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CURRENT TRENDS IN DESIGNING AND MANUFACTURING OF ELECTRICAL VTOL AIRCRAFT

Serafim MUNTEAN, Gheorghe OANCEA

Abstract: *The article presents a review of the literature in the area of the Electrical Vertical Take-off and Landing Aircraft (eVTOL) also known as "flying machines". It will be detailed the trends of air transport development, the importance of the transition from fossil fuel to electric power and the common problems of electrical aircraft. The main aim of this paper is to present a state of the art of Electrical Vertical Take-off and Landing Aircraft performance, and this data will serve as a starting point for the designing, developing, and manufacturing of new prototype of this aircraft type. The methodology of the work is to identify the performance parameters of Electrical Vertical Take-off and Landing Aircraft, to present them and then to identify the impediments and problems existing in the current eVTOL design and manufacturing technologies. The paper also presents the current trends in this new research direction.*
Key words: *Electrical Vertical Take-off and Landing Aircraft, designing, additive technologies, green manufacturing, rapid prototyping.*

1. INTRODUCTION

During the last century, humanity has experienced an exponential development in the field of transportation. The trend has been to develop faster vehicles with the capacity to carry larger volumes and masses. An example is the animal-drawn transport which can carry a weight of around 1t at a speed of a few km/h compared to the Airbus A300-600 ST "Beluga" aircraft which carries a considerable volume with a weight of 45.5 tones at a speed of Mach 0.7 (it means over 800km/h) [1].

These days, almost every family owns a car that they use on public roads, and this allows them to do their daily activities faster and to save time. The fastest method of public transport is by aircraft, which can fly through the atmosphere.
There are different types and categories of aircraft that can be used when traveling from one part of the world to the other. Either an airliner, which means public transport, or a smaller private plane or even a helicopter could be used.

Most passenger aircraft usually need a runway to fly their missions in the atmosphere. A helicopter, which does not need a runway, can take off and land in areas that are difficult for aircraft. The disadvantage of it is represented by complexity, high cost and maintenance, fuel consumption and large rotor blades.

The current trend is to design and manufacture airlifts that take off and land from almost anywhere, without the need for a special runway for take-off, and increase their efficiency compared to a helicopter. Vertical take-off and landing aircraft (VTOL), also known as „flying cars”, with conventional, hybrid or fully electric (eVTOL) propulsion are the ones that are currently undergoing major development.

VTOL aircraft have a great potential in transportation development, as this type of aircraft can be used in the near future as air taxi or personal vehicle for traveling between cities/towns or even within the local area, with an adopted and regulated infrastructure for them. The infrastructure can consist of helipads on the roofs of buildings with parking and private helipads in their own yard. Figure 1 shows some ideas of these infrastructures.

Fig.1. Examples of infrastructure for VTOL aircraft in urban areas [2]

This article presents and classifies vertical take-off and landing aircraft specifying their performance parameters. This data is interpreted and used to identify the performance required for future aircraft designs of this type to be competitive with or superior to current VTOL aircraft.

The transition from combustion or hybrid propulsion to fully electric propulsion will considerably reduce pollution as electricity generation increases using renewable or even nuclear sources by developing safer technology. However, the current problem is the batteries, due to their weight, which is also discussed in one of the sections of this paper.

2. CLASSIFICATION OF VERTICAL TAKEOFF AND LANDING AIRCRAFT

2.1 Definition of vertical take-off and landing aircraft

A vertical take-off and landing aircraft, according to European Union Aviation Safety Agency represents a heavier-than-air aircraft that can hover, take-off and land vertically, performing flight missions in the atmosphere [3], without the need for a runway for take-off/landing. If such an aircraft is electrically powered, it is called an electrically powered vertical take-off and landing aircraft (eVTOL).

2.2 Classification of VTOL aircraft

VTOL aircraft have a variety of configurations depending on the aerodynamic lift elements, number of engines, propulsion systems, etc. A classification of VTOL aircraft is below presented.

2.2.1. VTOL aircraft depending on how vertical propulsion and horizontal thrust are achieved.

a) VTOL aircraft with two independent propulsion systems.

These aircrafts have two independent propulsion systems. A dedicated system for take-off and landing only, allowing vertical flight, and another system that provides traction during horizontal flight. An example of an aircraft with independent lift propulsion and independent normal flight propulsion is Wisk Aero Cora (figure 2).

Fig.2. Wisk Aero Cora Aircraft [4]

b) VTOL aircraft with common propulsion systems.

This aircraft has only one common system, usually more complex, which allows both take-off and landing as well as normal flight. An example of an aircraft with common lift and normal flight propulsion is Airbus Vahana Alpha Two (figure 3).

2.2.2 VTOL aircraft depending on the configuration of the aerodynamic lifting elements

a) VTOL aircraft with blades (rotating wings).

This category includes all VTOL aircraft that do not have fixed wings and the lift is provided by rotary wings, as well as the thrust which is a resultant component of the rotor blades. Here could be mentioned highlight helicopters, gyrocopters, multi-rotor aircraft such as the Jetson ONE which has 8 rotors with 2 blades each (figure 4).

Fig.3. Vahana Alpha Two [5]

Fig.4. Jetsone ONE [6]

b) Flying wing VTOL aircraft.

It represents a vertical take-off and landing aircraft that has only a wing as a load-bearing element without any other longitudinal stabilization elements. This type of aircraft, whether it is a VTOL aircraft or a flying wing aircraft, has the best aerodynamic performance if it is referred to any aircraft. The disadvantage is the complexity of flight stability in the air. An example of a wing-type VTOL aircraft would be the Leonardo Helicopters (Augusta Westland) Project Zero prototype (figure 5).

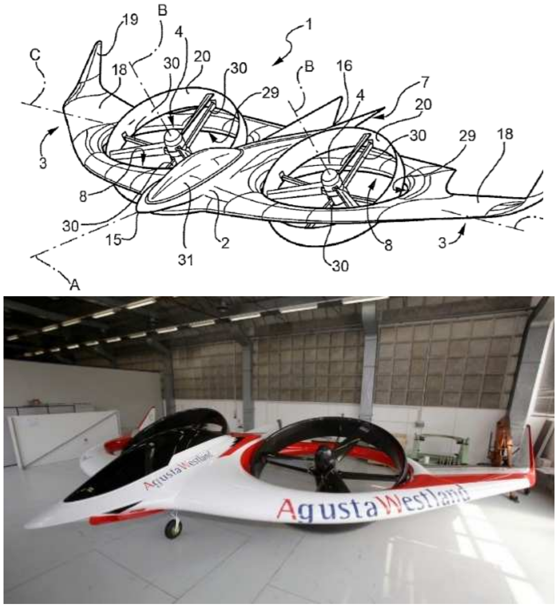

Fig.5 Leonardo Helicopters Project Zero[7,8]

c) VTOL aircraft configuration with wing and horizontal appendage located behind it.

This aircraft has a traditional configuration, the most common configuration of aerodynamic lifting elements nowadays in leisure, cargo or airliner aircraft. It consists of a wing that provides the lift force and a horizontal stabilizer located behind it. An example of VTOL aircraft with this configuration is the Maker Archer VTOL, figure 6.

Fig.6 Maker Archer [9]

d) VTOL aircraft with combined canard and traditional configuration.

These are vertical take-off and landing aircrafts that have one wing for lift and two or more horizontal stabilizers for longitudinal stability located in front and behind the wing. This configuration arose due to the need to place propulsion systems in front of and behind the aircraft center of gravity. An aircraft of this pattern is Kitty Hawk Heaviside, figure 7.

Fig.7 Kitty Hawk Heaviside [10]

e) VTOL aircraft with a two-wing configuration.

They are vertical take-off and landing aircraft that have two wings as aerodynamic components. Both wings create a lift and are in tandem. An example of a vertical take-off and landing aircraft with two tandem wings is Airbus Vahana Alpha Two, figure 3.

2.2.3. VTOL aircraft depending on wing type:

a) VTOL aircraft with pivoting wings.

This is vertical take-off and landing aircraft that have pivoted wings that change their position relative to the aircraft axis, or fuselage in other words. This change of position facilitates vertical take-off and landing. An example of this type is Alpha Vahana Two aircraft, figure 3.

b) Fixed wing VTOL aircraft.

This is vertical take-off and landing aircraft that have fixed wings. The wing or wings do not change their position relative to the aircraft axis (or to the fuselage). An example is Wisk Aero Cora aircraft (figure 2).

2.2.4 VTOL aircraft depending on the propulsion system type:

- *internal combustion;*
- *hybrid;*
- *electric.*

3. ENERGY SOURCES IN AVIATION

Moving from combustion or hybrid to full electric propulsion will significantly reduce pollution as electricity generation increases through the use of renewable or even nuclear power sources by developing safer technology. In this moment, there are VTOL aircraft that perform quite well compared to traditional aircraft. But the performance of eVTOL aircraft is not at the same level. In general, fully electric aircraft have a low range.

The main problem with electric propulsion is that the batteries are heavy. Combustion engines can easily be replaced with electric engines, and fuel tanks can be replaced with electric accumulators. In terms of efficiency, electric engines are more efficient than combustion engines, but electric batteries store less energy than kerosene can develop through combustion. If the amount of stored energy is related to mass or volume, the energy density is obtained, and its definition is as follows: the amount of stored energy related to one kg of matter is the energy density (or related to one liter) [11].

Kerosene has a higher energy density than electrical batteries. Its energy density is about 43 MJ/kg (this value represents the calorific value of kerosene), or 11944 Wh/kg, while the best energy density of electric accumulators is about 260 Wh/kg. This value was obtained from the specifications of a 21700 battery cell available on the market [12,13], with the specifications: 3.6V nominal voltage, 5000 mAh capacity and a mass of 69 g. This means that one kilogram of kerosene can provide more energy than the same mass of battery power. It can be said that the energy that can be extracted from fossil fuel is about 46 times more than the energy of an electric battery. If you consider that an electric motor has a higher efficiency than combustion engines. An electric motor can have up to 0.98 ratio of energy transformed to useful energy [14], while a combustion engine can reach up to 0.669 [15]. If this aspect is also taken into consideration, it can be said that, in this case, an electric propulsion system is 31 times inferior to a combustion engine.

This is why kerosene is used in aviation where weight is the critical factor, while electric batteries are used in electric vehicles and other applications where range is not a crucial factor and a shorter range can be accepted.

On the other hand, batteries are more energy efficient than kerosene in converting energy into useful power. Accumulators can provide more power in a shorter time than kerosene because kerosene has to be burned before it can produce power. Batteries are also much less polluting than kerosene because they do not emit combustion gases to produce power.

The foundations for the implementation of electric flight are currently being consolidated, and this is being felt by the emergence of light electric aircraft on the market, and the area that is least developed and has the greatest potential is electric flight with vertical take-off and landing.

The simplest electric propulsion system is composed of an electric power source, in other words a battery, an electric motor, an electronic control circuit, power supply, charging and an inverter. This system represents a simple configuration. Electric motors have the advantage of high efficiency and operate independently of air density. One of the most efficient electric motors used in aviation would be the electric motor made by the Emrax company [14]. This engine has a maximum efficiency of 0.98 according to the specifications provided by the company.

Comparison between fossil fuel used in aviation and electricity.

The advantages of electric propulsion systems over combustion propulsion systems are the following [16,17]:

- Low or zero emissions, making these systems more environmentally friendly;
- Reduced noise compared to combustion engines, which can reduce the impact on communities around airports, heliports or special places for take-off;
- The efficiency of electric motors is higher compared to combustion engines, which means that electricity losses are lower compared to energy produced by burning fossil fuel.
- The possibility of using renewable energy sources. The solar energy can be converted in electrical energy, even during the flight, using photovoltaic cells arranged on the wing, or using all other sources of renewable energy to store this energy in special stations that will later charge aircraft batteries;
- The possibility of accessing the maximum available power in a shorter time;
- The mass of electric motors is lower than combustion engines.

The disadvantages of electric propulsion systems compared to combustion propulsion are the following:

- Low range, as current batteries cannot store the same amount of energy as fossil fuels. The energy density of batteries per unit mass is about 46 times lower;
- The high cost of technology and batteries, which can make these systems more expensive than combustion systems;
- Environmental pollution from the production of electrical batteries and from the production of electricity from burning fossil fuels;
- The long charging time of the accumulators, which can cause these systems to have long interruptions of functionality to charge the accumulators;
- Electric systems have more mass due to the batteries, so they are less reliable than combustion ones because they will require more energy consumption to compensate.

Combustion propulsion systems have the advantage of longer range, higher reliability and lower cost compared to electric systems, but CO2 emissions and noise are considerably higher compared to electrical systems.

4. CURRENT STATUS OF VTOL AIRCRAFT

Presented next are the currently existing electric powered vertical take-off and landing aircraft, which are in various stages of development and have made at least one flight. The following performances have been considered:

- *Transport capacity in number of persons;*

- *Cruising speed;*
- *Flown distance (Range);*
- *Wingspan (this parameter shows the size of the space required for the aircraft to land);*
- *Maximum take-off weight (MTOW).*

Table 1

eVTOL aircraft specifications [18]

eVTOL	**Crew/Passen**	**Range** [km]	**Cruising speed** [km/h]	**Wingspan** [m]	**MTOW** [kg]
Archer Maker	2	96	241	12.2	1680
Archer Midnaight	5	100	241	15.3	3175
Airbus Vahana One	0	60	200	6.3	816
Airbus Vahana Two	1	50	200	6.3	816
Black Fly	1	64	128	4.1	255.4
Wisk Aero Cora [4]	2	100	180	11	-
Kitty Hawk Heaviside [10]	1	160	354	-	-
Joby S4	5	241	322	10.7	1815
Lilium Jet	5	300	300	-	-
Jetson One	1	34	102	3	181

The data in Table 1 have been converted into a graphical representation to better visualize the performance of these eVTOL aircraft (figure 8). In figure 8 the performance is shown according to their period of development of the latest eVTOL prototypes. It can be seen that only during the last 5 years, the performance shows a considerable increasing. The new vertical take-off and landing aircraft are becoming faster, the transport capacity and the distance traveled are increasing.

The average performance of electrically powered vertical take-off and landing aircraft at present, taking into account the aircraft described earlier, is shown in Table 2.

Table 2

Average performance of eVTOL aircraft

Crew/ Passengers	**Range**	**Cruising speed**	**Wingspan**
2.5	120.5 km	226.9km/h	8.6m

The best performances of electrically powered vertical take-off and landing aircraft are shown in Table 3.

Table 3

Maximum eVTOL performance

Crew/ Passengers	**Range**	**Cruising speed**	**Wingspan**
5	300 km	354 km/h	4.1 m

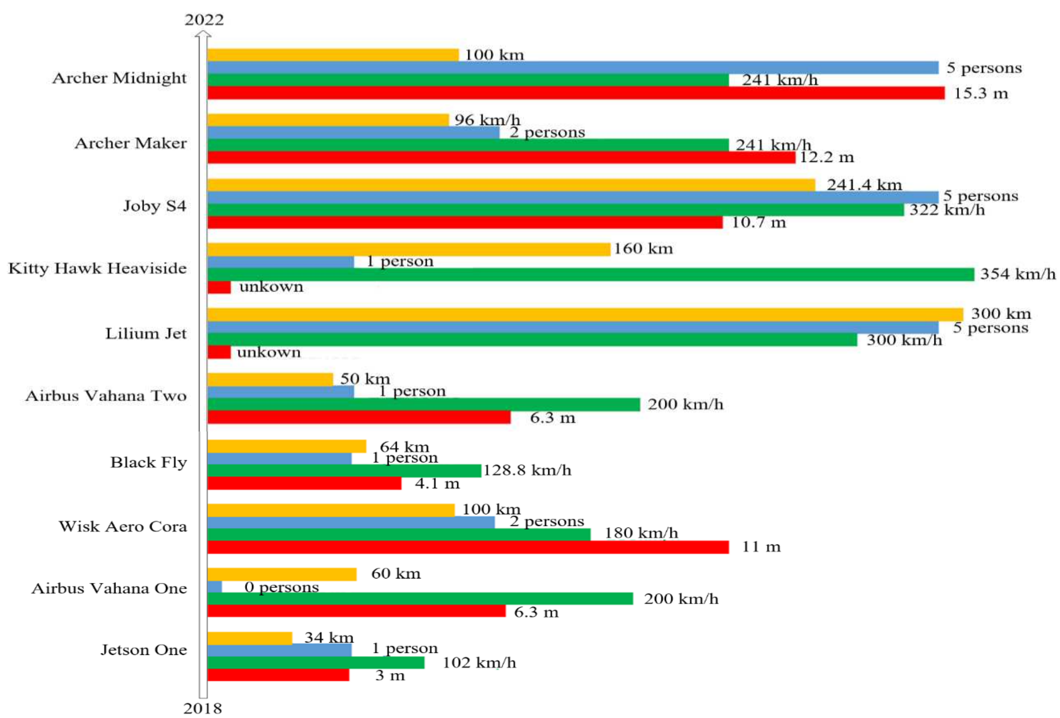

Fig.8 Performance of eVTOL aircraft

5. DESIGN OF ELECTRIC VERTICAL TAKE-OFF AND LANDING AIRCRAFT

To design an electrically powered vertical take-off and landing aircraft, in the first phase it is necessary to have input data on current aircraft performance. These data have been presented in section 4 of this paper. The input data is analyzed and compared with the desired performance of the future eVTOL aircraft. After establishing the desired performance, the next step is to choose the configuration of the aerodynamic elements and propulsion systems (section 2) taking into account the weight of the aircraft, developed in section 3. An aircraft should be as light as possible with sufficient strength to perform its flight missions properly. A large number of engines makes the aircraft heavier, and so do the wing or engine pivoting systems. A weight-efficient aircraft would be an aircraft with no pivoting elements and as few engines as possible.

The big challenge is to design an aircraft without pivoting systems so that aerodynamic performance can be as high as possible.

An aircraft concept is made on a repetitive cycle starting with a sketch of the aircraft, then 3D modeling, and aerodynamic profile selection followed by an aerodynamic simulation. For an improvement of the aircraft performance, these steps will be repeated until the desired performance is reached.

After the design of the aircraft a prototype will be built. The prototype is then tested for strength and functionality. During this phase, new modifications will be made and will be translated into new 3D models and other simulations. These will eventually lead to another prototype or even the final stage aircraft. The design of a vertical take-off and landing aircraft requires a series of steps that are repeated to achieve the desired results. These repetitions can lead to different prototype versions. A variety of prototypes means a considerable resource of money and time. To reduce these resources, rapid prototyping technologies can be implemented using additive manufacturing processes.

6. ADDITIVE MANUFACTURING OF EVTOL PROTOTYPES

6.1 Additive manufacturing

Additive manufacturing is used to produce three-dimensional products by adding successive layers of material [19]. The manufacturing needs to involve computer-aided design software (CAD) to model the product and specialized equipment (called a 3D printer), which uses the data from the CAD model to produce the product by depositing successive layers of material such as plastic, metal ceramic, etc. These layers are then consolidated to obtain a final 3D object.

This technology can be used in a variety of fields including the production of prototypes, spare parts, surgical instruments and components for machines and aircraft [20].

6.2 Advantages of additive manufacturing in the prototyping process

Additive manufacturing processes have several advantages in prototyping compared to traditional manufacturing processes. The main ones being the following [20,21]:

- Reduced time - additive manufacturing allows prototypes to be manufactured in a relatively short time, the part can be manufactured in final form.
- Cost savings – for additive manufacturing it is necessary only a machine and material for printing, and these eliminates the necessity of expensive tooling or other special equipment.
- Manufacturing complex parts - additive manufacturing technology allows prototypes to be produced with complex shapes that can be complex or impossible to manufacture using traditional methods.
- Reducing risk - additive manufacturing processes allow prototypes to be tested and evaluated before being in mass-producing.
- Diversity of designed shapes - additive manufacturing offers the freedom to create complex shapes, geometries, and structures.
- Waste reduction – in additive processes, the losses are only in the support material, they

are considerably lower compared to the cutting process.

Disadvantages of additive manufacturing processes [20,21]:

- Limited object size - the size of the objects that can be manufactured is restricted due to the limited capacity of additive manufacturing equipment;
- Manufacturing processes lead to some limitation of the range of possible applications;
- Manufacturing time - in some situations the process may be slower than traditional manufacturing processes due to the need for successive deposition of small amounts of material in layers.

In conclusion, additive manufacturing processes offer significant advantages in the production of prototype VTOL aircraft, which have a high complexity of shapes and require flexibility to reshape and re-manufacture new variants to finally obtain a version that meets the purpose for which it was designed.

6.3 Additive manufacturing of VTOL aircraft using the Fused Filament Fabrication process

The Fused Filament Fabrication (FFF) additive manufacturing process also known as fused deposition modeling (FDM) is used to manufacture parts from a thermoplastic filament [22, 28].

In the manufacturing process, the filament is heated until it becomes liquid, and a printing nozzle then distributes it in a thin layer based on a 3D digital model previously generated by a CAD software system. After cooling, the filament is solidified, and a new layer is added on top of the previous one. This process continues until the object is completely built [22].

The FFF process is used to create rapid prototypes, custom parts, and replacement parts for specific applications. The materials used can be different types of thermoplastic plastics. The most popular are the following materials [28]:

- polycarbonate (PC);
- polylactic acid (PLA);
- acrylonitrile-butadiene-styrene (ABS).

Advantages of the FFF process include low equipment costs as well as wide availability of the materials used. The quality of objects produced by this process can be affected by the size of the printing table, the printing speed and the melting temperature of the material, which can lead to objects with less precise details or less smooth surfaces.

The FFF process has also been used to manufacture aircraft, model aircraft and VTOL prototypes. These are some examples:

1. VoloDrone - is designed to carry large payloads. It was manufactured using FFF technology and is built from lightweight materials such as carbon fibre [23].
2. Unmanned aerial vehicle described in the reference [24] is a VTOL aircraft that has two propulsion systems, one system for vertical take-off and another system for horizontal flight. Elements of the fuselage and structure were made by additive manufacturing.
3. Unmanned aerial vehicle presented in article [25] is a prototype VTOL aircraft with only one wing and two propulsion systems. It has in its component a rotor system with larger blades for vertical flight and a folding system for both horizontal and vertical flight.
4. Twincopter VTOL is a prototype VTOL aircraft that has only a twin-rotor propulsion system built with the FFF process [26].
5. The printed ballistic carrier aircraft described in the article [27]. This is a weapon, a VTOl-type aircraft model carrying ballistic munitions that has been prototyped using FFF.

7. CONCLUSIONS

In aviation, additive manufacturing, including the FFF process, is quite well known and used in various applications. The above leads to the idea that the FFF additive process is best suited for prototyping new aircraft concepts in order to test their functionality and then develop and optimize derivative versions. A major advantage would be that lower density materials can be used, and in aviation weight is a very important factor.

The analysis of the current status of electric VTOL aircraft highlighted trends in aviation as well as the major problem of electric aircraft. By presenting examples of currently existing aircraft and interpreting performance data, it has been identified which performance values the new electric VTOL aircraft concepts should have in order to be considered competitive. However, before an eVTOL aircraft can be mass-produced, prototypes have to be produced, and here FFF technology for rapid prototyping can be used to facilitate the development of the new aircraft. The article also presents some examples of aeromodels, concepts or prototypes of VTOL aircraft that have been manufactured using the additive FFF process. This is the most used process for manufacturing new VTOL aircraft prototypes due to its flexibility, low cost, the complex shapes that can be obtained and the comparatively low density of the materials used in the manufacturing process.

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Tendințele actuale în proiectarea și fabricarea aeronavelor VTOL electrice

Articolul prezintă o trecere în revistă a literaturii de specialitate în domeniul aeronavelor electrice (eVTOL) cu decolare și aterizare pe verticală, cunoscute și sub denumirea de „mașini zburătoare”. În lucrare se detaliază tendințele dezvoltării transportului aerian, importanța tranziției de la combustibilii fosili la energia electrică precum și problemele comune ale aeronavelor electrice. Scopul acestei lucrări este de a prezenta stadiul actual al performanței aeronavelor electrice cu decolare și aterizare verticală, iar aceste date vor servi drept punct de plecare pentru proiectarea, dezvoltarea și fabricarea unui prototip al acestui tip de aeronavă. Metodologia lucrării constă în identificarea parametrilor de performanță ai aeronavelor electrice cu decolare și aterizare verticală, prezentarea acestora și apoi identificarea impedimentelor și problemelor existente în tehnologiile actuale de proiectare și fabricație a eVTOL. Lucrarea prezintă, de asemenea, tendințele actuale în această nouă direcție de cercetare.

Serafim MUNTEAN, PhD Student, Eng., Transilvania University of Brașov, Department of Manufacturing engineering, B-dul Eroilor No.29, Brașov, Romania, serafim.muntean@unitbv.ro

Gheorghe OANCEA, PhD Professor, Eng., Transilvania University of Brașov, Department of Manufacturing engineering, B-dul Eroilor No.29, Brașov, Romania, gh.oancea@unitbv.ro