EXonomy analysis for the Inter-domain comparison of electromechanical and pneumatic drives

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Abstract

Today the selection of drive technology for realizing of moving tasks is made by comparing of investment and energy costs in general. Pneumatic drives are characterized by their low purchase price, but at the same time they show high energy consumption in a comparison with electric drives. This general evaluation leads to the point, that in many cases the optimum drive structure for a certain handling task can't be found regarding functionality and efficiency. To reach that goal, the dynamic, energy and costs characteristics of the actuator have to be observed and summarized.

In this paper the EXonomy analysis is presented as a base for the inter-domain comparison of electric and pneumatic drives. Developed EXonomy approach enables the objective analysis and comparison of electric and pneumatic systems within 3 steps.

KEYWORDS: pneumatic, electric drives, exergy, economy analysis

1. Introduction

In industrial automation there are numerous automatic systems applied to perform various material handling and movement functions. They are typically operated by electric or pneumatic drives. Having said that, in the concept phase, a drive technology that is compatible with each single or combined driving task needs to be chosen. On the one hand, electric drives are highly dynamic, very precise and demonstrate tailored control concepts for position, velocity, and force. Pneumatic drives, on the other hand, are low in installation and maintenance costs, and have both a flexible and robust design.

Due to the fact that both technologies have varying advantages and drawbacks regarding functionality and costs, the decision has to be made considering their dynamic and energetic characteristics and, as well as Life Cycle Costs (LCC).

Several studies show the comparison of both technologies, /1/, /2/. However, they show the comparison considering the overall energy consumption. One source of uncertainty in these studies is the absence of economic analysis within the life cycle of the machine that plays a major role in the comparison. Furthermore, one of the main obstacles is the comparison of oversized pneumatic drives that presents dissimilar drive solutions. In conclusion, that leads to a subjective analysis of both technologies.

The aim of the paper is the further development the established LCC methods with regard to an objective comparability of electric and pneumatic drives. The exergy based approached in the current paper. EXonomy analysis is used to adapt the degree of oversizing of the compared drive solutions. Furthermore, it provides an information about the most cost-effective drive solution according to a certain motion task. This paper first gives an overview about the working principle of the method. The second part of the paper deals with typical parameters of motion tasks and standard sizing of pneumatic as well as electric drives. The third chapter is concerned with the methodology used for the current study. For this purpose each step of the EXonomy analysis is described by means of the example of a vertical drive. Therefore, the method uses different simulation and experimental results. Moreover, the proposed method is applied to 31 motion tasks, where the field of use of electric or pneumatic drives is determined. As a conclusion the application perspectives of the method are characterized and further steps are recommended.

2. EXonomy analysis for the comparison of pneumatic and electric drives

The starting point of the EXonomy analysis is a specific motion task and suitable drive structures that are dimensioned based on standard sizing strategies. In order to realize an objective comparison of these drive structures, the EXonomy analysis adapts the system sizing and calculates the overall cost per motion task for the well dimensioned drive systems. The method is comprised of three main steps as presented in **Figure 1**. These steps include

- the adapting of system sizing based on exergy analysis,
- the determination of LCC using the exergy consumption and
- the further analysis of LCC considering the sizing factor.

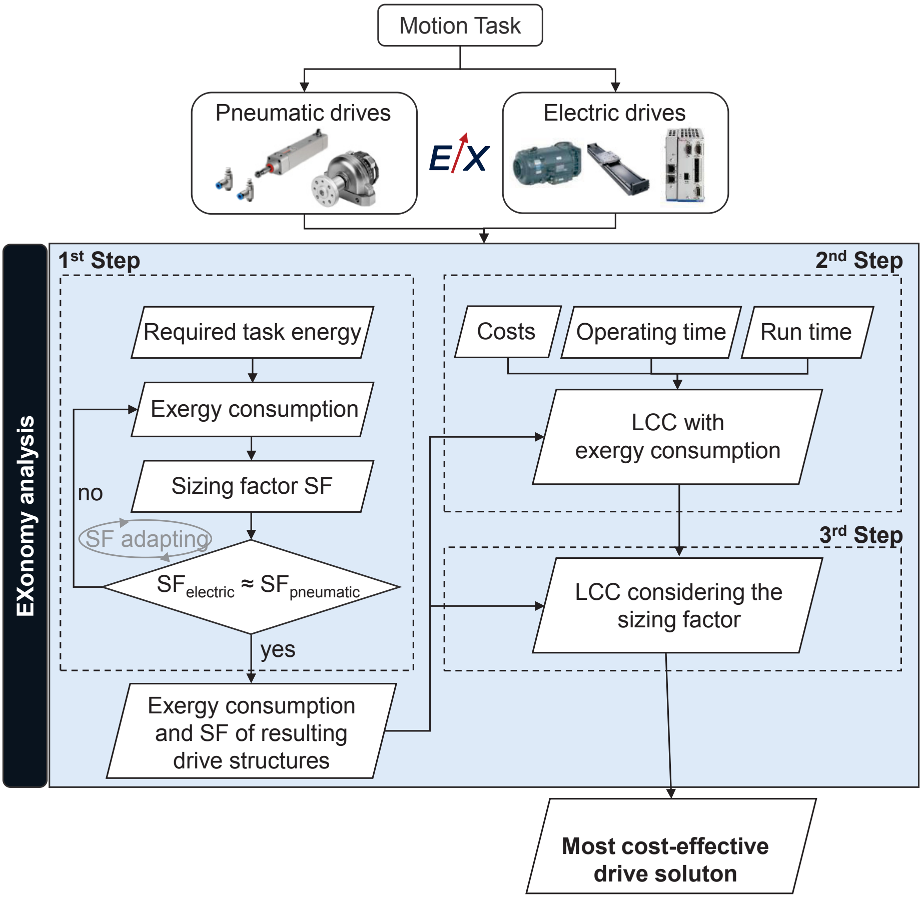


Figure 1: Flow chart of the EXonomy analysis

The system sizing (1st Step) is performed by calculating the exergy provided by the system and required energy for the task. The relation between these values is represented by the sizing factor SF. SF defines the ability of the system to fulfill the task and therefore, presents the central point of the comparison of two different drive technologies. Having said that, the further comparison is done for drive systems with approximately identical SF.

In order to determine the task energy, the mechanical energy of moving mass, including friction, kinetic and potential energy, has to be determined. Consequently, to fulfill the task, a certain amount of energy has to be generated by the system. In this case, the term exergy will be used as the maximum available energy generated by the system. The determination of the exergy of the drives and adaption of their system parameters according to SF leads to the further analysis of life cycle costs.

The LCC calculation (2nd Step) includes all expenses over the life cycle of the machine. There are three factor groups that are observed in the presented approach: operation time, run time of the machine and expenses during the life cycle. For this purpose, the hour rate approach was selected to determine the cycle costs and the payback period of the drive.

Third step of EXonomy analysis provides the information about the actual cost-effective improvement using specific cost and energy saving measures. The analysis of task costs shows the border line for the useful implementation of cost and energy savings including all investments.

3. Operating parameters and selection of typical motion tasks

To define relevant motion tasks for this study, the parameter field offered by Hesse /3/ from **Figure 2** has been analyzed. The following parameter matrix shows the mean velocity and load mass typically applied for standard handling tasks. Each group of these parameters is further divided into three levels (high, middle, low) and represents the dynamic characteristics of the drive.

Level	**Velocity [m/s]**	**Load mass [kg]**
high	0,5 … 1,5	10 … 50
middle	0,2 … 0,5	1 … 10
low	< 0,2	< 1

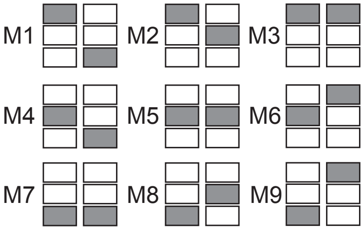


Figure 2: Field of parameters concerning motion tasks and possible combinations

The presented matrix illustrates nine possible combinations of load mass respectively force and velocity.

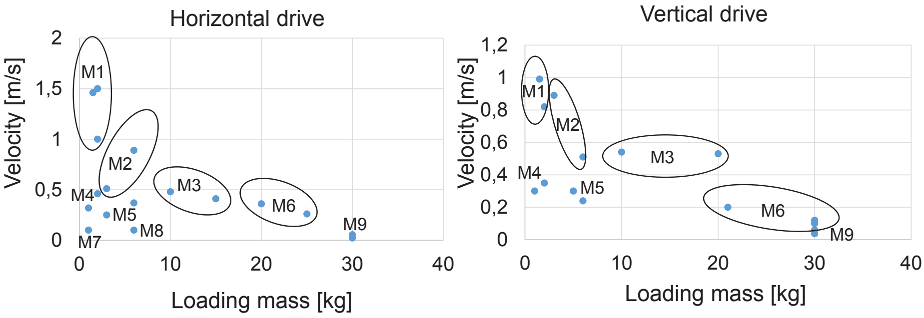


Figure 3: Chosen motion tasks for EXonomy method testing

Consequently, to test the application field of the method, EXonomy analysis is applied to different motion tasks within each matrix point. For this purpose, 31 task configurations in the field of horizontal and vertical drives were chosen and analyzed (see **Figure 3**). Motion tasks in industrial applications typically show either high velocities or high load masses.

4. Selection and parametrization of the drive structures

Basically, both electric and pneumatic drives are divided in three parts (see **Figure 4**). The first part represents the energy supply and the distribution of it. In case of pneumatic systems the input energy is transferred to pneumatic energy at the compressor and distributed within the pipelines to the user. In contrast, the electric drive uses the electric energy in a direct way. The second part realizes the transformation of pneumatic or electric energy into mechanical energy of the moving mass. In the case of the pneumatic system, it is represented by cylinders and valves, and in case of electro-mechanic (EM) drive, it is represented by a motor and actuator, as for example, a toothed belt or ball-screw. Third part of the drive is performed by a control. Which in the case of pneumatic system is accomplished by an SPS-system and for electrical system by motor controller.

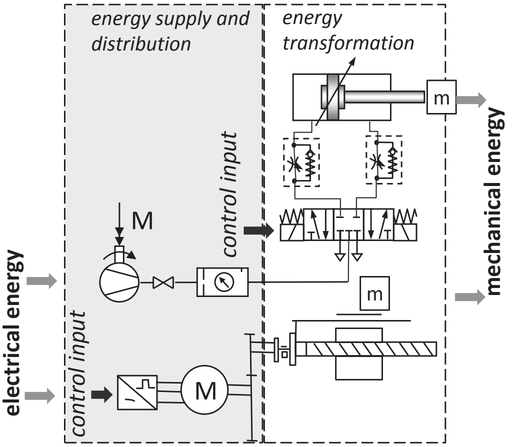


Figure 4: Principal schematics of pneumatic and electro-mechanical actuators

The choice of a drive system is usually done in 2 steps:

- Definition of principal schematic and components
- Sizing of the chosen components

Inasmuch as the study focuses on the linear motion tasks, the pneumatic cylinder and the motor with gear box were chosen as an example drives. The strokes for studied drives were selected according to the mean velocity range with the various motion time from 1 to 20 sec.

4.1. Selection and sizing of electro-mechanical drives

The first step of selection of the electric actuator is the choice of the motor technology and required mechanical transmission. Frequently used technologies are the ball screw drive and the tooth chain belt. The ball screw drive shows high load capacity, but the maximum achievable speed is around 2 m/s. Whereas, the tooth chain belt is characterized by higher dynamic response with velocity up to 5 m/s, but with lower load capacity compared to ball screw drive. Thus, the maximum studied velocity achieves 1,5 m/s, the both technologies were used to perform vertical as well as horizontal motions.

As for the EM drive, the sizing of electric motor and mechanical gearbox is based on the maximum load specification. The choice of the electric motor represents the torque of the motor based on power definition. The power of the motor is related to the maximum load of the drive and its inertia. The output torque of the ball screw actuator is calculated as follows /4/:

$$M = J \cdot \omega + (m \cdot g + F_{fr}) \cdot R_s \tag{1}$$

The strokes for studied drives were selected according to the mean velocity range with various motion times from 1 to 20 s. Thus, the drives parameters were chosen from the technical catalog according to their maximum load, inertia and stroke.

4.2. Selection and sizing of pneumatic drives

In a similar way to EM drives, the selection of pneumatic drives is based on a maximum load definition.

The foundations for choosing a pneumatic system are mainly based on the required actuator and its geometrical parameters. In case of a pneumatic cylinder, the standard sizing of the actuator is based on a force balance (2) and considers the maximum load

(F_{load}) and pressure in the cylinder chambers. Moreover, the friction and load reserve are considered with the equivalent coefficients c_1 and c_2 /5/.

$$d_{piston} = 1{,}13\sqrt{\frac{F_{load}}{c_1 \cdot c_2 \cdot (p_A - p_B)}} \tag{2}$$

The friction coefficient c_1 for the motion task has a value range from 0,75 to 0,9. The load reserve coefficient c_2 depends on the mass and vary from 0,5 to 0,6.

For the presented study a selection of horizontal and vertical pneumatic cylinders is done that is shown in **Figure 5** and **Figure 6**. The chosen example drives refer to the dynamic parameters presented in Figure 2 and are dimensioned on base of standard load sizing.

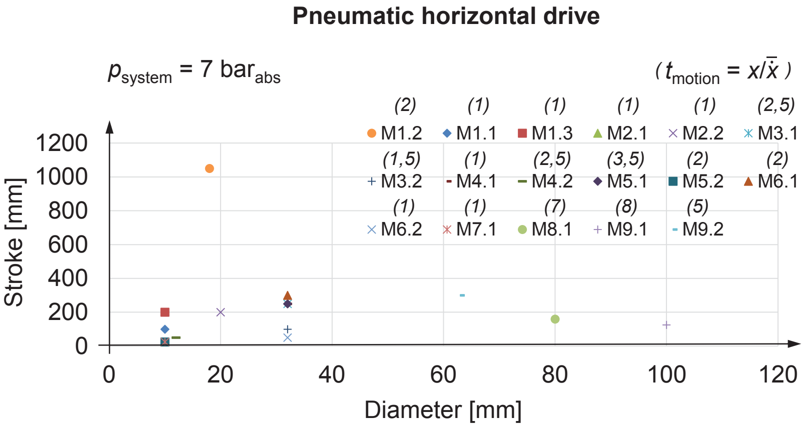


Figure 5: Selection of horizontal pneumatic actuators for presented study

The diameter of the horizontal cylinder drives vary from 10 to 100 mm with low loading masses, which represents a focus on high dynamic motion tasks.

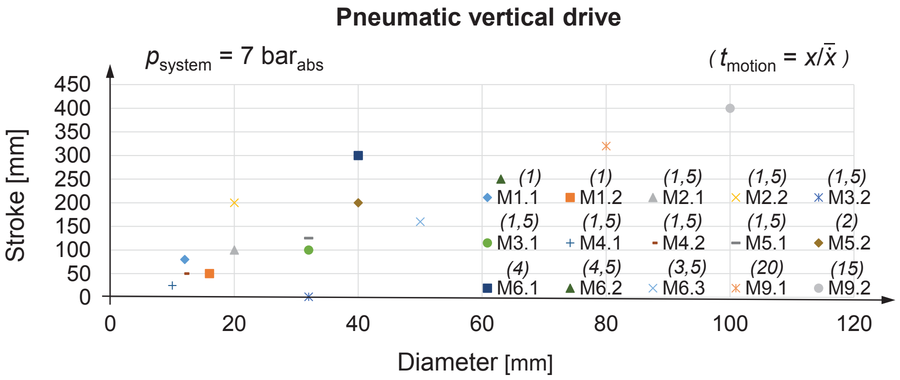


Figure 6: Selected vertical pneumatic actuators for the study

The vertical drives with diameters from 10 to 100 mm were considered for a higher loading mass, but lower velocities.

The load based sizing considers the type of motion and a static force analysis with an absolute system pressure of 7 bar. Hence, the dynamic characteristics as motion time or required moving velocity are neglected. The absence of this information for cylinder sizing leads to an increase in safety coefficient and results in an oversized pneumatic cylinder. That leads to a high energy consumption and a rise in operating costs. In this case, a method for the correct sizing of the drive has to be determined.

4.3. Selection of studied drives according to their sizing factor

Pneumatic and electric drives exhibit different principles of energy transmission which makes their energetic analysis more complicated. Since, the energetic flow variables; i. e. the volume flow rate and the current, differ physically, an exergy based analysis has to be applied. However, in many cases the standard pneumatic drive show a lower energy efficiency in comparison to an equivalent EM drive. Inasmuch as chosen pneumatic drives are usually oversized, the comparison of these drive technologies leads to incorrect conclusions. To solve this problem, the analysis of the system sizing has to be done at first. The previous study /6/ shows the use of exergy balancing for pneumatic drive sizing. The approach is based on adapting the useful energy (exergy) E_{ex} of the system to the required energy of the motion task E_{task}.

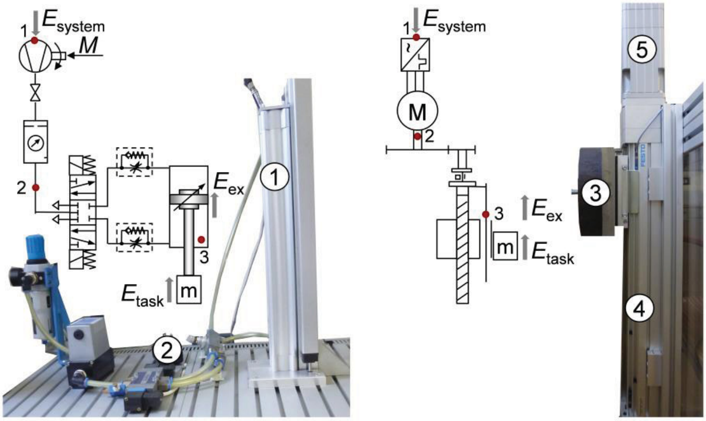


Figure 7: Energy flows within the vertical pneumatic as well as electric drive and test rigs of studied actuators: 1- pneumatic cylinder, 2- switching valve, 3- moving mass, 4- ball screw drive, 5- electric motor.

Figure 7 shows the principle schematics with the energy flow directions and the test rig of vertical pneumatic vertical and EM drive. The detailed system sizing is described by means of parameter matrix point M6.1. This sizing process was supported by using simulation models and validated with experiments. The measurement of the pneumatic drive includes the stroke, velocity, pressure in both cylinder chambers and volume flow rate at the pressure source. Whereas, measurement of electric drives implies stroke, velocity, current at the motor with constant voltage. Consequently, all this data was used to calculate and simulate provided exergy and the task energy of both systems.

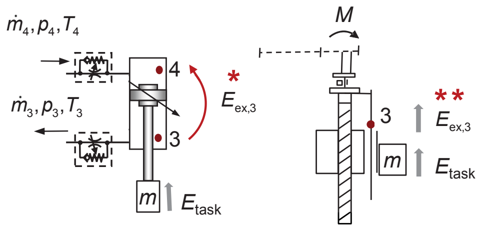
4.3.1. Comparison of system sizing using an exergy approach

In general, exergy is the maximum available technical work that can be transferred in mechanical energy to move the mass. Exergy calculation can be applied for different forms of energy such as compressed air or electric energy.

In case of pneumatic systems, exergy is the work that can be received via the transition from the current thermodynamic state of the system to the ambient state. Exergy is determined as the difference between the enthalpy and the entropy which represents the losses of available energy. An exergy model of a pneumatic system is based on four component types: actuator, valve, pipe and connector, which differ through their loss description. Exergy flows can be determined at certain observation points. To determine the amount of exergy transformed into the task energy, the difference of the exergy values of input and output at the cylinder within the motion time has to be calculated according to the equation of exergy flows in **Figure 8**.

The exergy flow at the ball screw depends on the torque and the efficiency of the motor and, moreover, on the efficiency of the used mechanical transmission.

To enable a comparison between measurement and simulation data, an exergy calculation was implemented into the pneumatic drive model. According to the simulation and measurement results, the calculation of task energy and emitted exergy at the actuator have to be done. The values represent the time integral of the exergy and energy flows.



$$\overset{*}{E}_{\mathrm{ex},3} = \int_{ds} \dot{m}_1 \cdot \left(c_\mathrm{p} \cdot T_3 - c_\mathrm{p} \cdot T_0 \right) \cdot dt - \int_{ds} \dot{m}_3 \cdot T_0 \cdot \left(-c_\mathrm{p} \cdot \ln \frac{T_3}{T_0} + R \cdot \ln \frac{p_3}{p_0} \right) \cdot dt$$

$$\overset{**}{E}_{\mathrm{ex},3} = \frac{M \cdot n \cdot 2\pi}{60} \cdot \eta_m \cdot \eta_a$$

Figure 8: Determination of exergy of a pneumatic cylinder and EM drive

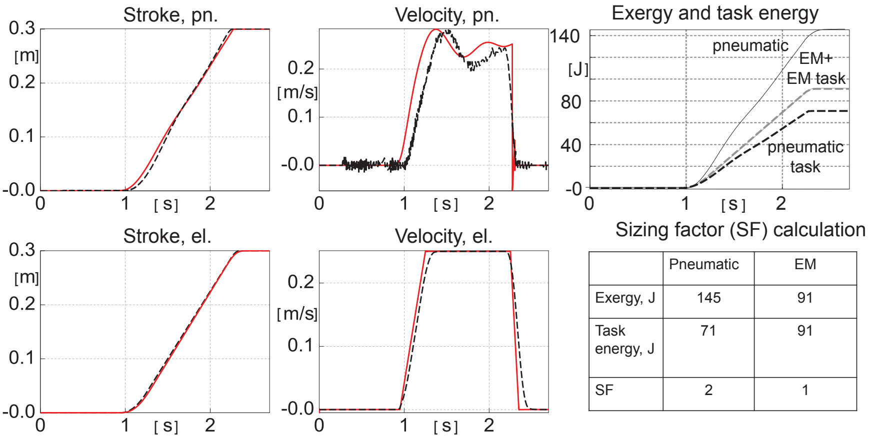
The task energy is calculated as a sum of friction, kinetic and potential energy of the motion mass. It differs by the friction energy that occurs in different drive technologies.

The results (**Figure 9**) obtaining from the calculation of SF of the EM drive show that the exergy matches with the task energy according to SF = 1. Whereas, the exergy of pneumatic drive is 2,9 times bigger than task energy. This leads to the evidence that the system parameters are oversized and are not comparable to the electric drive. In this case, two measures to reduce the SF can be applied:

- Use of a smaller cylinder
- Reducing pressure level

In this case study, the strategy of lowering pressure level was applied. To distinguish the limit of SF, numerous simulations were done to obtain the minimum possible pressure level while sustaining the motion profile.

The results of stroke and velocity measurement as well as the calculation of SF for the pneumatic drive with reduced pressure by 4 bar and for the standard EM drive are presented in Figure 9a and 9b. Further simulation results showed that the further reduction of $SF_{pneumatic}$ leads to a time delay of the cylinders motion. Hence, the limit of $SF_{pneumatic}$ for this certain motion task is 2. The task energy differs through the various friction forces during motion.



Sizing factor (SF) calculation

	Pneumatic	EM
Exergy, J	145	91
Task energy, J	71	91
SF	2	1

Figure 9: Left: Simulation (solid line) and measurement (dash line) results of stroke and velocity of the pneumatic and electromechanical vertical drives.
Right: Simulation of required energy (dash line) and exergy (solid line) of pneumatic (black line) and electromechanical (light grey line) vertical drives.

Further analysis regarding the achievable minimal SF of the studied drives is shown on **Figure 10** (horizontal drive) and **Figure 11** (vertical drive). For the comparison of the determined values, the SF of the standard load based system is also presented. To determine the SF for the system choice, the maximum value has to be determined. As long as the decisive SF has to be defined on the rodless side of cylinder, the types of the motion: push and lift were considered for vertical drives.

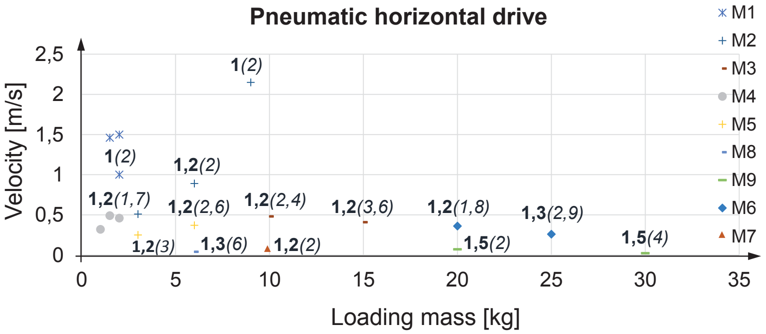


Figure 10: Determination of SF for exergy based (bold) and load based (italic) approaches for pneumatic horizontal drives

The analysis of studied horizontal drives reveal the tendency of increased SF with the decrease of mean velocity and rise of the loading mass. The velocity values below 0,25 m/s and the loading mass over 25 kg are represented by a SF between 1,3 and 1,5. The SF in the range of 1 and 1,2 is presented by systems with velocities over 0,25 m/s.

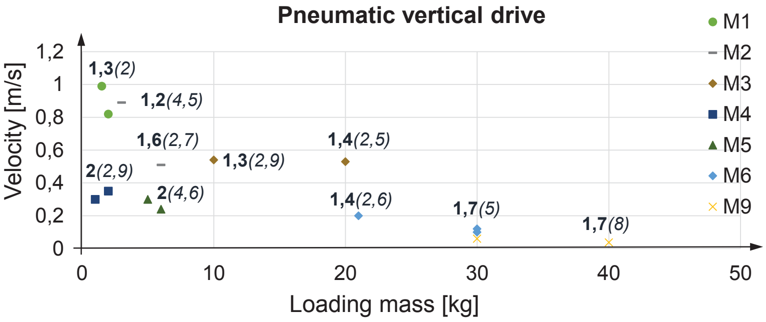


Figure 11: Determination of SF for exergy based (bold) and load based (italic) approaches for pneumatic vertical drives

The level of SF of vertical drives is also mainly characterized by the velocity, The maximum values between 1,7 and 2 are related to the velocity under 0,4 m/s; SF in the range of 1,3 and 1,7 refers to 0,4 m/s up to 0,8 m/s. Therefore, the highest velocity is presented by the SF of 1,2 to 1,3.

The analysis of the SF illustrates the typical oversizing of pneumatic drives. Therefore, an objective comparison with electric systems can be reached based on similar SF of each drive system. Moreover, the analysis of the limit of SF is based on dynamic characteristics of the task as well as motion time that provides the full information about sizing for further comparison. All in all, this method can be used for well dimensioning of horizontal and vertical pneumatic drives.

The next step provides the information about energy consumption of studied systems for the following economy analysis

5. Determination of energy consumption for economy analysis

There are two methods for the determination of the energy consumption of pneumatic drives /8/.First method - the air consumption calculation - enables the determination of the air consumption depending on the design parameters of the drive. The consumed air is calculated in norm liters and can be expanded to an energy value including the compressors efficiency. This result is needed for further calculation of energy costs. Second method represents a calculation based on exergy consumption. Hence, this method does not take into account the compressors efficiency and considers only the available energy, the value has to be converted according to the system efficiency. In this case, the calculated compressor efficiency shows 47 %. The results of energy consumption based on exergy consumption of pneumatic load based and improved exergy based sizing are presented in **Figure 12** and **Figure 13**. The energy consumption of the electric drives depends on the current and voltage at the motor with an assumption for the efficiency of the system components. For the studied cases the energy consumption of the EM in comparison to pneumatic drives is presented by values of 35-50% of exergy based sizing and therefore the results are not shown on this graph.

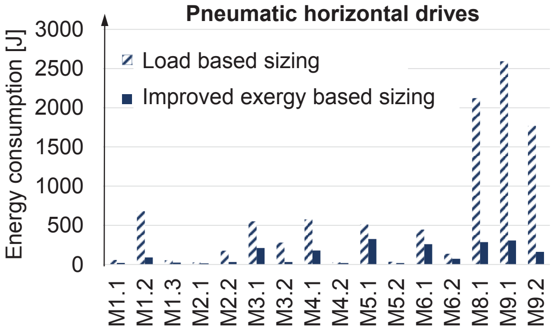


Figure 12: Comparison of energy consumption of studied horizontal pneumatic actuators according to load and exergy based approaches

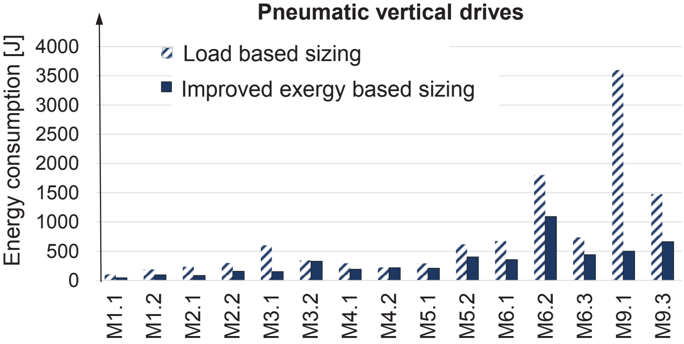


Figure 13: Comparison of energy consumption of studied vertical pneumatic actuators according to load and exergy based approaches

The comparison of energy consumption of load based and exergy based sized drives shows a significant difference about 25 % for systems with SF 1 - 1,6 up to 70 % for drives with higher SF. This fact proofs the importance of the correct system sizing from the technical as well as economical point of view.

6. Economy analysis of studied drives

In many cases the decisive factor of the application of a specific drive technology is the price. To make this decision, the life cycle costs (LCC) have to be analyzed.

The goal of LCC analysis is to choose the most cost-effective drive solution from a series of possible solutions, so the lowest long-term cost of ownership is achieved. An objective estimation of LCC includes static as well as dynamic costs. As a matter of fact, there are several criteria besides acquisition and energy costs that have influence on the calculation. The LCC analysis takes in account all cost components of a technical system and helps to distinguish them into different groups. Investment costs consider one-time expenses as acquisition and commissioning costs for the installation, warranty, transport, and training. While operating costs include energy costs and non-energy costs, that consider expenses for breakdown and maintenance, as personal costs and spare parts. Having said that, operating costs rise during the life cycle of the machine. Therefore, they have to be calculated over the life time, which, consequently, defines the work and operating time of the actuator. To reach that goal, the economic calculation that observes following groups of factors such as task, costs, operating and life time has to be determined. In that definition, the group “task” does not define the dynamic parameters of the motion, but observes the end product done by the system.

Thus far, several calculations are known for the economy analysis of technical systems, these are LCCBOU /7/, product costs, and hour rate accounting. Each has its advantages and drawbacks.

LCCBOU approach takes into account the investment and maintenance costs within a certain period of time. Results are presented as a sum of the cost due to the work of machine. Hence, there is no related parameter suitable for the comparison of two technologies, this method has not been observed. Other economic approaches are standardized and enable the calculation of all cost components due to life cycle of machine. However, the product cost accounting is relegated to the product, whereas hour rate provides the result of cycle cost.

Methods Group factor		LCCBOU	Product costs accounting	Hour rate accounting
Task/End parameter		No	Product	Machine hour
Costs	Investment	✓	✓	✓
	Operating	✓	✓	✓
Operating time			✓	✓
Run time			✓	✓

Table 1: Common economic methods for the comparison of technical systems

The review of each method in **Table 1** shows, that hour rate accounting is the most suitable calculation for economic analysis of technical systems. It includes all group factors and the end parameter is presented with machine hour cots, what in a case of abstract handling tasks is applicable. The hour rate calculation includes the estimation of five values: acquisition costs, percentage rate, maintenance and energy costs as well as the costs for the usable area in production hall.

Results of calculation of machine hour rate of the example system are presented in **Figure** . The calculation was done under the following working conditions: 3,2 million cycles per year and 5000 km life-time of the actuator. The life-time of other components is neglected.

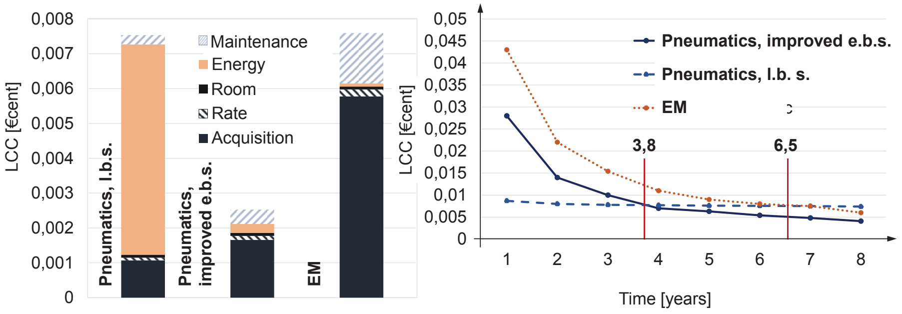


Figure 14: Comparison of LCC of pneumatic drives with exergy based (e.b.s.) as well as load based sizing (l.b.s.) and EM drives according to EXonomy analysis and payback period

The presented results on the left side of **Figure 14** show the LCC for the studied matrix point M6.1. In this case, the LCC of standard pneumatic and EM drive are the same, whereas, the improved system shows a significate cost reduction. However, the acquisition costs of the improved system are bigger due to the use of a pressure regulator. The other graph shows the amortization time of presented systems due to their life-time. These results show a payback period of 3,8 years for the improved system and 6,5 years for the EM drive.

The LCC calculation for all studied drives is presented on the **Figure 15**. In the most of cases the costs of improved pneumatic system are lower than EM drive. The most important role in this case plays the SF adaption.

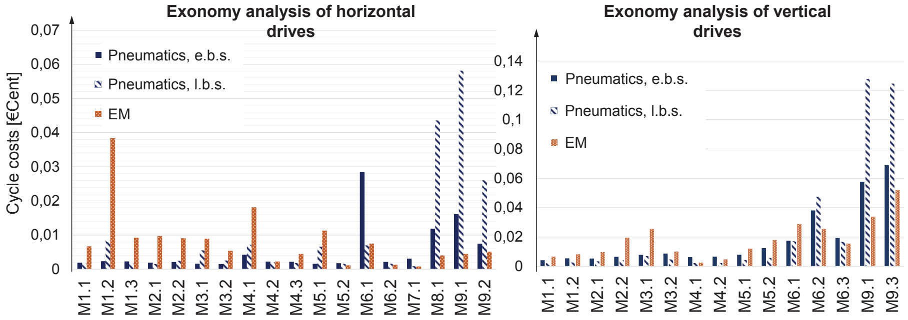


Figure 15: LCC of studied pneumatic e.b.s., pneumatic l.b.s. and EM drives

Finally, on the base of presented calculation all cost and time parameters are observed and guidelines for selecting pneumatic or EM drives can be formulated.

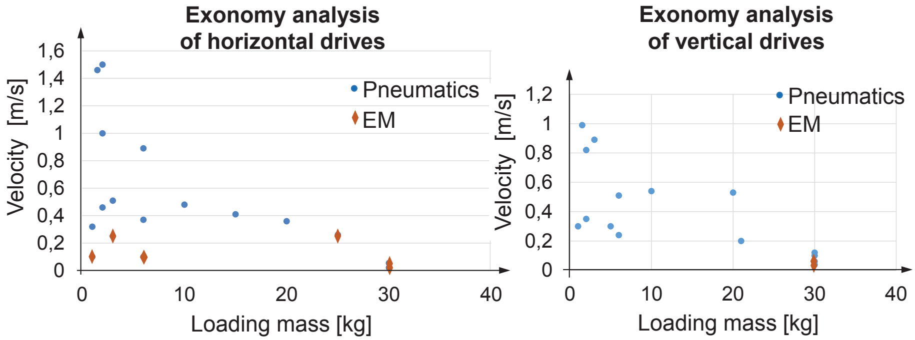


Figure 16: Preferred application fields of the studied drives according to the results of EXonomy analysis

From **Figure 16**it can be seen that the costs of pneumatic drives with SFs in the range of 1,7 to 2 are higher than EM drives. All in all, the preferred application fields of both technologies are characterized by the actual mean velocity of the motion task and additionally by stroke and loading mass. This circumstance proves the importance of considering the motion time for drive system selection.

7. Conclusion

The main goal of the current study was the development of a method for selecting a suitable drive technology for a certain motion task in the field of industrial automation. The proposed approach targets at an inter-domain comparison between pneumatic and electro-mechanical drives. To reach that goal, different criteria, e.g. with regard to the system sizing, have to be analyzed and an optimal cost-effective solution according to specific motion control task has to be found. Based on an exergy and economy analysis, the EXonomy method has been invented. Moreover, 31 drive systems within a typical parameter range of motion tasks for handling systems were defined to test the method experimentally and with the help of simulation models.

The EXonomy analysis enables an objective comparative analysis based on three steps. At first it realizes an energetic analysis of usable drive systems according to the dynamic parameters of the motion task. To compare different drive systems with similar properties an exergy analysis was applied and a criteria, named sizing factor SF, was invented. SF represents the relationship between the emitted actuator exergy and the required task energy. Consequently, this study has raised important questions about the oversizing of the pneumatic drive systems. In this context, the achievable SFs for chosen drive systems were analyzed with regard to the dynamic requirements of the motion task.

All in all, the EXonomy analysis is an extended economic valuation method that implies a correct sizing of a drive system, LCC, amortization times and the possible use of cost and energy saving measures. The further analysis has shown potential fields of the application for pneumatic and EM drives considering their mean velocity and loading mass.

Further work needs to be done to establish general guidelines for using energy saving measures for pneumatic as well as for EM drive systems

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9 Nomenclature

E	Energy	J
E_{ex}	Exergy	J
J	Inertia	$kg \cdot m^2$

m	Loading mass	kg
M	Torque of electric motor	Nm
n	Speed of electric motor	rpm
p_A, p_B	Pressure in cylinder chamber A and B	bar
T	Temperature	K
x	Displacement	m
$\dot{x}$	Velocity	m/s

10 Shortcuts

EM	Electro-mechanical
e.b.s.	Exergy based sizing
l.b.s.	Load based sizing
SF	Safety factor

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