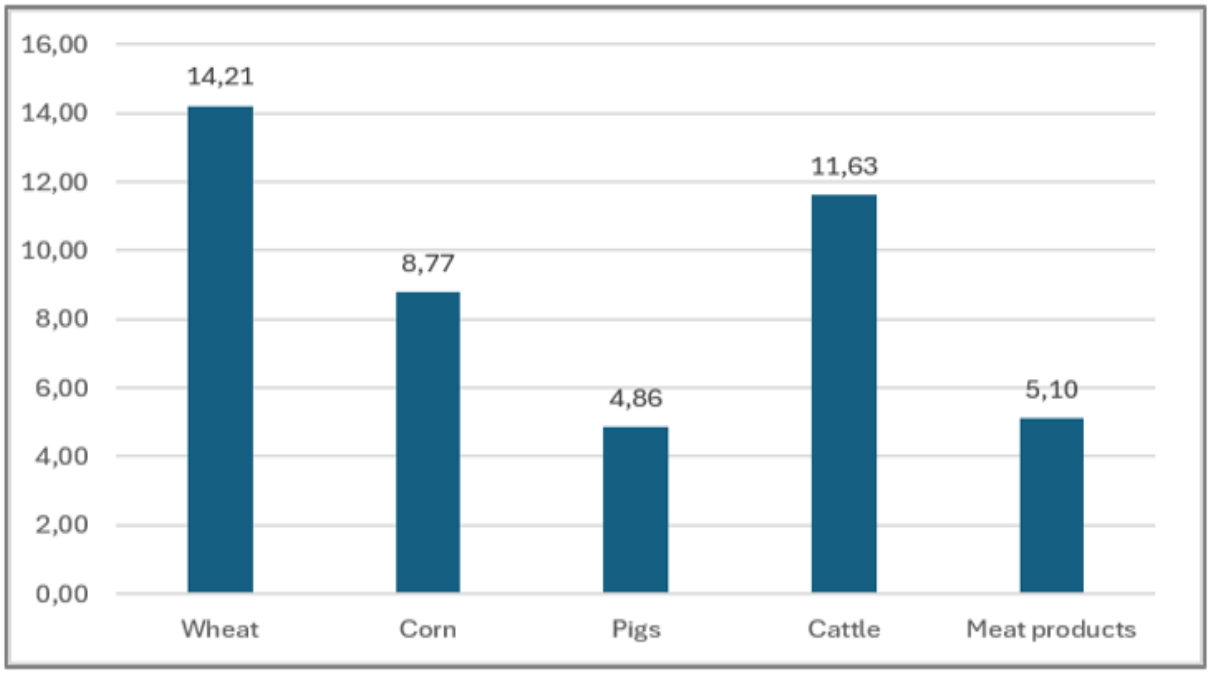


Fig.2. Net effective tariff protection for wheat, maize (corn), pigs, cattle and meat products, 2021-2025

Table 4 indicates that the dinar appreciated in real terms during the period under review, reducing the net effective tariff protection of the sectors analysed. In this case, we can quote Max Corden: "Exchange rate fluctuations always generate pressure for increased protection in the USA when the dollar is in a phase of real appreciation". This reflects the importance of exchange rate policy, which is inevitably linked to the operation of macroeconomic policy as a whole and the tariff protection policy.

Actual tariff protection shows values that can be interpreted as follows:

- In the wheat production sector, the value is positive, 1.21%, which is interpreted as barely managing to cancel out the negative effect of the strong dinar. Wheat producers have minimal, almost negligible actual protection.
- In the cattle sector, the value is negative, -1.37%, which can be interpreted as domestic producers being in a worse position compared to foreign competition.
- In the maize production sector, the value is negative, -4.23%, which means that imported maize is more easily placed on the domestic market.

- In the meat processing sector, the value is negative, -7.90%, which means that the domestic industry is under strong pressure and is exposed to competition from cheaper imported meat.
- In the pig farming sector, the value is negative, -8.14%. The combination of low tariff protection and a strong dinar means that domestic pig farmers operate under conditions of deep negative protection (Figure 3).

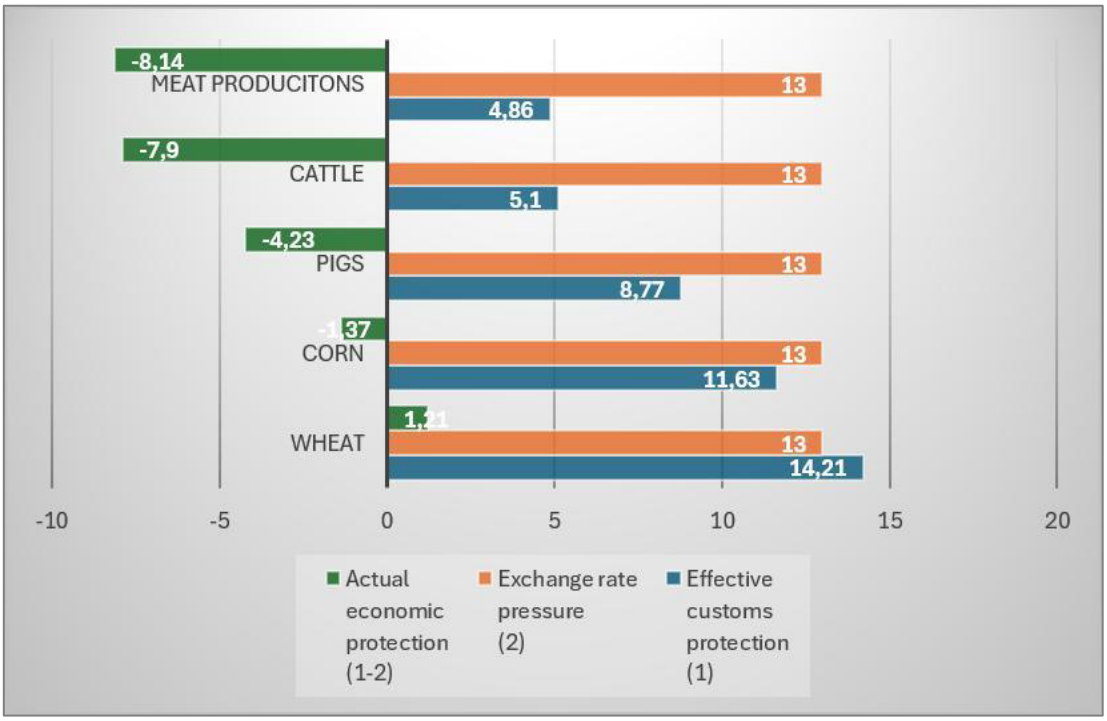


Fig. 3. Quantitative decomposition of effective and real protection

The use of such a policy of a strong dinar exchange rate in the long term inevitably leads to a weakening of the domestic economy and a decrease in competitiveness, which encourages excessive imports. It is therefore necessary to link the dinar exchange rate policy and harmonize economic policy measures to protect domestic production sectors.

4. DISCUSSION

Varietal cultivation technology is necessary for successful wheat production (Mladenović Drinić et al., 2024, Popović, 2010; 2015; Glamočlija et al., 2015, Maksimović et al., 2018, Božović et al., 2022, Popović et al., 2020, 2025) and maize (Pavićević, 1984, Popović et al., 2024, 2025). Global maize production for the 2025/2026 season reached a historic record of almost 1.3 billion tons, putting enormous pressure on the world market and driving down prices. While key global competitors recorded record yields, Europe and Serbia faced a drastic drop in production in 2025 due to extreme droughts and high temperatures. Serbia suffered a drop in production in 2025 due to drought. About 4.44 million tons were produced, which is a 12.90% drop compared to the previous year and as much as 27.20% less than the ten-year average (Popović et al., 2026).

More than 80 different countries produce wheat worldwide, with the majority of global wheat production coming from just a few countries, according to the Food and Agriculture Organization of the United Nations (FAO, 2026). The top five wheat producing countries in the world, based on total yield in tonnes from 2000 to 2020, are China, Russia, India, the United States and France. Compared to 2025, less maize (by 3.80%), soybeans (by 7.50%) and sugar

beets (by 5.70%) were sown in Serbia, and more sunflowers (by 3.5 percent). Compared to the ten-year average (2016–2025), wheat is up by 27.80%, sunflowers by 9.30%, and maize (by 3.60%), sugar beets (by 24.30%) and soybeans (by 10.30%) (RZS -Statistical Office of the Republic of Serbia, 2026).

Wheat, unlike other field crops, has been producing good production results for years, ranging from average to slightly below or slightly above average. So, at first glance, it is a fairly reliable agricultural crop with relatively small deviations in production results.

In the period 2009 - 2021, the average wheat yield per hectare was 4.20 tons. If we exclude 2011, with a 20.00% drop in yield compared to the aforementioned average, all other years were at the same level, below or above the average by up to 10.00%. In the period 2022 - 2026, the average yield increased significantly and for the aforementioned five-year period is 5.50 t/ha, which is a 30.00% increase compared to the previous observed multi-year period. Improvements in agricultural technology and seed genetics, together with increased investment, contributed to a substantial increase in yield per hectare. In the observed five-year period, deviations in yields from year to year were minimal.

The wheat yield in 2026 is about 5.50 tons per hectare, which, based on the sown area of 630,000 hectares, would be a total yield of approximately 3.50 million tons. More than enough for our needs, which, with transitional stocks, "frees" a significant export potential of 1.80 - 2.00 million tons. The quality of the grain is good on average. Some varieties have shown good yield potential. The application of better agricultural techniques, better seed genetics, significantly higher investments, have resulted in such yield results. In a five-year period, deviations in yields from year to year were minimal.

The price of wheat in 2011 was on average 20.50 dinars/kg excluding VAT. The price of diesel fuel in the same year was around 120.00 dinars/l. The price of NPK fertilizer was on average 35.00 dinars/kg, the price of UREA fertilizer was around 33.00 dinars/kg, and the price of CAN was around 23.00 dinars/kg.

The price of wheat today, in 2026, i.e. 15 years after the comparative year 2011, is between 19.50 - 20.00 dinars/kg, or about 4.00% less. Diesel fuel today is around 200.00 dinars/l, and we must emphasize that farmers, with the rebate (and all the hassle of refunding it) and other discounts when purchasing D-2, have a lower price than commercial ones. In any case, the price is significantly higher than the 120.00 dinars/l it was in 2011. The price of NPK fertilizer is around 80.00 dinars/kg (2.3 times more expensive than 15 years ago). The price of UREA fertilizer today is around 70.00 dinars/kg or 2.10 times more expensive than in the previous year. The price of CAN fertilizer today is around 50.00 dinars/kg, which, as in the case of UREA fertilizer, is 2.10 times more expensive than in 2011.

If we rely on the estimate of the average yield in 2026 of 5.50 t/ha, this is a 30.90% higher yield than the 2011 yield of 4.20 t/ha. So the increase in yield per unit area can hardly offset the huge disproportion between price and production costs this year compared to the period fifteen years ago. According to estimates, a farmer who produced 7.00 t/ha in 2026 covers the invested production costs (https://www.agroklub.rs/kolumna/provalija-izmedu-troskova-i-cene-psenice-na-nuli-samo-onaj-koji-je-skinuo-7-tha/113611/). A deliberate balancing act between a high rate of customs protection for cattle and grains and a lesser rate of customs protection for the pig farming and processing industries is reflected in the analyzed model of customs protection in Serbia. The state intends to guaranty a high level of self-sufficiency in essential agricultural products that also function as input (food) for the livestock sector, which is why cereals receive the highest protection. On the one hand, high effective rates safeguard domestic farms and jobs, but on the other hand, they force domestic consumers and the food industry to pay more for these goods than they would on the open market.

5. CONCLUSIONS

The results indicate that Serbia's tariff structure provides stronger protection for cereals and cattle than for pig farming and the meat-processing industry. Customs policy provides an incentive to the domestic agricultural sector. The highest protection is directed towards cereals, which implies that the state wants to ensure a high degree of self-sufficiency in basic agricultural crops that also serve as input (food) for the livestock sector. High effective rates, on the one hand, protect domestic jobs and the existence of farms, but on the other hand, mean that domestic buyers and the food industry pay more for these products than they would on the open world market. Due to the exchange rate policy, processors are given room to import processed meat and semi-finished products from other markets, which become cheaper by about 8% (live pigs have a customs protection of 4.86%, so the exchange rate advantage is -13%, the difference is -8%). An overvalued domestic currency can offset the protective effect of tariffs by making imported goods less expensive in the domestic market. Economic policy through the exchange rate actively stimulates imports, while placing domestic farmers and processors in an unequal position, making their products more expensive. The combination of customs and monetary policy in the period 2021-2025 worked in favor of importers, which had the effect of reducing domestic production. Considering the results of the work, it is concluded that H1 is partially acceptable. The rate of net effective customs protection is by definition higher than the nominal (real) customs rate on the finished product precisely when tariffs on intermediate goods, raw materials and inputs (animal feed, components) are lower than customs duties on the final product. From Chart 3 it is visible that primary sectors such as wheat (14.21) and cattle (11.63) enjoy high effective protection, which implies that customs rates on their imported inputs are low, leaving them more room to create added value under the customs shield. The hypothesis is not completely confirmed, however, because the effective protection in the meat processing sector (5.10) and pork (4.86) is low, which means that the inputs for these sectors (livestock, corn for food) are more heavily protected by tariffs than the final product itself. H2 is fully confirmed because the real cumulative appreciation of the dinar of 13.00% acts as a direct, linear import subsidy. Since imported goods on the domestic market become 13.00% cheaper solely due to monetary policy, this pressure directly erases and nullifies tariff barriers. When the tariff protection from the graph is reduced by 13.00% of the exchange rate pressure, the positive effects of tariffs completely disappear for most sectors. Pig farming falls into a deep deficit (-8.14%), meat processing to -7.90%, corn to -4.23%, and cattle farming to -1.37%. Even highly protected wheat drops to a critical +1.21%. Trade concessions, quotas, or preferences negotiated within the WTO framework are rendered meaningless if the domestic currency is overvalued in favour of the import lobby.

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Original research article

DIFFERENTIATION OF MIXED FLOWER BUDS IN STRAWBERRY (Fragaria × ananassa DUCH.) IN THE SKOPJE REGION

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Abstract

This study focuses on the differentiation of mixed flower buds in June-bearing strawberry (Fragaria × ananassa Duch.). The first visible sign of mixed flower bud initiation (stage III) in the studied cultivar occurs during the first decade of August. The formation of the inflorescence axis (stage IV) is followed by differentiation of the primary (stage IV') and secondary (stage IV") axes, which occurs during the first half of September. In stage V, the primordia of floral parts are formed and differentiated. At the tip of the inflorescence axis, an initial depression is formed (stage Va). The formation of the calyx primordia (stage Vb) follows in the second half of September. From late September through the first half of October, differentiation and intensive development of the calyx occur, along with the formation of petal primordia (stage Vc), stamen primordia (stage Vd), and carpel primordia (stage Ve). By the onset of flowering, the newly formed primordia reach a certain degree of differentiation (stage Vf). Archesporial tissue (stage VIa) forms during the first half of November, followed by meiosis in November (stage VIb). Young microspores are formed at the end of December (stage VIc). Before flowering, microgametogenesis (stage VId) proceeds until formation of mature pollen, while macrogametogenesis (stage VIIIa-d) continues until the formation of the embryonic sac with the egg cell. Flowering begins in the first decade of April, and fruit ripening in the first half of May.

Keywords: *Strawberry, mixed flower buds, microphenophases, phenophases.*

1. INTRODUCTION

The strawberry forms flower buds of mixed character, in which the generative elements differentiate at the apex of growth (Lučić et al., 1995). Each mixed flower bud has two meristems: an axillary meristem (with a vegetative function) and an apical meristem (with a transitional function from the vegetative to generative phase, as well as a generative role). The axillary meristem undergoes three vegetative periods (a major ontogenetic cycle). During the first year, in the spring-summer period, new daughter cells are formed in the axillary leaves. During the second year of vegetation, in the spring - summer period, these daughter cells begin to form new buds. The meristem that was previously axillary becomes the apical meristem of the new bud (Vitkovskii, 1984). At a certain moment, under the influence of genetic and external factors (ecological, morphological, physiological, chemical), vegetative buds begin to

transform into generative buds, enabling them to survive the winter period. In the third year of vegetation, microsporogenesis and macrosporogenesis occur during winter, followed by flowering, fertilization, and embryogenesis in spring.

The minor ontogenetic cycle in Cormophyta proceeds through twelve stages, following a defined developmental pattern (Kuperman, 1968; Vitkovskii, 1984). The development of vegetative organs occurs in the initial two stages, while reproductive organs are formed throughout the subsequent ten stages. Each vegetative bud completes an organogenetic cycle within a specific temporal interval. Isaeva applies a similar classification tailored to fruit organogenesis further subdividing certain phases into subphases (Lučić et al., 1995). and Gjuric (1989) adopted Isaeva's scheme to propose a new framework for the differentiation of June-bearing strawberry flower buds.

Flowering is an integral developmental process in angiosperms, crucial to reproductive success and continuity of the species. Some angiosperms complete their life cycle within one year (annual plants), while others have a longer reproductive lifespan, characterized by the production of new flowering and vegetative shoots every year (perennial plants). Despite the differences in lifespan, the underlying genetic mechanisms controlling flower induction and floral parts formation appear to be similar among these plants (Tan Fui-Ching & Swain, 2006). Using Arabidopsis thaliana as a model, these authors have elucidated the transition from vegetative to reproductive growth and the subsequent formation of individual floral parts, and how this knowledge has facilitated the identification of homologous genes from perennial crops. Although annuals share many similarities with perennials in terms of gene function, they differ in their commitment to flowering.

Flowering in higher plants is a complex process involving tightly regulated interactions between external and internal factors. External cues act as flowering stimuli, which are perceived by reproductively competent plants and transduced into developmental responses through the action of transcriptional regulators, photoreceptors, and phytohormones. Genes controlling flower initiation and development have been identified in Arabidopsis and other model annual species using genetic and molecular approaches. This knowledge has subsequently enabled the discovery of homologous genes in a wide range of plant species, including rice, eucalypts, Citrus, grapevine, and apple, suggesting that these regulatory mechanisms are conserved across the evolution of flowering plants (Tan Fui-Ching & Swain, 2006).

Understanding the organogenetic cycle, specifically the sequence and dynamics of microphenophases and phenophases during organ development, provides valuable insights into managing developmental processes to optimize fruit yield potential.

2. MATERIALS AND METHODS

The research was conducted on one June-bearing strawberry cv. 'Alba'. Mixed flower buds from the mother plant were analyzed every 10–15 days from August to May (2024/2025). The research focused on the top mixed buds, i.e., the central axis of the inflorescence. Microphenophases were determined according to the scheme proposed by Mićić and Gjurić (1994). Observations were performed using a binocular microscope. The following microphenophases were studied: the flower bud initiation, the establishment of the inflorescence axis, and the formation of the vegetative floral parts (calyx, petal) as well as reproductive floral parts (anthers, carpels).

To monitor microsporogenesis, differentiation of the archesporial tissue, meiosis, and the appearance of young microspores, anthers were excised, fixed in Carnoy's solution, stained with acetocarmine, and temporary preparations were made using the Squash method.

The research was conducted at the strawberry production orchard owned by a private grower. The Skopje region is situated at 41°59'46"N and 21°25'54"E at an altitude of 235 m, and is classified within a continental–Mediterranean climatic, vegetation, and soil zone. The mean annual air temperature is 12 °C, and the average annual precipitation is 507 mm. The De Martonne aridity index averages 19.7, with the highest aridity recorded in July, August, and September, indicating a semi-arid climate (Gjorgji Filipovski et al., 1996).

The Skopje valley is surrounded by a mountain massif and is characterized by a modified continental climate under a Mediterranean influence. The region experiences moderately cold and humid winters, as well as hot and dry summers. The average De Martonne aridity index of 19.7 indicates that the climate is semiarid. In recent decades, this area has experienced noticeable effects of global climate change, including decreased annual precipitation, higher aridity, shifts in rainfall patterns, lower temperatures, especially during winter, and occasional severe frosts.

3. RESULTS

In the axils of all the leaves that are in the process of forming, vegetative domes can be observed. Under the influence of certain endogenous factors, some of these develop into flower buds. Before flower bud initiation (FBI), changes occur during induction and initiation. The first and second phases of organogenesis are characteristic of the bud's vegetative stage. Subsequently, the apical meristem becomes elevated and broadened, acquiring a semi-spherical form. This marks the beginning of morphological changes in the meristem dome. These changes signify the transition from the vegetative stage to the generative stage (phase III of organogenesis). Under our climatic conditions, this transition is observed during the first decade of August.

The initiation of flower bud differentiation in fruit species occurs from late June to early August, and is influenced by genotype (Ristevski & Simovski, 1986; Grupce, 1966; Ristevski & Petrovska, 1986; Selamovska & Ivanovska, 1999; Selamovska & Miskoska-Milevska, 2018; Mićić & Gjurić, 1989; Mićić, 1988), photoperiod (Paunović et al., 1974; Nasr & Wareing, 1961b; Sonsteby & Heide, 2011; Heide & Sonsteby, 2012), cultivation practices (Nasr & Wareing, 1961a), climatic and orographic conditions (Selamovska & Ivanovska, 1999; Irene Tinklin et al., 1970; Sonsteby & Heide, 2013), the plant nutrition (Pejkić, 1978; Atsushi Yamasaki et al., 2002; Lieten, 2002), among other factors.

The formation of the inflorescence axis (stage IV) is followed by the differentiation of the primary (IV') and secondary (IV") axes. These changes usually occur during the first half of September. Their development is acropetal. The floral primordia initially exhibit a cylindrical form, first appearing in the upper meristem. The main inflorescence axis occupies a central position within the flower bud. Along this axis, six or more lateral bud primordia are present, with their degree of differentiation decreasing from the apex toward the base of the central axis. In the axils of the young primordia, in addition to vegetative buds, the primordia of the secondary peduncle (flower stalk) are differentiated. The degree of differentiation of these secondary peduncle primordia is lower than that observed in the third-order floral primordia. The lateral mixed buds have a shape similar to that of the apical mixed bud; however, they exhibit a lower degree of differentiation. Within the lateral mixed buds, one to two leaf primordia are present, together with a vegetative cone and the primordia of a central inflorescence axis and a primary peduncle. The primary flower develops from the terminal

growth point, whereas secondary flowers arise from the lateral buds. During phase V, the primordia of the floral parts are formed and differentiated. At the apex of the inflorescence axis, an initial depression is formed (stage Va). This is followed by intensive growth and the formation of the calyx primordia (stage Vb) in the second half of September. Subsequently, in late September and the first half of October, the petal primordia (stage Vc) and stamen primordia (stage Vd) are formed. Carpel primordia (stage Ve) develop simultaneously with the formation of sporogenous tissue in the anthers. These differentiation processes are observed from the second half of October until the end of November. The sequence of floral parts formation is genetically controlled.

In the anthers, microsporogenesis (stage VI) begins. Under the agro-climatic conditions of the Skopje region, the archesporial tissue (stage VIa) forms during the first half of November, and meiosis occurs in December (stage VIb), resulting in the formation of microsporocytes (tetrads). Simultaneously, differentiation of the pistil continues, with the development of the style and stigma. All floral parts increase in length and width and continue to differentiate (stage Vf). The flower stalk elongates and continues to grow. By this stage, the primordia reach a high degree of differentiation, which is necessary for the normal transition to dormancy.

During the winter period, most processes of bud development are greatly reduced or temporarily halted. The flower buds of cherry, sour cherry, and other stone fruit species remain in the archesporium phase throughout the winter until the onset of vegetative growth (Mićić, 1992; Gjurić, 1988, 1989). According to Vitkovskii (1984), Mihailov and Topciiski (1975), and Ristevski and Petrovska (1986), this period represents an apparent state of dormancy, as a slight increase in the size of stamens and pistils can still be observed during winter. The authors further report that under different soil and climatic conditions, the degree of development of the generative buds varies. In the southern and warmer regions, the flower buds overwinter at the seed-bud stage, whereas in northern, cooler regions they overwinter at the stage of a fruiting body primordium.

In January, young microspores are formed, and microgametogenesis proceeds (stage VIc). By the onset of vegetation growth, or at the beginning of leaf emergence, pollen matures and becomes fully developed (stage VId), and the anthers acquire an amber-yellow coloration. Concurrently with pollen development, macrosporogenesis occurs (stages VIIa–c). Intensive growth of the floral parts continues, accompanied by the formation of male and female gametophytes. The pistils attain their final morphology, and macrogametogenesis takes place within them (stages VIIIa–d).

The climate factors, the timing of runner plant establishment, and plantation management determine the start of microsporogenesis in strawberry cultivars (Ana Selamovska et al., 2009b). The degree of differentiation of the generative buds is reflected in the number of flower stalks formed and the development of individual flower primordia. This represents a varietal characteristic and a fundamental component of yield potential. However, to a large extent, it is also a result of the interaction between applied agrotechnical and pomotechnical practices and the level of possible control over environmental conditions. The quantity and the quality of these processes vary and depend on the genetic, ecological, agrotechnical, pomotechnical, and other factors (Mićić & Gjurić, 1989).

After the completion of winter dormancy and the microphenophases of development, and with an increase in air temperature above 5 °C, phenophases in the mixed buds of strawberry occur a few days after leafing. These involve visible changes in the buds (stages IX-XII), including bud swelling, flowering and pollination (stage IXa), fertilization (stage IXb), zygote formation and early embryogenesis (stage X), embryogenesis and seed formation (stage XI), and the development of physiologically mature fruit and fruiting (stage XII).

The emergence of the inflorescence is the first visible sign of the awakening of the mixed bud. The inflorescence is cymose, with sympodial branching. The terminal flower develops and blooms first, marking the cessation of growth of the main axis. A single flower stalk may bear 10-25 flowers. This typically occurs in the third decade of March.

Blooming begins in the first half of April, with full flowering occurring approximately seven days later. The development of flower buds and flowering is successive in nature: primary flowers bloom first, and these give rise to the largest fruits.

The results of this study are consistent with data reported in the literature (Stančević, 1971; Veleva & Tešić, 1973; Kiprijanovski, 2001), which indicate that under moderately continental climatic conditions, June-bearing strawberry cultivars bloom in the first half of April.

Fruit ripening occurs from the first decade of May to the end of the first decade of June. According to the literature, under temperate-continental climatic conditions, single-cropping cultivars typically ripen in the second decade of May, depending on the genotype, climatic conditions, altitude, and cultivation practices. In northern and cooler regions, strawberry cultivars ripen later. Plants grown at lower altitudes tend to bloom and ripen earlier, and the use of black mulch further accelerates flowering and fruit ripening (Veleva & Tešić, 1973; Kiprijanovski, 2001; Selamovska, 2006).

4. DISCUSSION

The differentiation of the flower buds in fruit species occurs in several phases: induction (occurring in the leaves after their emergence); initiation (physiological and chemical changes in the bud); differentiation and development of floral parts in the buds (internal or hidden changes-microphenophases of differentiation occurring from stages III-VIII); and development of floral parts outside the bud (visible changes-phenophases occurring from stages IX-XII). During the first and second phases, the flower bud remains in a vegetative state. The formation of new stem growth and leaf emergence marks the beginning of the first stage (I) of organogenesis. In the second stage (IIa–b), primary vegetative buds are formed and differentiated in the leaf axils. Reproductive organs are subsequently formed throughout the remaining ten stages. Under appropriate conditions, the differentiation of the generative organs begins, marking the transition of the vegetative bud into the generative phase (stage III). The factors responsible for the transformation of the vegetative cup into a generative bud remain unknown (Mićić & Gjurić, 1994).

The timing and dynamics of flower bud formation are specific to each variety (Kuperman, 1968). In moderate continental and Mediterranean climates, strawberry varieties initiate flower buds in September (Paydaş & Kaska, 1997; Stančević, 1971). In the northern and colder regions of Russia, the flower bud initiation occurs from late September to early October (Vitkovskii, 1984). Izhar (1997) identified an additional group of strawberry varieties known as ISD (infra-short-days), in which flower bud initiation, flowering, and fruit ripening occur earlier than in June-bearing varieties. The onset of flower bud initiation varies from year to year, indicating that climatic changes influence the timing of early or delayed differentiation.

Darrow (1966) determined that the effects of temperature and photoperiod on strawberry flower bud induction and flower bud initiation (FBI) are of greater importance than temperature conditions during flowering and fruit ripening (Doving & Mage, 2001). Improved differentiation occurs under longer day lengths and an optimal temperature for FBI between 15-20 °C; however, for most varieties, the optimal temperature range is 18-25 °C. The cultivation system also influences the initiation of flower bud differentiation. According to Eshghi and Tafazoli (2007), higher temperatures and long-day conditions, similar to those in the Skopje region, have

a positive effect on early differentiation, and in June-bearing strawberry varieties, FBI begins during the first decade of August.

The differentiation of mixed flower buds in strawberry is influenced by the interaction of multiple factors that affect the progression of all microphenophases and phenophases of development. These factors include genotype and environment conditions (Lučić et al., 1995; Šoškić, 1998; Sonsteby, 1997; Keo Intabon et al., 1995; Stančević, 1971; Veleva & Tešić, 1973; Kiprijanovski, 2001; Skupien & Oszmianski 2004; Selamovska, 2006; Ana Selamovska et al., 2013), plant age (Ana Selamovska et al., 2007); planting material (Lutchoomun, 1999; Ana Selamovska et al., 2008c), runner ordering (Selamovska & Ristevski, 2008; Selamovska & Najdenovska, 2010; Hamann & Poling, 1997; Ana Selamovska et al., 2013), rosette quality (Mensur Kamberi et al., 2012; Ana Selamovska et al., 2011), planting time (Ana Selamovska et al., 2008b, 2008c), day length (Darrrow, 1966; Izhar, 1997; Sonsteby, 1997; Nishijama & Kanahama, 2002; Maria Konsin et al., 2002; Voyiatzis & Paraskevopoulou-Paroussi, 2002), altitude (Kremenović, 1977; Pirlak et al., 2002; Paydaş & Kaska, 1997), latitude (Stančević, 1971; Vitkovskii, 1984), cultivation method (Martti Pietila et al., 2002; Gast & Pollard, 1988; Plekhanova & Petrova, 2002; Pejović and Mišković, 1972; Kiprijanovski, 2001; Ana Selamovska et al., 2008a, 2009a; Valda Laugale et al., 2002; Ewelina Hallmann et al., 2016), plant nutrition (Atsushi Yamasaki et al., 2002; Lieten, 2002; Ozguven & Yilmaz, 2002; Georgia Paroussi et al., 2002; Olga Najdenovska et al., 2012) and other related factors.

5. CONCLUSIONS

In the Skopje region, under modified continental climatic conditions with Mediterranean influences, the initiation of mixed flower buds in the studied strawberry cultivar ‘Alba’ begins during the first decade of August, under long-day conditions of 13.5-14 hours. The formation of the inflorescence axis (stage IV) occurs in the first half of September. During stage V, the primordia of the floral parts are formed and differentiated, followed by the formation of the calyx primordia in the second half of September. From the end of September and during the first half of October, differentiation and intensive development of the calyx, petal, stamen, and carpel primordia take place. By the onset of flowering, the newly formed primordia reach a certain degree of differentiation. Archesporial tissue forms during the first half of November, followed by meiosis later in the month. Young microspores are formed at the end of December. Until the onset of vegetation growth, both microgametogenesis and macrogametogenesis proceed. Flowering begins in the first decade of April, and fruit ripening occurs in the first half of May.

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Original research article

BETWEEN ART AND MATHEMATICS: MULTIFRACTAL COMPARISON OF AN ORIGINAL PAINTING AND AI-GENERATED IMAGES

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Abstract

Generative artificial intelligence can produce images that closely resemble human-created artworks, yet human observers may still perceive subtle differences that are difficult to describe objectively. This study investigated whether such differences could be identified through mathematical analysis of the spatial organization of images. One original painting by an academic painter, who had completed university studies in painting, and two images generated by artificial intelligence were compared. The painter was also one of the authors and prepared the visual description used to generate the images, and later evaluated the generated results from an artistic perspective. The artificial intelligence model did not receive the original image and generated both images exclusively from textual descriptions of composition, color, lighting, style, and overall visual impression. The first image was generated from the initial description, whereas the second was generated from an expanded prompt containing additional information, mainly concerning composition and color. The three images were evaluated through artistic and perceptual analysis and two-dimensional multifractal analysis. The mathematical analysis examined several Red-Green-Blue, Hue-Saturation-Value, and CIELAB color channels using generalized Hurst exponents, and multifractal spectra. The results showed that the original painting exhibited a more complex spatial organization than the AI-generated images. The second generated image (AI2) was closer to the original than AI1, particularly in the analyzed color channels, but it still retained a degree of spatial uniformity that was less pronounced in the human-created artwork. These results suggest that, despite the improved visual similarity achieved with a more detailed prompt, the AI-generated image retained characteristics of a more uniform spatial organization.

Keywords *generative AI, 2D-MFDFA, visual similarity, image processing, multiscale analysis, prompt design.*

Highlights

- The painter's prompt reflected the intended artistic concept and enabled its quantitative analysis.
- A more detailed prompt produced an AI-generated image that was visually closer to the original.
- AI2 showed more stable multifractal behavior than AI1 across the analyzed channels.

Prompt details affected image brightness and multiscale spatial organization

Nomenclature

q - Moment order used in multifractal analysis
s - Spatial scale [pixels]
Fq(s) - q-order fluctuation function
h(q) - Generalized Hurst exponent
τ(q) - Mass exponent
α - Singularity strength
f(α) - Multifractal spectrum
Δα - Multifractal spectrum width
D(q) - Generalized dimension
RGB / HSV / CIELAB - Analyzed color spaces

1. INTRODUCTION

Generative AI has become widely available and can produce complex images from short textual instructions. It is especially popular for creating unusual, surreal, or imaginary scenes. However, a short prompt usually describes only the main semantic content. It does not always describe the exact position, shape, and relation of all visual elements.

This problem is especially important for artworks that combine realistic and abstract forms. The original painting used in this study contains a realistic female portrait, fire, and smoke, but the smoke also changes into semi-abstract forms. Such forms are difficult to describe precisely with words. Even realistic motifs such as smoke, clouds, or mist have variable shapes and cannot be completely defined by text.

This study is unique in that one of the authors is also the painter of the original image. The painter's style combines realistic painting with elements of contemporary surrealism and expressionism. Realistic painting follows the visible appearance of the motif, while surrealistic elements introduce unexpected combinations and transitions toward abstraction. Expressionistic elements may include distortion that emphasizes movement, emotion, or individual characteristics of a portrait. Because the painter participates directly in the experiment, the artistic intention of the original image can be compared with the AI interpretation of the written description.

The primary research question is whether a textual description can convey sufficient characteristics of an original artwork to reproduce them in an AI-generated image. Similarity is considered from two sides. The first is artistic and perceptual, including composition, color, tonal values, lighting, and style. The second is mathematical and considers spatial organization and multiscale complexity. Multifractal analysis is useful here because it does not reduce image structure to one global number; it describes how fluctuations and irregularities behave over different spatial scales and for different intensity ranges (Gu & Zhou, 2006; Sarkar & Chaudhuri, 1995). Fractal analysis has also been applied to the structural characterization of artworks (Taylor et al., 1999). Recent studies have also explored the use of fractal analysis to compare original paintings and their replicas. Ruiz de Miras and Martín (2025) examined how fractal dimensions and color information can help identify structural differences between artworks. This supports the use of mathematical methods as an additional tool for studying visual similarity.

The aim is to examine how well generative AI can reproduce visual characteristics and structure when it receives only text, and whether changes in the prompt also produce changes in multifractal characteristics.

2. MATERIALS AND METHODS

2.1. Original artwork

The original work is a vertical portrait of a young woman surrounded by smoke. She touches one of the small flames in the central part of the painting with her index finger. The general composition is diagonal. The portrait and hand are placed on the same side of the main diagonal, and the main light also follows a diagonal direction. This arrangement creates visual tension (Figure 1).



(a) Original **(b) AI1** **(c) AI2**

Fig. 1. Original painting and the two AI-generated images used in the experiment. The AI model did not receive the original image as visual input. Source: Authors' research

The palette is dominated by skin tones, gray smoke, and orange flames, complemented by a near-black background and reddish hair. The strongest tonal contrast is between the illuminated parts of the face and body and the dark background. Smoke occupies intermediate gray and brown tonal values. The orange flames are visually strong because they contrast with the mainly gray and brown environment.

The main light comes from the upper-right part of the image. The shadows on the face and body are relatively soft, and the orange flames create a secondary reflection on the shaded side of the face and on the fingers. The style combines realism in the portrait with abstraction in the smoke. The pronounced light-dark contrast evokes Baroque chiaroscuro, while the transformation of smoke into abstract forms creates a surrealistic impression. Important details are the small flames, the focused expression of the girl, and the moment of touching the fire.

2.2. Prompt formation and AI generation

The first prompt was formed from the painter's written analysis. For each important aspect of the image, several characteristics were described. Composition and color information were transferred directly, while stylistic features and the general impression were summarized.

Instructions about composition, color, light, and style were included. The original image was not shown to the AI model and had never been published or made available online.

After AI1 was generated, the painter identified the main differences: composition, position of the head and hands, and the shapes of smoke and flames. The second prompt therefore contained additional information, especially about composition and color. AI2 was judged by the painter as closer to the original artistic intention, although visible differences remained.

Both AI-generated images were created using OpenAI ChatGPT Image Generation through a paid ChatGPT account. OpenAI image generation technologies include the diffusion-based DALL-E 3 and the autoregressive GPT-4o image generation approach. Image generation was performed on OpenAI's remote servers. However, the authors did not have access to information about the exact model version used to generate the images.

2.3. Multifractal analysis

All three digital images were prepared at the same target size of 1122 × 1402 pixels. The analysis used q values from -5 to 5 with a step of 0.5 and spatial scales from 16 to 256 pixels. For each scale, local planar trends were removed from image blocks and the residual variance was used to calculate fluctuation functions. Four shifted partitions were used to reduce dependence on one fixed grid position (Gu & Zhou, 2006).

The analysis was performed separately for R, G, and B channels, HSV saturation and value channels, and CIELAB L*, a*, and b* channels. Before multifractal processing, every channel was standardized by subtracting its mean and dividing by its standard deviation.

For each q and spatial scale s, the fluctuation function Fq(s) was calculated. A scaling relation $Fq(s) \sim sh(q)$ was then fitted, where h(q) is the generalized Hurst exponent. For a 2D image, the mass exponent was calculated as $\tau(q) = qh(q) - 2$. The singularity strength α was obtained from the derivative of τ(q), and the multifractal spectrum was calculated using the Legendre transform $f(\alpha) = q\alpha - \tau(q)$. The spectrum width $\Delta\alpha = \alpha max - \alpha min$ was used as an indicator of the range of scaling behavior. A wider spectrum indicates a more heterogeneous multiscale structure. Spectrum asymmetry and generalized dimensions D(q) were also calculated (Sarkar & Chaudhuri, 1995; Wendt et al., 2009).

The analysis was performed using a custom Python program based on a modified 2D-MFDFA approach. The program used a least-squares method to estimate and remove a local planar trend from each image block. The detrending was applied directly to the normalized color channels, without calculating a cumulative image profile. Blocks with a variance below 10^{-14} were excluded to avoid numerical problems. Scales with fewer than 20 valid blocks were also excluded. The generalized Hurst exponents were estimated using linear regression in logarithmic coordinates, while the singularity strengths were calculated by numerical differentiation. The same program and parameters were used for all three images. The analysis was performed using a custom Python program (Python 3.10.5) on a personal computer equipped with an Intel Core i3 processor. The program used NumPy for numerical calculations, pandas for data processing, Matplotlib for visualization, Pillow for image resizing, and scikit-image for color-space conversion. No specialized hardware was required.

3. RESULTS

3.1. Artistic comparison

From an artistic perspective, the AI-generated images aligned more closely with the original in color and lighting than in composition. AI1 has clear differences in the position of the head and hand and in the shapes of smoke and fire. The second prompt improves the composition, so AI2 is closer to the original, but it is still not a copy. The largest similarity is in the general palette, strong light-dark contrast, and warm orange light. The most difficult elements to reproduce are the exact spatial arrangement and the unusual semi-abstract smoke forms.

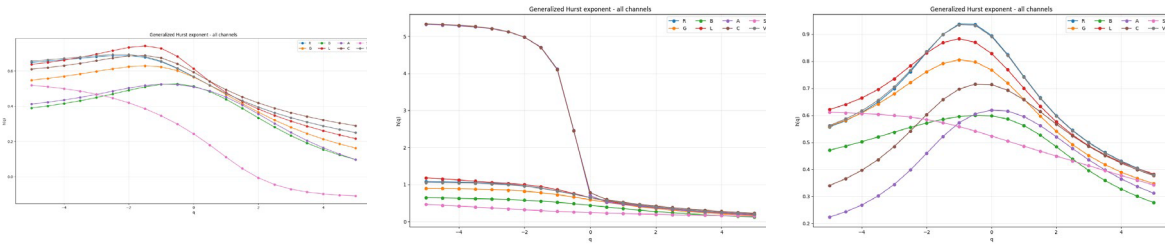
This observation is important because the prompt contained detailed compositional information, but text still could not fully describe irregular and semi-abstract forms. In contrast, color and lighting instructions were easier for the model to reproduce.

3.2. Multifractal results

The generalized Hurst exponent shows a clear difference among the three images. The original has relatively consistent and smooth curves for most channels. AI1 shows very strong deviations in several channels, especially A, C, and V for negative q values. In these cases h(q) rises above 5, which is very different from both the original and AI2. AI2 returns to a much more moderate range, approximately 0.2-0.95, with more regular curves.

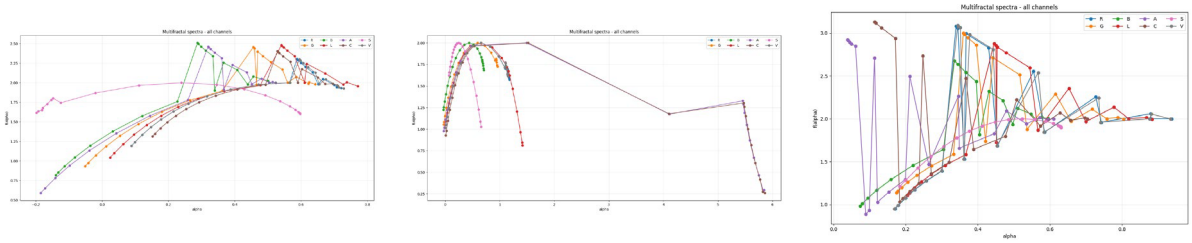
The multifractal spectra show the same general tendency. The original has relatively wide spectra, but their organization across channels remains structured. AI1 contains extreme spectrum expansion, especially in the A and C channels. In AI2, Δα values return to a range much closer to the original. This means that the first, less detailed prompt produced a very uneven multifractal structure in some color spaces, while the more detailed second prompt produced a more stable organization.

AI2 is still not mathematically identical to the original. The generalized Hurst curves and the relations among channels remain different. Therefore, the second prompt reduced some extreme differences but did not reproduce the complete multiscale organization of the painting.



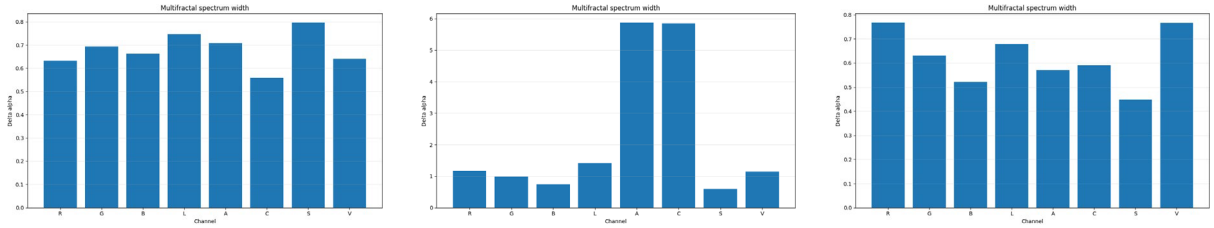
Original **AI1** **AI2**

Fig. 2. Generalized Hurst exponent h(q) for all analyzed channels. AI1 shows strong deviations, while AI2 has a more stable range closer to the original. Source: Authors' research



Original **AI1** **AI2**

Fig. 3. Multifractal spectra f(α). Extreme expansion is visible for AI1 in selected channels; AI2 is more compact and closer to the organization of the original. Source: Authors' research



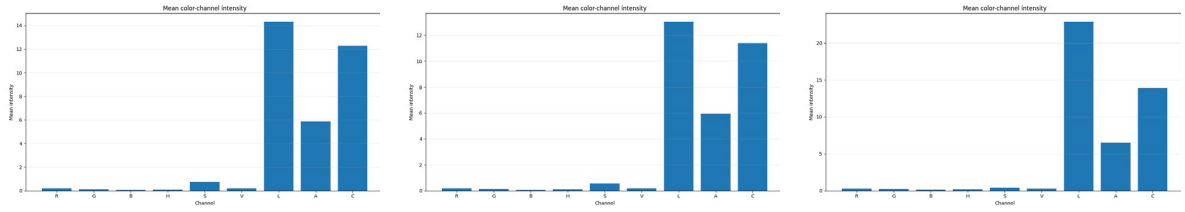
Original **AI1** **AI2**

Fig. 4. Multifractal spectrum width Δα by channel. AI1 has very large widths in A and C, while AI2 returns to values closer to the original. Source: Authors' research

3.3. Color-channel intensity and relation to the prompt

The mean channel intensity gives additional information about what changed after the second prompt. AI2 shows a strong increase in the L* lightness channel. This indicates that the more detailed prompt not only altered colors subjectively, but also modified the luminance distribution in the generated image. This result can be related to the additional description of lighting, bright elements, contrast, and tonal relations in the second prompt.

Taken together, the artistic and mathematical analyses show the same broad direction. The painter judged AI2 as visually closer to the original, and the multifractal analysis also shows that AI2 is more stable and, for several parameters, closer to the original than AI1. However, the agreement is not complete, which supports the idea that perceptual similarity does not necessarily imply full structural similarity.



Original **AI1** **AI2**

Fig. 5. Mean color-channel intensity. The strongest change in AI2 is visible in the L* lightness channel. Source: Authors' research

4. DISCUSSION

The experiment shows that some visual characteristics are easier to communicate through text than others. Color, lighting, and general style were reproduced relatively well. Replicating exact compositions and irregular forms proved more challenging. This is understandable because terms such as dark background, orange fire, or light from the upper-right corner can be described clearly, while the exact geometry of smoke or semi-abstract forms is much harder to express in words.

The multifractal results add information that cannot be obtained from artistic observation alone. AI1 can look generally related to the original while still showing extreme multiscale behavior in selected color channels. AI2 reduces these anomalies. This suggests that prompt changes can affect the spatial organization of image characteristics, not only the visible subject of the image.

At the same time, multifractal similarity should not be equated with artistic equality. A viewer may consider originality, expression, and the individuality of the portrait very important, while multifractal analysis measures statistical organization across scales. The two approaches therefore describe different aspects of similarity and are most useful when considered together.

The main limitation is the small experimental set: one original artwork and two AI images. Another limitation is the inability of text to describe all visual information consistently and precisely. Future studies should include a larger sample of paintings, additional generated variants, multiple AI models, and evaluations from independent art experts.

The channel-intensity comparison supports the visual observation that the second prompt changed the light structure of the generated image. The strongest difference appears in the L* channel. This is useful because the painter explicitly added more information about lighting, bright areas, contrast, and tonal relations in the second description. The result suggests a direct connection between a verbal artistic instruction and a measurable image property.

A larger study should repeat the same procedure on several original paintings. For each painting, several AI outputs should be generated from the same prompt so that random variation of the generator can be separated from the effect of prompt design. It would also be useful to compare several AI image models and to include more than one independent art evaluator.

Another possible extension is to calculate a numerical distance between complete multifractal spectra of the original and generated images. Such a measure could be compared with expert similarity scores. This could show more clearly when human visual judgment and mathematical structure agree and when they describe different properties of the image.

5. CONCLUSIONS

Comparing the original painting with AI1 showed significant structural differences in composition and motif morphology, particularly within smoke and flame elements. Similarity was higher for color and lighting. The second, more detailed prompt produced a visual result that was closer to the original, although important differences remained. The multifractal analysis showed a similar general trend. AI1 introduced strong changes in multifractal organization, with extreme behavior in some channels. AI2 had more stable generalized Hurst curves and spectrum widths closer to the original. The detailed prompt also strongly changed the luminance structure of the generated image. Consequently, the results indicate that prompt design influences not only semantic content and visual appearance, but also multiscale spatial organization. Multifractal parameters can provide additional information that subjective artistic evaluation does not directly capture. However, mathematical similarity is not the same as artistic similarity. The combination of the two perspectives is the main value of the proposed approach.

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Review article

COMPARATIVE ANALYSIS OF DIFFERENT TYPES OF ACTUATORS USED IN AIRCRAFT FLIGHT CONTROL SYSTEMS AND MAINTENANCE CONSIDERATIONS

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Abstract

Actuators are essential for moving the primary and secondary control surfaces of an aircraft. This professional paper compares mechanical, hydraulic, electrohydraulic, electromechanical (EMA), electrohydrostatic (EHA), and pneumatic actuators, with particular emphasis on reliability and maintenance. The aim is to explain how differences in power source, construction and control affect failure modes and maintenance requirements. A qualitative comparative review of aircraft-systems literature, recent actuator research and maintenance guidance is used. The technologies are assessed against common criteria: typical applications, advantages, limitations, maintenance tasks, and reliability considerations. A second comparison examines the same symptom—slow response or reduced output force—in hydraulic, EMA and EHA arrangements and identifies relevant checks. The comparison shows that removing central hydraulic interfaces does not eliminate maintenance requirements: EMA requires attention to transmission wear, lubrication and potential jamming, while EHA retains checks on local hydraulics, the pump and electrical components. Feedback and redundancy support reliable operation, but their effectiveness depends on failure modes and system architecture. Maintenance must therefore assess relevant performance and condition indicators, rather than merely confirm movement or the absence of external leakage. The practical contribution is a consolidated comparison linking actuator characteristics to maintenance priorities. No original reliability calculations, experimental measurements or numerical cost rankings are presented. The findings provide technology-level insight; actuator selection and maintenance limits depend on the specific design and approved maintenance data.

***Keywords**: Actuators, flight control system, input parameters, output parameters, malfunctions.*

1. INTRODUCTION

Actuators play an essential role in executing pilot commands and ensuring stable and precise control of the aircraft. Actuators are devices that convert mechanical, hydraulic, or electrical control signals into physical movement of the aircraft's flight control surfaces.

In modern aircraft, actuators are used to operate primary flight control surfaces such as the ailerons, elevator, and rudder, as well as secondary control surfaces including flaps, slats, and spoilers. Their primary function is to ensure that the pilot's commands from the cockpit are accurately transmitted and translated into the desired aerodynamic response of the aircraft.

Actuators significantly contribute to flight safety and control precision. They must operate reliably under varying loads, temperatures, and flight conditions, providing sufficient force and actuation speed for the effective movement of flight control surfaces. In larger and more advanced aircraft, hydraulic and electrohydraulic actuators are most commonly used due to their favorable power-to-weight ratio (Moir and Seabridge, 2008).

Furthermore, modern flight control systems, such as fly-by-wire (FBW) systems, rely extensively on electronically controlled actuators. In these systems, pilot commands are transmitted electronically, while the actuators execute these commands with a high degree of precision. Feedback control is also employed to improve the stability and controllability of the aircraft (Stevens et al., 2015).

Therefore, actuators play a key role in ensuring the controllability, safety, and performance of an aircraft, making them indispensable components of every flight control system.

The objective of this paper is to compare the principal actuator types in terms of their operating characteristics, reliability considerations, and maintenance requirements. The practical question is how a change in power source and construction changes the faults to be considered and the checks needed to confirm satisfactory operation. The contribution is a consolidated qualitative comparison, retaining the operating-principle and maintenance descriptions as its technical basis.

2. COMPARATIVE ANALYSIS OF DIFFERENT TYPES OF ACTUATORS IN THE AIRCRAFT FLIGHT CONTROL SYSTEM

Actuators used in aircraft flight control systems can be classified according to their operating principle, energy source, and design. Their selection depends on the size of the aircraft, the complexity of the system, and the required levels of reliability and performance.

The comparison is based on a targeted, non-systematic review of aircraft-systems and hydraulic-control literature, supplemented by recent actuator research and publicly available maintenance guidance. Six arrangements are compared against the same criteria: applications, advantages, limitations, maintenance tasks, and reliability considerations (Table 1). Three representative power architectures are then compared for the same operational symptom (Table 2). The entries represent engineering interpretations rather than measured rankings. No experimental sample or fleet cost dataset is used. Numerical reliability and cost comparisons and statistical inference are therefore outside the scope of this professional paper (Merritt, 1967).

2.1 Mechanical Actuators

Mechanical actuators (Figure 1) are the simplest actuator type and are primarily used in small, light aircraft. They transmit pilot commands directly to the control surfaces through cables, pushrods, levers, and gears. Their main advantages are simplicity and low weight; however, they are limited in the force they can provide and in their suitability for larger aircraft. Figure 1 shows a screw-based mechanical transmission. Cable and pushrod controls are other mechanical arrangements, rather than the construction shown in that figure.

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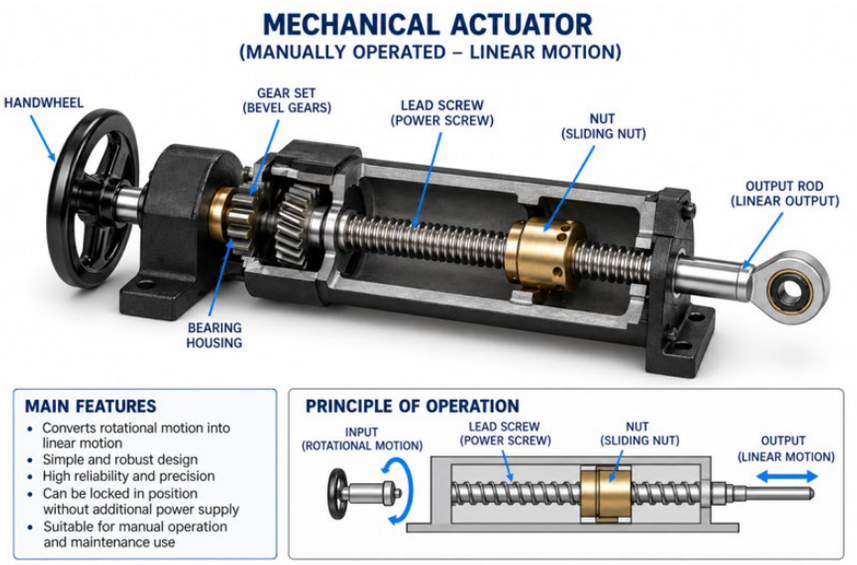


Figure 1: Mechanical actuators. Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

2.2 Hydraulic Actuators

Hydraulic actuators (Figure 2) are the most commonly used type of actuator on medium-sized and large aircraft. They use hydraulic pressure to generate the high force required to move flight control surfaces. They are characterized by high force output, reliability, and the ability to operate under high loads. Their disadvantages include the complexity of the hydraulic installation, maintenance requirements, and the possibility of hydraulic fluid leakage. Subtypes of hydraulic actuators include piston actuators, servo actuators, and double-acting actuators.

Aircraft such as the Boeing 737 and Airbus A320 use hydraulic actuator systems for their primary flight controls.

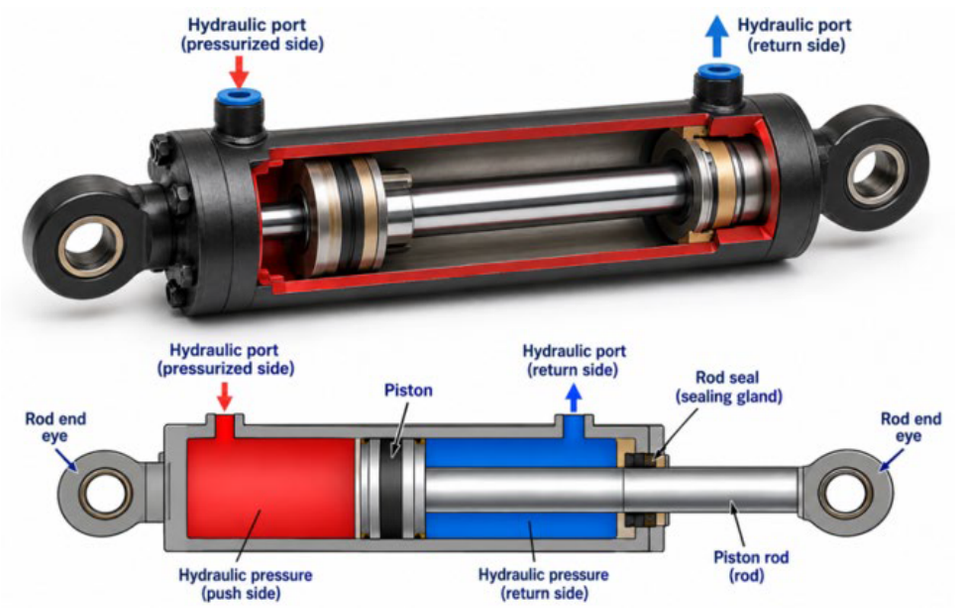


Figure 2: Hydraulic actuators. Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

2.3 Electro-Hydraulic Actuators

Electrohydraulic actuators (Figure 3) combine electrical control with hydraulic power.

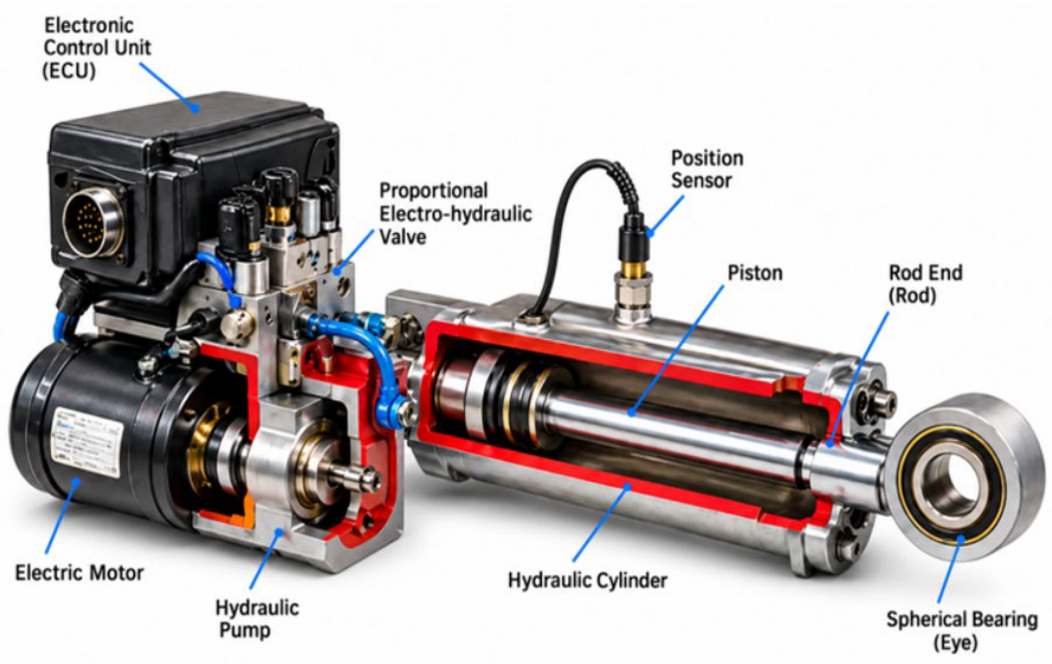


Figure 3: Electrohydraulic actuators. Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

An electrical signal from the flight control system controls the hydraulic actuator. These systems are widely used in modern aircraft with fly-by-wire technology because they provide high precision, automation, and reliability. In conventional centrally supplied arrangements, electrical power controls the valve, while hydraulic power drives the cylinder. Figure 3 is a general illustration of a combined electrohydraulic assembly containing local electric-motor and pump components; it should not be interpreted as the component arrangement of every centrally supplied hydraulic flight-control actuator.

2.4 Electric Actuators (EMA – Electromechanical Actuators)

Electric actuators (EMAs; Figure 4) use electric motors and mechanical transmission systems, such as ball screws, to directly actuate aircraft control surfaces. Their operating principle is based on an electric motor generating rotational motion, which is then converted into linear motion by means of a mechanical transmission mechanism.

Their main advantage is the elimination of hydraulic supply and return connections at the actuator, which can simplify installation and remove hydraulic-leakage checks at that location. However, reduced aircraft weight and maintenance cost depend on the complete system architecture. Their disadvantages include heat generation, wear of mechanical components, sensitivity to overload conditions, and the possibility of transmission jamming (Yin et al., 2022).

EMAs are used for selected aircraft controls and auxiliary functions. For example, Moog identifies an electromechanical spoiler actuator for the Boeing 787; this does not mean that all flight controls on that aircraft use EMA (Moog).

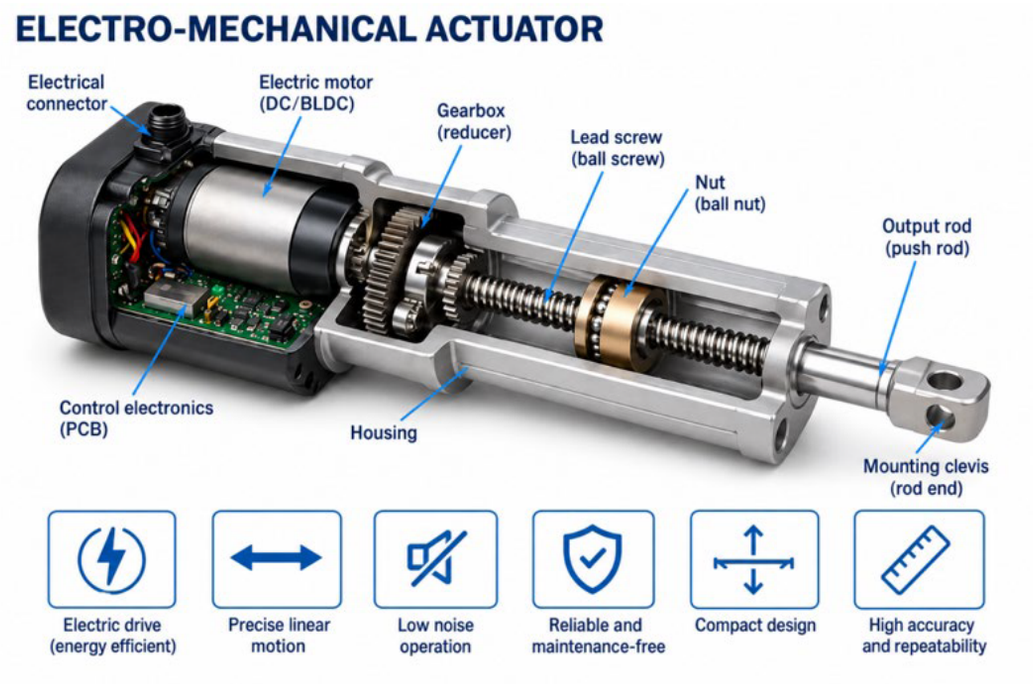


Figure 4: EMA – Electromechanical Actuators. Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

2.5 Electro-hydrostatic actuators (EHA)

Electrohydrostatic actuators (EHAs), shown in Figure 5, represent an advanced arrangement in which an electric motor drives a self-contained local hydraulic system. These actuators combine an electrical power supply with hydraulic force generation. Their energy efficiency depends on the duty cycle and losses in the electric motor, pump, and local hydraulic circuit.

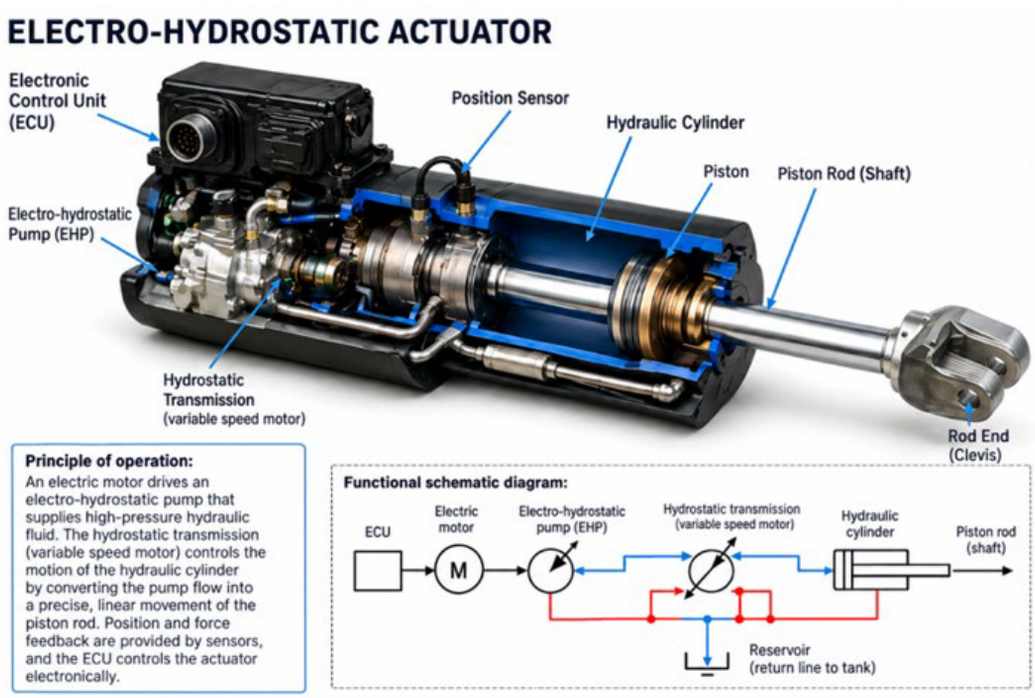


Figure 5: Electro-Hydrostatic Actuators (EHA). Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

Their main advantage is independence from a centralized hydraulic supply for the particular actuation channel, rather than elimination of all aircraft hydraulics. Localized power conversion also introduces pump, sealing, electrical, and thermal requirements. The Airbus A380 uses EHA in its flight-control architecture alongside other actuator arrangements (Airbus 2025).

2.6 Pneumatic Actuators

Pneumatic actuators (Figure 6) use compressed air to produce motion. They are less commonly used for primary flight controls because air compressibility affects stiffness and precise positioning. They may be suitable for auxiliary functions when the available pressure, required force, and response are compatible.

In modern aviation, there is a growing trend toward the “more electric aircraft” concept, in which electric and hybrid actuators are being investigated to improve energy use and simplify some system interfaces. The selection of an appropriate actuator type remains dependent on the required performance, failure tolerance, and maintenance support. Recent work addresses redundant electrical actuation and EHA architecture (Annaz & Kaluarachchi, 2023; SAE International, 2024).

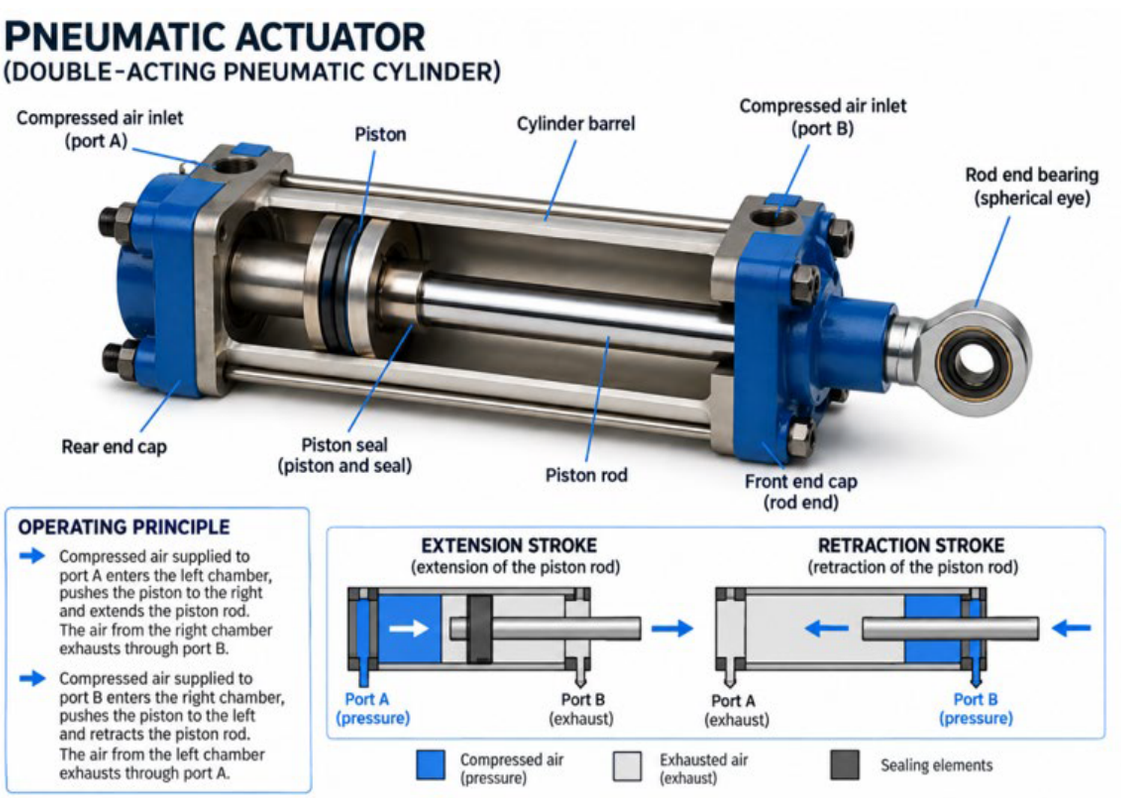


Figure 6: Double-acting pneumatic actuator. Source: AI-generated illustration prepared with OpenAI tools according to the author’s technical specifications.

2.7 Summary of the comparative analysis

The main distinction is the transfer of maintenance tasks rather than their universal reduction. EMA removes hydraulic-fluid tasks at the actuator but retains transmission and electrical tasks. EHA reduces dependence on central hydraulic distribution while retaining local fluid, pump, and electrical tasks. Consequently, neither technology can be ranked as universally more reliable or less costly from its name alone.

Table 1. Qualitative comparison of the principal actuator arrangements

Type	Typical application	Main advantages	Main limitations	Maintenance focus	Reliability considerations
Mechanical	Manual controls; mechanical transmissions	Direct force transmission; simple components	Force and routing limits; backlash	Cables, joints, rigging or screw wear	Breakage, wear and jamming
Hydraulic	Powered flight-control surfaces	High force from hydraulic pressure	Central-supply dependence; leakage	Seals, fluid cleanliness, valve and load tests	Supply loss; internal leakage; valve seizure
Electrohydraulic	Electronically commanded hydraulic surfaces	Electrical command; hydraulic output	Hydraulic and electrical interfaces	Hydraulic checks; wiring and feedback	Valve/sensor faults; shared-power dependencies
EMA	Selected controls, including 787 spoilers	No local hydraulic supply connections	Transmission wear/jam; heat	Lubrication, backlash, motor and drive	Electrical backup may not resolve a mechanical jam
EHA	Distributed powered channels, including A380 applications	Local hydraulic power generation	Local pump, fluid and drive complexity	Seals, local fluid, pump and electrical tests	Local conversion faults; electrical dependencies
Pneumatic	Suitable auxiliary functions	Uses available compressed air	Compressibility; pressure limits	Leakage, moisture and valve operation	Supply loss; seal or valve faults

*Entries are design-dependent and do not represent measured reliability or cost rankings. Source: Author's qualitative synthesis based on the literature cited in this article.

3. OPERATING PRINCIPLE OF ACTUATORS

The operating principle of actuators in an aircraft flight control system is based on converting control signals into mechanical movement of the flight control surfaces, thereby enabling control over the aircraft's movement and attitude. Regardless of their type, all actuators perform a common function—to provide an accurate, rapid, and reliable response to commands from the pilot or automatic control systems.

The basic operating principle can be divided into several stages. In the first stage, the control signal is generated. In conventional systems, this signal originates from the pilot's mechanical inputs, such as movement of the control column or control pedals. In modern systems, such as fly-by-wire, pilot commands are converted into electrical signals.

The second stage involves transmission of the control signal to the actuator. In mechanical systems, the signal is transmitted through cables and control rods, whereas hydraulic and electrical systems use energy transmission through pressurized fluid or electrical power.

The third stage is energy conversion. The actuator receives the input signal and converts it into useful mechanical energy. For example, a hydraulic actuator uses fluid pressure to move a piston within a cylinder, while an electric actuator uses an electric motor which produces linear or rotary motion through gears or a screw mechanism.

The following section provides a more detailed explanation of the functions and operating principles of two particularly sensitive and critical components: the directional control valve in hydraulic actuators and the solenoid valve used in electrically controlled actuators.

The hydraulic directional control valve, or spool valve, is a key component in the control of a hydraulic actuator because it determines the direction of movement, speed, and stopping of the actuator by regulating the flow of the working fluid. Specifically, the directional control valve directs hydraulic fluid, typically hydraulic oil, from the pump to the appropriate side of the cylinder or hydraulic motor, while simultaneously allowing the fluid to return to the reservoir.

Figure 7 illustrates an explanatory 4/3 directional control valve (four ports, three positions), with a closed-centre arrangement in the neutral position. It is not a universal layout for aircraft flight-control servo valves. The ports are:

- P (Pressure) – supply of pressurized fluid from the pump;
- T (Tank) – return of fluid to the reservoir;
- A and B – connections to the actuator chambers.

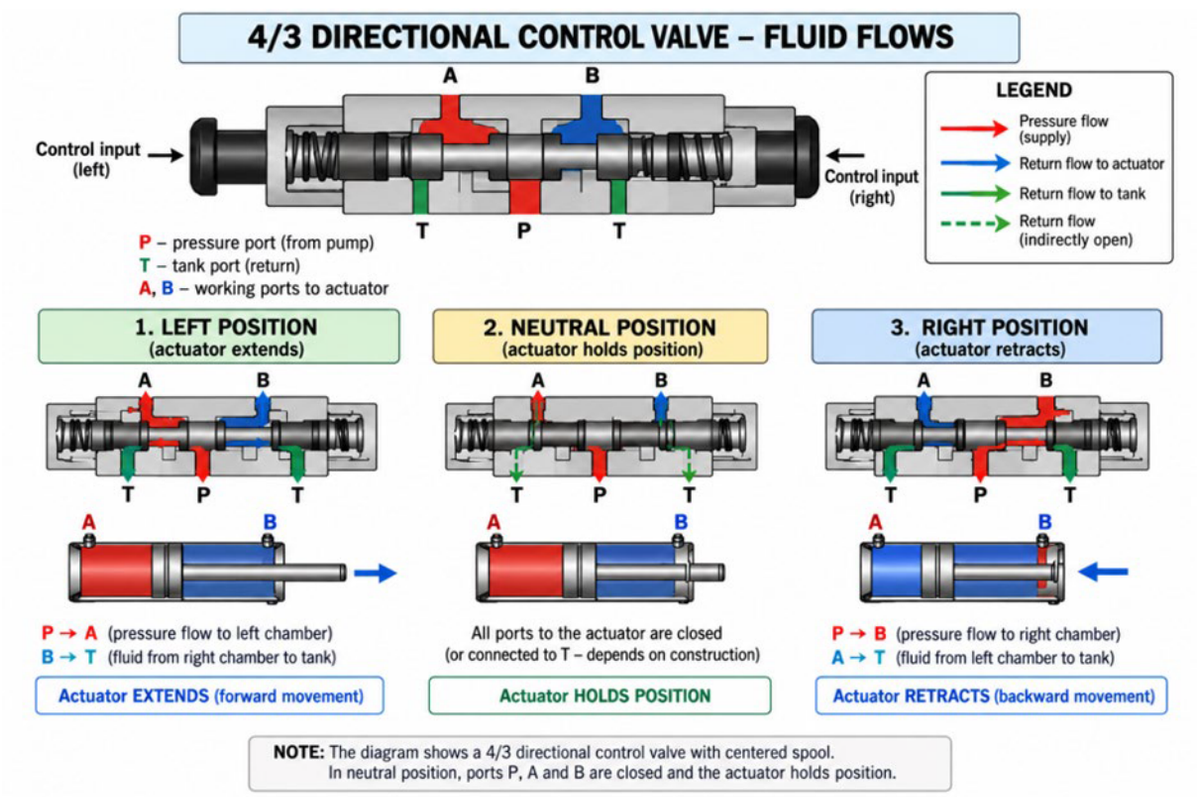


Figure 7: Schematic of a hydraulic directional control valve showing fluid flows. Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

The three characteristic positions correspond to the neutral (center) position, the first operating position, in which fluid flows from P to A while fluid from B returns to T, resulting in extension of the actuator, and the second operating position, in which fluid flows from P to B while fluid from A flows to T, resulting in retraction of the actuator (Merritt, 1967).

The directional control valve can be operated manually (by means of a lever), electromagnetically (by a solenoid), pneumatically, hydraulically, or electronically. In modern

aircraft hydraulic systems, the valve is characterized by three principal functions: directional control, flow-rate and actuator-speed control, and safe and reliable operation.

The directional control valve of a hydraulic actuator functions as a kind of traffic controller within the hydraulic system because it determines where the hydraulic fluid will flow and, consequently, directly controls actuator operation. Without a directional control valve, precise control of movement in hydraulic systems would not be possible, particularly in applications such as aircraft flight control systems.

Solenoid valves used in electrically controlled actuators serve to convert an electrical signal into mechanical movement of the valve, thereby controlling fluid flow and indirectly controlling actuator movement. At the heart of the valve is a solenoid (electromagnet) consisting of a coil and a movable ferromagnetic core, commonly referred to as a plunger or armature.

When an electric current flows through the coil, a magnetic field is generated, which attracts the movable core. The core then moves the valve element, opening or closing the fluid passage. When the electrical current is interrupted, a spring returns the core to its initial position, and the valve returns to its original state.

Thus, there are two characteristic valve configurations, illustrated in Figure 8:

- Normally Closed (NC) – the valve remains closed when the solenoid is de-energized and opens when the solenoid is energized;
- Normally Open (NO) – the valve remains open when the solenoid is de-energized and closes when the solenoid is energized.

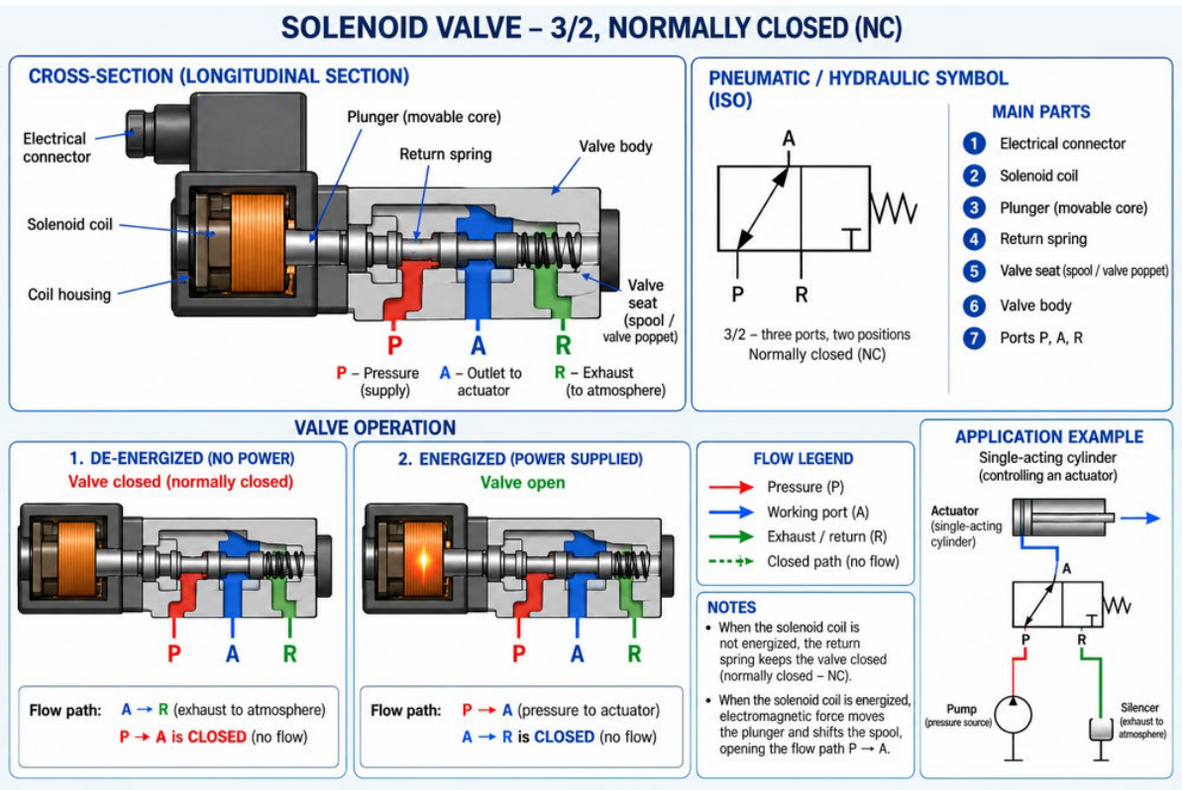


Figure 8: Schematic of a solenoid valve showing fluid flows. Source: AI-generated illustration prepared with OpenAI tools according to the author's technical specifications.

In fluid-powered arrangements, solenoid valves can start or stop flow, select a flow path, or provide an isolation function. They are distinct from continuously modulating servo valves used for precise control. Switching time, reliability, and energy consumption depend on the valve design and duty cycle; these characteristics cannot be inferred solely from the presence of a solenoid.

An important element in actuator operation is the feedback system. This system enables monitoring of the actual position of the control surface and comparison with the commanded position. Based on the difference between the actual and commanded positions, referred to as the position error, the control system automatically adjusts actuator operation to achieve the required level of precision and stability.

In addition, actuators are equipped with safety and redundant systems. In modern aircraft, multiple actuators are often provided for a single control surface, along with multiple power sources, such as hydraulic or electrical systems. This arrangement ensures continued functionality even in the event of a failure of one component or one part of the system.

Overall, the operating principle of actuators in an aircraft flight control system involves receiving a command, transmitting the command, converting energy into mechanical movement, and continuously monitoring execution through a feedback system. This process enables precise aircraft control and represents a key element of aircraft safety and controllability.

4. DESIGN CHARACTERISTICS OF ACTUATORS IN AIRCRAFT FLIGHT CONTROL SYSTEMS

The design characteristics of actuators in aircraft flight control systems determine their reliability, precision, power capability, and resistance to various operating conditions. Regardless of whether they are hydraulic, electric, or electrohydraulic, actuators share certain structural elements and specific design features.

The basic structural element is the actuator housing, which must be sufficiently strong to withstand high mechanical loads and pressures while also being as lightweight as possible in order to meet aircraft weight-reduction requirements. Actuator housings are commonly manufactured from high-strength aluminum alloys, titanium, or steel.

In hydraulic actuators, the key components are the cylinder and piston. Piston movement within the cylinder is achieved by the action of pressurized hydraulic fluid. The internal surfaces must be precisely machined to minimize friction and ensure proper sealing. Seals play a critical role in preventing fluid leakage and maintaining system pressure.

Electric actuators contain an electric motor, a reduction gearbox, and a mechanism for converting rotary motion into linear motion, most commonly a threaded spindle or ball screw. In this respect, the design must ensure high transmission efficiency and minimal energy losses.

Electrohydraulic and electrohydrostatic actuators combine electrical control or power with hydraulic force transmission. In centrally supplied electrohydraulic arrangements, the pump and reservoir normally belong to the aircraft hydraulic system. An EHA instead incorporates a local motor-driven pump and fluid circuit within or alongside its actuator assembly.

An important part of the actuator design consists of control and regulating components, such as servo valves in hydraulic systems and electronic control units in electric actuators.

These components enable precise regulation of energy delivery as well as control of actuator speed and position.

Sensors and feedback systems are indispensable components of modern actuators. The most commonly used devices include position sensors, such as potentiometers and LVDTs (Linear Variable Differential Transformers), as well as pressure and temperature sensors. These devices enable continuous monitoring of actuator operation and a high degree of control accuracy.

The actuator design also incorporates redundant and safety-related elements, such as dual hydraulic circuits, multiple motor windings, and mechanical systems for locking and limiting actuator travel. This is particularly important in aviation, where system reliability is a fundamental requirement.

In addition, actuators must be designed to operate under extreme conditions, including large temperature variations, vibration, pressure changes, and high loads during flight. Consequently, special attention is given to sealing, lubrication, and corrosion protection (RTCA 2010).

In modern aircraft, there is an increasing trend toward compact and modular actuator designs, which facilitate maintenance and component replacement. The design characteristics of actuators directly affect the overall performance, safety, and efficiency of the aircraft flight control system.

5. ACTUATOR RELIABILITY IN AIRCRAFT FLIGHT CONTROL SYSTEMS

The reliability of actuators in aircraft flight control systems represents one of the key factors determining the overall safety and functionality of an aircraft. Since actuators directly control the flight control surfaces, their proper operation must be ensured under all flight conditions and throughout a wide range of operating environments.

One of the fundamental principles for ensuring reliability is redundancy. This means that, in modern aircraft, a single flight control surface is often operated by multiple actuators or supplied by multiple independent power sources, such as hydraulic or electrical systems. In this way, if one system fails, another can take over its function without resulting in a loss of aircraft controllability.

An important aspect of reliability is the distinction between fail-safe and fail-operational designs. A fail-safe design limits the consequences of a failure so that a safe state can be maintained; the appropriate response depends on the system. A fail-operational design retains the required function after a specified failure. Neither property follows solely from the actuator type or the number of redundant elements.

The quality of the design and materials also has a major influence on reliability. Actuators are manufactured from high-quality materials resistant to fatigue, corrosion, and temperature variations. All critical components undergo rigorous testing and certification in accordance with stringent aviation standards.

Monitoring and diagnostic systems enable assessment of actuator condition where the relevant sensors are installed. Parameters such as position, pressure, temperature, and rate of movement can reveal irregularities. Recent research on EMA fault diagnosis and health management also investigates predictive maintenance, but validated prediction capability is not a universal feature of every installed actuator (Yin et al., 2022; Kulida & Lebedev, 2024).

A comparison of reliability must distinguish loss of power from mechanical jamming. An independent power source may support continued operation after supply loss, but it does not automatically overcome a seized screw, blocked valve, or common transmission. The redundancy architecture must therefore provide an appropriate response to the failure being considered. No actuator-level failure rates are inferred in this comparison (Annaz & Kaluarachchi, 2023).

6. MAINTENANCE OF ACTUATORS IN AIRCRAFT FLIGHT CONTROL SYSTEMS

Maintenance plays a critical role in preserving actuator reliability. Regular inspections, testing, and replacement of worn components are performed in accordance with strictly defined procedures. A modular design approach enables rapid replacement of defective actuators without keeping the aircraft on the ground for extended periods.

Actuators are also designed to operate under extreme conditions, including large temperature variations, vibration, pressure changes, and high mechanical loads. Therefore, additional protective measures are applied, such as sealing, fluid filtration, and overload protection.

Ultimately, actuator reliability is verified through extensive testing and certification, including endurance tests, material fatigue tests, and failure simulation tests.

Overall, high actuator reliability ensures safe and stable aircraft control, making actuators one of the most critical components of the aircraft flight control system.

6.1 Actuator Maintenance Procedures

Maintenance procedures for actuators in aircraft flight control systems have a direct impact on flight safety. Maintenance is based on preventive and corrective tasks, with condition-based or predictive methods where approved and validated, in accordance with the applicable technical documentation and aviation requirements (European Union Aviation Safety Agency).

Preventive maintenance includes regular visual and functional inspections of actuators. During these inspections, the condition of the housing, connections, mounting points, and fittings is checked, as well as any signs of damage, deformation, or fluid leakage in hydraulic systems. Particular attention is paid to seals and connections because even minor leakage can result in pressure loss and reduced system efficiency.

For hydraulic actuators, the quality of the hydraulic fluid is also checked. This includes inspection of fluid cleanliness and the presence of contaminants, moisture, and metallic particles. Regular filter replacement and fluid sampling are standard maintenance procedures. The operation of servo valves and actuator response to control commands are also checked.

Functional testing involves verifying actuator operation under actual or simulated operating conditions. These tests include checking actuator travel, rate of movement, force output, and positioning accuracy. Modern maintenance facilities use specialized test equipment and diagnostic software that enable detailed analysis of actuator performance.

For electric and electrohydraulic actuators, maintenance includes inspection of electrical connectors, wiring, insulation, and electronic control units. Voltage, current, and resistance

measurements are used to verify the condition of electric motors and control circuits. The operation of sensors and feedback systems, such as LVDT sensors, is also checked because these components play a critical role in control accuracy.

Lubrication is an important aspect of maintenance, particularly for mechanical and electromechanical actuators. Moving components, such as bearings, joints, and threaded spindles, must be properly lubricated to reduce friction and wear. Specialized lubricants resistant to high and low temperatures, as well as extreme operating conditions, are used.

Corrective maintenance is performed in the event of a failure or abnormal actuator operation. It most commonly involves replacing defective components or replacing the complete actuator, particularly in modular systems where detailed repair is not performed on the aircraft but rather the complete assembly is replaced. Defective actuators are subsequently sent to specialized maintenance facilities for overhaul.

Predictive maintenance uses condition-monitoring data to identify trends that may indicate degradation. Parameters such as vibration, temperature, pressure, and response time must be interpreted in relation to operating load and conditions. Such methods may improve maintenance planning, but reductions in cost or failure occurrence require operational validation (Yin et al., 2022; Kulida and Lebedev, 2024).

Where required by the approved maintenance programme or component instructions, periodic overhaul is performed at specified intervals. During an overhaul, the actuator is disassembled, cleaned and inspected, and components such as seals, bearings and valves are replaced as required. After reassembly, the actuator undergoes the prescribed tests before being returned to service. A universal overhaul interval is not assumed for every actuator type.

In addition, all maintenance procedures must be properly documented in the relevant technical records. This enables the operating and maintenance history of the actuator to be tracked and supports future maintenance planning and compliance with regulatory requirements.

Overall, actuator maintenance is a complex and systematic process that ensures long-term reliability, precision, and operational safety, thereby directly contributing to the safety of the entire aircraft.

Maintenance must be performed in accordance with applicable maintenance data and approved procedures. Certain repair or overhaul tasks may require specialist facilities, equipment or original equipment manufacturer (OEM) support. The work must fall within the capabilities and approval of the maintenance organisation, but this does not mean that the manufacturer has exclusive maintenance rights in all cases (European Union Aviation Safety Agency).

6.2 Comparative maintenance interpretation and limitations

Comparative maintenance interpretation and limitations identifies different investigation paths, rather than three confirmed diagnoses. Checks must follow applicable maintenance instructions and limitations; no invented numerical acceptance criteria are introduced. Table 2 compares the same symptom—slow movement or reduced output force—across three architectures.

Table 2. A common operational symptom and architecture-specific maintenance checks

Actuator arrangement	Same observed symptom	Possible causes to distinguish	Relevant checks
Centrally supplied hydraulic/electrohydraulic	Slow movement or reduced output force	Insufficient supply pressure/flow; internal leakage; metering fault	Supply condition, leakage/holding performance and valve response
EMA	Slow movement or reduced output force	Electrical supply/drive fault; increased transmission friction; damage or wear	Supply/drive checks, current under known load, lubrication and transmission condition
EHA	Slow movement or reduced output force	Motor-drive or pump problem; local leakage; local fluid-circuit condition	Electrical drive, local pressure, pump operation, fluid and sealing condition

Source: Author's qualitative synthesis based on the literature cited in this article.

The comparison explains why a simple movement check is insufficient: similar symptoms can originate in different components. Assessment of hydraulic performance requires consideration of both the supply and leakage. For EMA, electrical faults must be distinguished from resistance in the transmission mechanism, while EHA requires checks on electrical components and local hydraulics. A maintenance-cost comparison would additionally require task intervals, labour hours, repair or replacement costs, actuator removal frequency and records of aircraft downtime. These data are unavailable, so no numerical cost savings are claimed.

A strength of this review is the use of common criteria to link operating principles with practical maintenance priorities. A limitation is its reliance on published information without a common test platform or fleet reliability and cost records. The tables provide qualitative comparisons at technology level and cannot establish a numerical ranking of commercial actuator models.

7. CONCLUSIONS

This paper emphasizes that actuators represent an essential link between the aircraft control system and its flight control surfaces, enabling reliable and precise flight control under all operating conditions. Throughout the development of aviation, the role of actuators has evolved from simple mechanical solutions to sophisticated hydraulic, electro-hydraulic, and electromechanical systems, particularly within modern fly-by-wire architectures.

Different types of actuators, although based on similar principles of converting energy into mechanical movement, differ in their design characteristics, control methods, and levels of reliability. These differences directly influence their application within specific segments of an aircraft flight control system.

With regard to actuator maintenance, this paper emphasizes the need for a systematic and strictly controlled approach, including regular inspections, diagnostics, preventive measures, and timely replacement of components. Reliability is of particular importance because an actuator failure or malfunction can have serious consequences for flight safety.

For this reason, modern aircraft employ advanced condition-monitoring methods and built-in fault-detection systems, which are closely associated with the feedback control system. Finally, an effective combination of appropriate actuator selection and properly organized maintenance provides the foundation for achieving a high level of safety, performance, reliability, as well as a long aircraft service life.

The comparative result is that actuator selection changes the focus of maintenance rather than eliminating it: hydraulic arrangements require fluid and valve checks, EMA requires transmission and electrical checks, and EHA requires local hydraulic as well as electrical checks. No universal best actuator is identified. Future work should test comparable designs under the same loads and use verified operator records to quantify reliability and maintenance costs.

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Review article

ISO-ALIGNED CLOSED-LOOP ARCHITECTURE FOR DIGITAL-TWIN-ENABLED METAL CUTTING

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Abstract

Contemporary metal-cutting systems increasingly integrate sensors, connectivity, analytics, and manufacturing software, but many implementations do not establish a traceable path from process observation to governed manufacturing action. This study develops an ISO-aligned closed-loop architecture for metal cutting supported by a digital twin through a targeted integrative review of 28 scientific, normative, engineering, and industrial sources. Sources were selected for direct relevance and coded against measurement, manufacturing context, digital representation, analytical modelling and assurance, decision support, execution, machinery safety, and industrial cybersecurity. The resulting architecture comprises five functional blocks linking the physical machining process, edge acquisition, semantic manufacturing data, digital-twin services, and governed decision and execution. A source-to-function evidence matrix makes the synthesis traceable. The proposed minimum data contract links machining commands, timing and synchronization, machine state, process response, tool and workpiece identity, quality evidence, and model-assurance information. An explicit execution-authority boundary separates analytical recommendations from executable actions, while subsequent measurement closes the operational loop. The framework provides an implementation-oriented basis for monitoring, predictive maintenance, and bounded optimization in brownfield CNC environments. Experimental validation remains necessary to quantify latency, uncertainty, model drift, false-alarm behaviour, and the effects of bounded parameter updates.

***Keywords**: digital twin; metal cutting; cyber-physical production system; OPC UA; tool condition monitoring; manufacturing interoperability; predictive maintenance.*

Highlights

- States four research questions and traces them to synthesis outputs
- Maps 28 sources to five CNC architecture blocks and governance controls
- Defines a timing-aware minimum data contract for brownfield machining cells
- Introduces an execution-authority boundary and a closed-loop criterion

Nomenclature

CNC - computer numerical control;
CPPS - cyber-physical production system;
DT - digital twin;
IACS - industrial automation and control system;
IEC - International Electrotechnical Commission;
ISA - International Society of Automation;
KPI - key performance indicator;
MES - manufacturing execution system;
NIST - National Institute of Standards and Technology;
OEE - overall equipment effectiveness;
OME - observable manufacturing element;
OPC UA - OPC Unified Architecture;
RQ - research question;
SRP/CS - safety-related parts of control systems;
VVUQ - verification, validation, and uncertainty quantification.

1. INTRODUCTION

Industry 4.0 links physical production with computation, communication, and data services, but that connection creates industrial value only when data support a reliable operational decision. Cyber-physical production systems must therefore synchronize shop-floor events with models and enterprise information instead of merely adding dashboards to isolated machines (Galar Pascual et al., 2020; Monostori et al., 2016; Xu et al., 2018). Interoperability remains difficult because machine tools, metrology equipment, maintenance systems, and MES applications use different identifiers and time bases for the same job, tool, or part (Lu, 2017).

Metal cutting makes the integration problem concrete. Cutting speed, feed, depth of cut, tool geometry, work material, lubrication, machine-tool dynamics, and fixturing jointly affect force, temperature, vibration, tool wear, dimensional deviation, and surface texture (Nedić & Lazić, 2007; Teti et al., 2010). Spindle power without the active cutting edge, material lot, operation, and coordinate context can reveal change but cannot distinguish wear from a new workpiece condition or a commanded process transition.

Digital twin terminology covers different integration levels. A digital model has no automatic data exchange, a digital shadow receives one-way data from the physical asset, and a digital twin supports automated bidirectional exchange (Kritzinger et al., 2018). Many manufacturing applications provide monitoring or simulation without returning validated analyses to the physical counterpart (Cimino et al., 2019). In machining, model fidelity, communication latency, collaboration among twin components, and control granularity determine whether a digital twin progresses from visualization to process support (Bergs et al., 2023; Liu et al., 2023). Multi-scale quality representation must also connect machine and process behaviour with surface and material characteristics (Fu et al., 2025).

However, the reviewed literature did not provide a sufficiently explicit implementation-oriented mapping that connected ISO 23247 functions with machining-specific data, OPC UA machine-tool interoperability, model assurance, and a controlled path from analytical recommendations to authorized shop-floor execution. The study therefore addressed four research questions: RQ1, which functional blocks are required for an operational closed-loop digital twin in metal cutting; RQ2, which data and contextual information must cross the architecture boundaries; RQ3, how safety and cybersecurity should constrain the transition from analytical

recommendation to machine execution; and RQ4, which minimum information and deployment states are required for brownfield implementation.

The original contribution is threefold. First, the study operationalizes ISO 23247 through a five-block closed-loop architecture specific to metal-cutting operations. Second, it defines a timing-aware minimum data contract that links machining commands, machine state, process response, tool and workpiece identity, quality evidence, and model assurance. Third, it introduces an execution-authority boundary between analytical recommendations and executable machine actions. Unlike frameworks centred on connectivity, monitoring, or digital representation, the proposed architecture specifies the complete path from an observable manufacturing element to governed operational action.

2. MATERIALS AND METHODS

2.1. Review Strategy and Evidence Selection

The study used a targeted integrative review rather than a systematic review or meta-analysis and covered records available through 31 August 2026. Candidate literature was located through author-shared ResearchGate records, targeted searches of publisher and university pages, and the official catalogues of ISO, IEC, ISA, the OPC Foundation, and NIST. Representative literal queries were "digital twin" AND ("metal cutting" OR machining) AND ("closed loop" OR control); "tool condition monitoring" AND (sensor OR "machine learning") AND machining; and ("OPC UA" OR "OPC 40501-1" OR "ISO 23247") AND (CNC OR manufacturing). Operators were adapted only to the syntax of each site. Author, year, venue, pages, and DOI were verified against the corresponding publisher or institutional record.

Sources were retained when they supplied architecture-relevant evidence on measurement, manufacturing context, digital representation, analytical modelling and assurance, decision support, execution, machinery safety, or industrial cybersecurity. Marketing-only claims, records without traceable bibliographic provenance, and sources without relevant technical content were excluded. The targeted search was not exhaustive; therefore, PRISMA-style counts of hits, duplicates, and rejected records were not claimed. The final set comprised 28 items: 13 peer-reviewed papers, 11 standards or industry specifications, two engineering texts, one NIST implementation report, and one current NIST standards program.

2.2. Evidence Coding and Architectural Synthesis

Evidence was coded in two passes. The first pass recorded source type, publication year, machining scope, validation basis, reported limitations, and the eight functional categories used in this study. The second pass mapped each supported claim to an architecture block, required interface data, governing standard, and governance constraint. A source could support more than one category, but each assignment required explicit technical or normative support in the full text. Ambiguous assignments were resolved by returning to the cited passage and retaining only the narrowest defensible mapping. Table 1 is the resulting audit trail from source group to architecture function.

Architectural synthesis followed three rules: every block had to expose an evidence-supported input, engineering function, and output; every datum crossing a block boundary had to retain identity, unit, time, provenance, and quality state; and every path to physical execution had to cross an explicit authority boundary governed by machinery safety and industrial cybersecurity. These rules yielded five operational blocks and three cross-cutting governance controls. No experimental equipment, proprietary review software, or statistical package was used because the study synthesizes published evidence rather than testing a physical machining cell. No pooled effect estimate was calculated for the heterogeneous machines, sensors, materials, and validation procedures.

3. RESULTS

The results derive from the evidence synthesis and architectural mapping in Section 2; they do not represent experimental validation of a deployed machining cell. Figure 1 answers RQ1 through the five-block architecture; Table 2 and Section 3.4 answer RQ2 through the data contract and verification indicators; the execution-authority boundary and governance controls answer RQ3; and the staged deployment pathway answers RQ4. The architecture begins at an OME and ends when an authorized decision changes a manufacturing operation, consistent with the observable, device-communication, digital-twin-entity, and user-function domains of ISO 23247 (International Organisation for Standardization [ISO], 2021a, 2021a, 2021b, 2021c, 2021d; Shao & Helu, 2020).

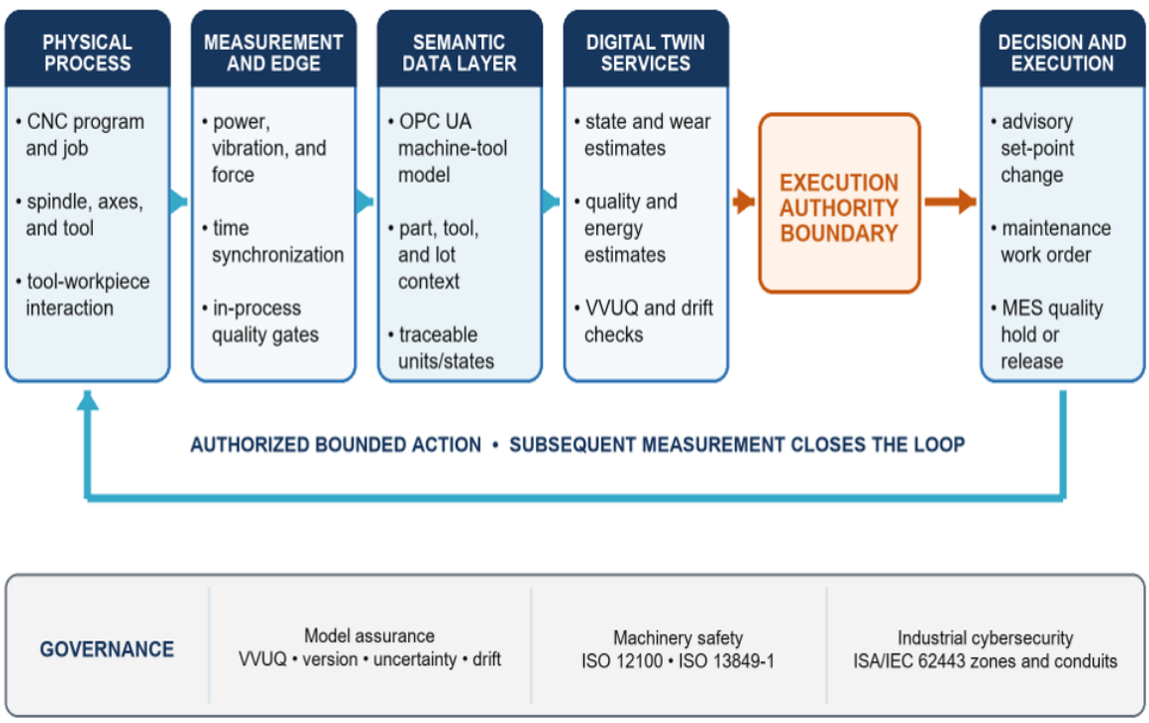


Fig. 1. Proposed ISO-aligned closed-loop architecture for smart metal cutting. Cyan arrows show operational data and feedback; the orange gate separates analytical output from authorized execution; the lower lane shows model assurance, machinery safety, and industrial cybersecurity controls. Source: Authors' research

3.1. Functional Architecture

The physical-process block receives machining commands, job context, and physical state; performs material removal; and outputs process responses and quality-relevant signals. ISO 23247 governs the observable manufacturing domain, while machinery safety is a non-negotiable constraint. The measurement-and-edge block receives controller, sensor, and metrology signals; aligns time, filters data, constructs features, and detects events; and outputs time-stamped process and quality features. ISO 13374-1 governs the acquisition-to-presentation chain, while latency, provenance, and failure-mode relevance constrain signal selection (ISO, 2003; Teti et al., 2010; Tran et al., 2023).

The semantic-data block binds time-stamped features and production records to the machine, job, operation, cutting edge, workpiece, unit, provenance, and quality state, and then publishes traceable OPC UA objects. IEC 62264-1 governs enterprise-control context, and OPC 40501-1

governs machine-tool semantics (International Electrotechnical Commission [IEC], 2013; OPC Foundation, 2024). Digital-twin services estimate state, wear, quality, and energy, and return predictions together with information on the model version, training domain, residual behaviour, uncertainty, and drift status. ISO 23247 governs digital representation, while NIST guidance makes VVUQ and traceability explicit assurance constraints (National Institute of Standards and Technology [NIST], 2026).

The decision-and-execution block classifies assured analytical output as operator information, approval-dependent advice, or an automatically executable command and issues only actions permitted by the authority boundary. A maintenance work order or MES quality hold is an operational action even without a CNC set-point change (Kibira et al., 2016; Shao, 2021). The loop closes only when an authorized decision causes a bounded change in the physical manufacturing state, and the next measurement cycle observes that change.

3.2. Evidence and Standards Traceability

Table 1 exposes the source-to-function mapping used in the synthesis. It also prevents any single framework or protocol from being treated as if it defined process physics, semantic context, model assurance, performance measurement, safety integrity, and cybersecurity simultaneously.

Table 1. Evidence-synthesis and standards-traceability matrix

Source group	Evidence or governing function	Supported architecture element
Nedić and Lazić (2007); Teti et al. (2010); Tran et al. (2023)	Machining physics, sensing, and condition features	Physical process and measurement/edge
Monostori et al. (2016); Lu (2017); Xu et al. (2018); Galar Pascual et al. (2020)	CPPS integration and interoperability	Semantic layer and enterprise context
Kritzinger et al. (2018); Cimino et al. (2019); Liu et al. (2023); Bergs et al. (2023); Fu et al. (2025)	Twin maturity, fidelity, and quality representation	Digital-twin services and closed loop
ISO (2021a-d); Shao and Helu (2020); Shao (2021)	OME, reference architecture, representation, and use cases	Five-block architecture
IEC (2013); OPC Foundation (2024); ISO (2003, 2014)	Context, machine semantics, condition chain, and KPIs	Edge, semantic layer, twin, and MES
NIST (2026); Kibira et al. (2016); Khan et al. (2025)	VVUQ, performance assurance, and predictive modelling	Model-assurance governance
ISO (2010, 2023); ISA (2025)	Risk reduction, execution integrity, and IACS security	Authority boundary and governance

Source: Authors' research

3.3. Minimum Data Contract

The proposed minimum data contract in Table 2 is an implementation-oriented contribution. It links process input, timing, machine response, tool health, and part quality. Sampling rate and latency depend on the signal path and decision objective, so the contract requires declared values rather than one universal frequency or response limit.

Table 2. Proposed minimum data contract for a metal-cutting digital twin

Data group	Representative variables and units	Context and use
Command	Cutting speed [m/min], feed [mm/rev] or feed per tooth [mm/tooth], depth and width of cut [mm], spindle speed [min^{-1}]	Program block and operation; reproduce the intended cutting condition
Timing and synchronization	Timestamp, clock source, sampling/event rate [Hz], acquisition, communication, inference, and action latency [ms]	Align cause and response; verify that the end-to-end delay satisfies the decision objective
Machine state	Mode, channel state, override [%], axis load [%], alarm code	Timestamped event stream; separate cutting, idle, setup, and fault states
Process response	Power [kW], torque [N·m], vibration [m/s^2], force [N], temperature [°C]	Declared sampling and filters; detect load, chatter, wear, collision, and thermal drift
Tool and workpiece	Tool ID, edge count, accumulated cutting time [s], material and lot, fixture ID	Traceability unit for model transfer and remaining-useful-life estimates
Quality	Mean roughness Ra [µm], dimensional deviation [µm], good and total quantity [1]	Measurement method, uncertainty, feature and datum; support release and KPI calculation
Model assurance	Model/version ID, residual, prediction interval, drift status, approval state	Determine whether advice is valid, reviewable, and eligible for execution

Source: Authors' research

The contract makes unit, provenance, timing, and operating state part of every observation. Without them, a tool-condition model may learn machine identity, material batches, or scheduling patterns instead of degradation. Planned and actual quantities support consistent OEE calculation under ISO 22400-2 and the OPC UA Machine Tools companion specification (ISO, 2014; OPC Foundation, 2024).

3.4. Brownfield Deployment Pathway

Six indicators provide minimum deployment evidence: 95th-percentile end-to-end latency L95 = P95(t_action - t_acquisition); false-alarm rate FAR = false alarms/normal observations; missed-detection rate MDR = missed detections/reference events; prediction-interval coverage PICP = covered observations/all observations; energy per conforming part E_good = E_total/N_good; and surface-quality capability Cpk = min[(USL - mean)/(3s), (mean - LSL)/(3s)]. Process-specific acceptance limits must be fixed before the shadow-mode trial and reported with the operating condition and sample count.

Brownfield deployment proceeds through four controlled states. First, select one operation and one decision, such as detecting abnormal tool wear before a quality limit is exceeded. Second, synchronize signals and bind them to tool, part, program, and metrology records. Third, run the model in shadow mode and review residuals, uncertainty, drift, false alarms, missed detections, and end-to-end latency. Fourth, introduce bounded feedback only after documenting change limits, the approval rule, the safe fallback state, and safety and cybersecurity reviews. Monitoring and work-order generation can therefore provide value before automatic set-point control.

4. DISCUSSION

4.1. Comparison with Existing Approaches

Compared with digital-twin frameworks centred on representation and information exchange, the proposed architecture adds a governed path from process observation to manufacturing action. Compared with machining-monitoring architectures, it places tool, workpiece, quality, timing, and production context in one semantic contract. Compared with purely data-driven prediction, it requires the model version, uncertainty, residual behaviour, and drift status to accompany every analytical output. Khan et al. (2025) show the predictive potential of such models, but transferability remains bounded by the machine, tool, material, parameter range, sensor placement, and measurement procedure. Execution authority is therefore treated as a separately governed engineering function (Cimino et al., 2019; Kritzinger et al., 2018; Tran et al., 2023).

4.2. Safety and Cybersecurity Implications

Machinery safety and industrial cybersecurity remain independent governance constraints. ISO 12100 requires life-cycle risk assessment and reduction, while ISO 13849-1 governs the design and integration of SRP/CS that perform safety functions (ISO, 2010, 2023). An optimization service may recommend feed or speed within a validated process window, but it cannot bypass an interlock, alter a required performance level, or redefine a safety function. ISA/IEC 62443 adds system partitioning, access control, secure change, and IACS auditability (International Society of Automation [ISA], 2025). The execution-authority boundary prevents an analytics update from silently changing the machine risk profile.

4.3. Limitations

The architecture was derived from an integrative evidence synthesis and was not experimentally validated on a physical CNC machining cell. The targeted evidence set supports the selected manufacturing, interoperability, safety, and cybersecurity functions but is not an exhaustive systematic review of digital-twin research. The minimum data contract defines a functional baseline rather than a universal sensor, sampling, or latency configuration; those values depend on the machining process, diagnostic objective, machine dynamics, and measurement system. Finally, the authority boundary must be validated for the specific machine, process, safety functions, and cybersecurity environment before automated parameter modification is enabled.

5. CONCLUSIONS

Within this framework, an Industry 4.0 machining cell qualifies as an operational digital-twin system only when physical measurements, manufacturing context, an assured model, a reviewable decision, and an authorized execution path form a traceable loop. ISO 23247 supplies the digital-twin framework; IEC 62264 and OPC UA supply production and machine-tool context; ISO 13374 and ISO 22400 support condition information and performance measurement; and ISO 12100, ISO 13849-1, and ISA/IEC 62443 constrain intervention.

The minimum data contract and execution-authority boundary are the main implementation contributions. They allow a plant to trace abnormal tool wear to the active edge and material lot, issue reviewable maintenance or quality-hold actions, and evaluate bounded set-point changes against latency, false-alarm, surface-capability, and energy-per-conforming-part indicators. These are intended industrial benefits and acceptance measures, not experimentally demonstrated gains. Future work should apply the architecture to a defined CNC operation and publish the full indicator set together with uncertainty, model drift, and change-control evidence.

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