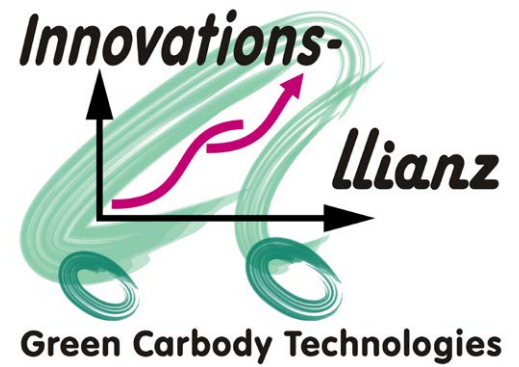


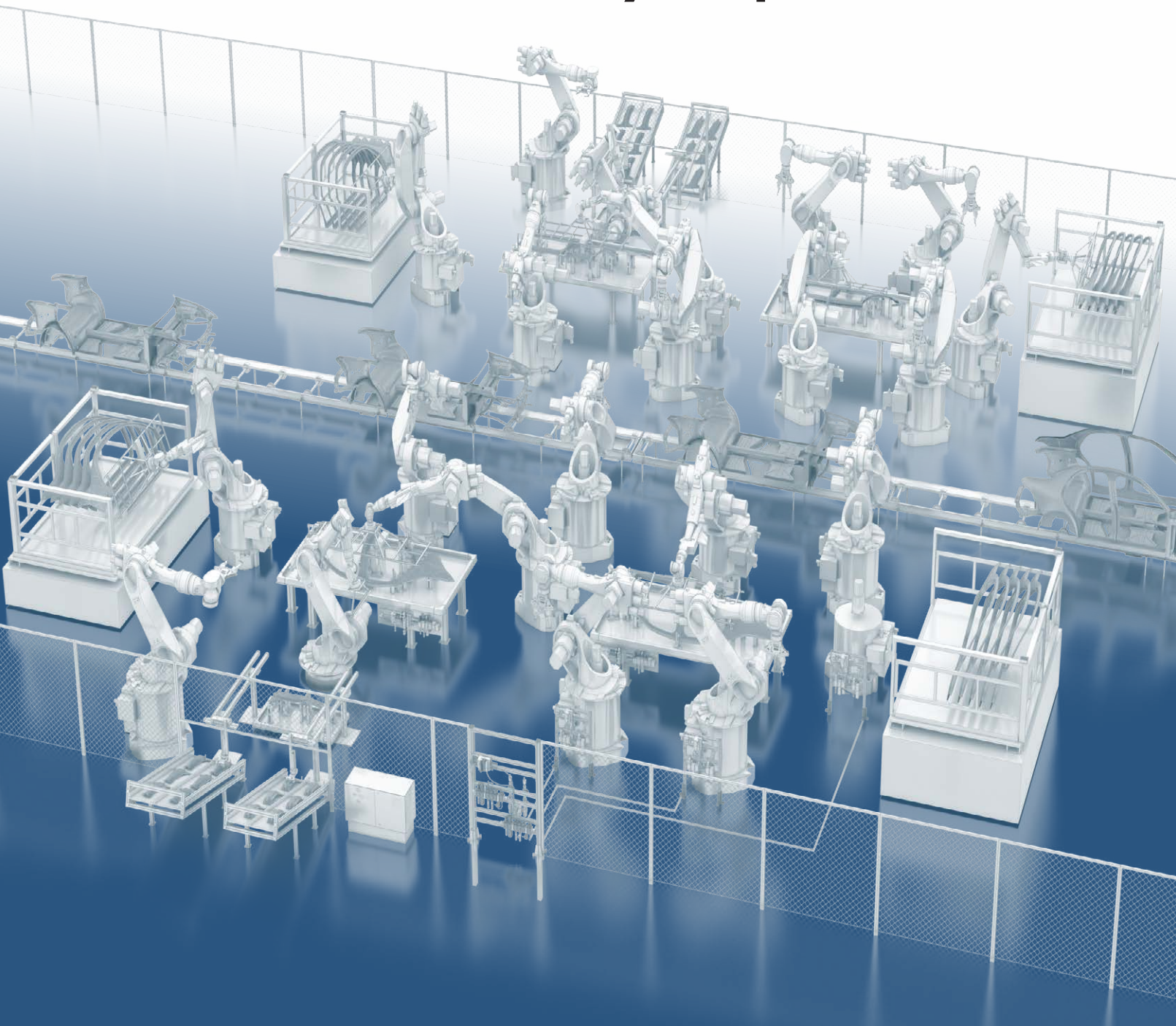
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# Planning the efficient use of compressed air in the body shop



# Imprint

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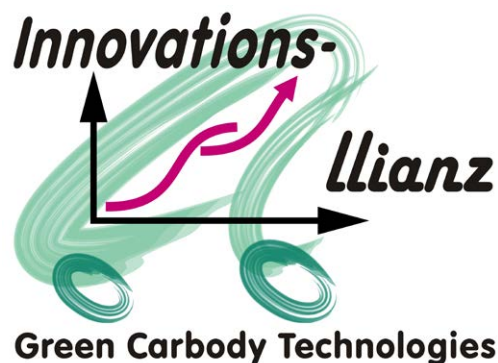
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# Foreword

Recent years have seen the topics of climate protection, energy efficiency and the responsible use of resources climb further and further towards the top of the agenda. For the customers of the future, buying a car will be about more than just fuel consumption figures. Instead, they will also be interested in what goes on behind the scenes: how much energy is required during production and what kind of emissions are created during the production process. With this in mind, achieving excellent energy efficiency standards in automotive production should not only be seen as a way to save on costs and handle resources sustainably but also as something that caters to market demands.

The "Green Carbody Technologies" innovation alliance explored the extent to which energy savings of 30% or more are a feasible goal in a body manufacturing context. Meanwhile, the sub-project that formed part of this – "Energy-efficient use of compressed air" – concentrated on pneumatic applications.

Pneumatic technology is simple, sturdy and inexpensive to purchase. Despite this, the compressed air generation process is frequently said to offer limited overall efficiency. Evidence from practice has shown, however, that pneumatic drive technology can in fact be a highly economical and efficient choice if it is used in the right application and is designed correctly. Body shop work involves many different clamping, gripping and holding tasks – and in these cases pneumatic drive technology proves to be a perfect match if it is used correctly, as not only can it generate high levels of force in small spaces, but it also requires no extra power for holding and clamping.

In this context, a holistic and systematic approach to compressed air efficiency is extremely important, both when planning new plants and when retrofitting existing ones: measures that only affect one specific part of the plant and have no long-term outlook are usually not enough. In most cases there is a lack of consistent coordination between the generation, distribution and use of compressed air.

From this point of view, one of the primary aims of producing this planning guide was to create transparency in consumption and loss figures. The work in this area involved comprehensive analyses of air consumption in body shop facilities, a practice which enables more efficient coordination between generation and consumption.

Nevertheless, energy consumption cannot be viewed in isolation when evaluating a drive technology. Purchasing costs, maintenance costs and the expenses associated with disposal have to be considered too – which means that technology evaluations must always be based on the TCO (total cost of ownership). One example of the benefits gained from taking this approach consistently is that it enables even high-pressure systems to be highly efficient solutions if the consumers operate inexpensively and efficiently.

The data from the theoretical and measurement-based analyses has also been used to develop several useful methods for improving energy efficiency in body shops. In some cases, only very little expenditure is required to produce a marked improvement in the efficiency of the production facility's pneumatic components.

This planning guide compiles and contains detailed descriptions of both the analysis results and the measures derived from these. As a document that aims to help production facilities use energy and finances efficiently, it may be especially useful when it comes to planning new facilities, although it is designed with maintenance and retrofitting work in mind too.

The institutes and industrial companies involved in this project wish to express their gratitude to the BMBF and the Karlsruhe Project Management Agency (PTKA), whose funds and support made this project possible.



*Dr. Jan Bredau, Festo AG & Co. KG*

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## 1.1 The joint project

1

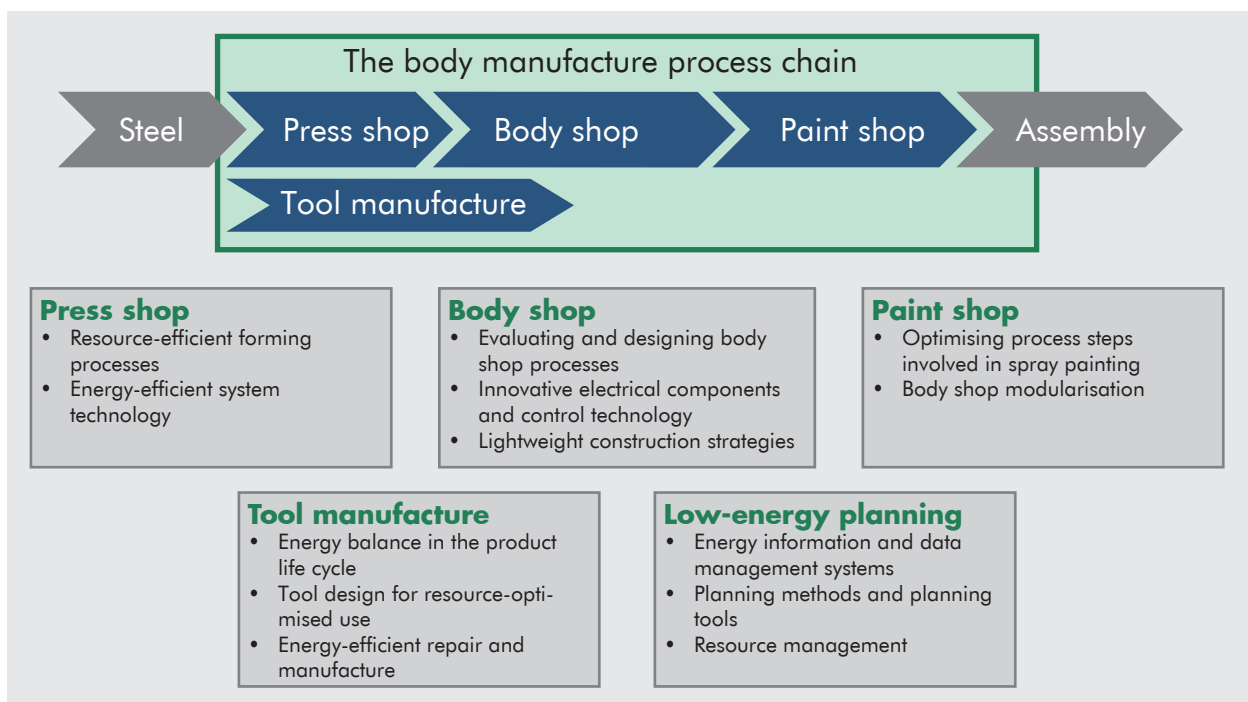
The **"Green Carbody Technologies" innovation alliance** is an initiative launched by German automotive equipment suppliers in 2008. As a technology alliance, its members have a common goal: to work together in a way that is focused on the market and on specific applications, in the hope that this will drive energy and resource conservation in the car body production industry.

One task of the innovation alliance is to communicate the latest results of research conducted by the five joint projects in the area which the BMBF has accorded priority funding status. These projects involve collaborative work by more than 60 companies and research institutes.

The alliance focuses on body manufacture, incorporating the process chain made up of tool manufacture, the press shop, the body shop and the paint shop. The reason for this focus is the fact that the car body, as a functional mass, is a major contributor to CO<sub>2</sub> emissions and therefore offers the greatest potential for savings in this area. The figure below illustrates the key areas on which the innovation alliance concentrates, as well as the stages of body manufacture in chronological order.

This particular report summarises the results of the sub-project "Planning the efficient use of compressed air", which received input from Volkswagen AG, Boge Kompressoren GmbH & Co. KG, Festo AG & Co. KG and the Fraunhofer Institute for Machine Tools and Forming Technology (IWU).

Pneumatic drive technology is used in factory automation because it offers advantages over other technologies in terms of its simplicity, the robustness of its components in harsh environments, its ease of maintenance, and its durability. Now, the effectiveness of these pneumatic systems and how efficiently they use energy are significant items on the agenda and hence the subject of much discussion. Although compressed air technologies are often said to be of limited overall efficiency, in practice the decision as to which drive technology offers the most favourable use of energy and financial resources depends on the application. Therefore, there is generally little use in making sweeping statements without knowledge of the specific application concerned. Instead, energy efficiency has to be explored using a two-pronged approach that looks at both the research relating to it and how this can be applied in practice.



Topics of the "Green Carbody" innovation alliance

This project focused on **body shops**, as these are areas that make particularly heavy use of pneumatic drive technology. Questions that typically surround this technology are:

- How high are the actual consumption values for compressed air in the body shop?
- How are these energy consumption values represented in the overall context of purchasing and maintenance costs (total cost of ownership, TCO)?
- What advantages does decentralised or centralised compressed air production offer?
- Viewed from the perspective of the entire production process, which compressed air system has the most favourable costs?
- Is it possible to save costs in high-pressure (12bar) systems, or does it even make sense to abolish the high-pressure system totally?
- How significant are the leakages involved? Do these have an impact on costs?
- What effect does decentralised pressure reduction have?
- Where does it make sense to include shut-off systems, monitoring systems and diagnostic systems?
- What quantifiable effects are achieved through measures such as tube length optimisation, optimum component sizing, and so on?
- What are the preferred and most practical planning tools for determining consumption and sizing compressor systems?

Analysing the characteristics of typical facilities is the key to answering these and similar questions. But this raises an issue: measurement results that are both reliable and transparent have always been difficult to obtain, and yet they are the only means of quantifying the extent to which savings

can be made and examining a system's feasibility in a cost/benefit analysis. Therefore, the primary concern in body manufacturing contexts is to achieve this total transparency in actual consumption figures as well as losses relating to planning and operation.

With these goals in mind, the sub-project laid the foundations for ensuring better coordination between compressors and consumers as a means of cutting down on the costs associated with energy. This involved the following steps:

1. Significant compressed air consumers were identified, pinpointed and incorporated into an optimisation concept. To do this, actual system statuses were recorded using measurement technology. Energy and condition monitoring systems were used during operation to identify deviations from the ideal status and detect weak points on this basis.
2. Factors affecting energy efficiency during operation of the facility were identified, and optimisation measures designed to ensure efficient operation were derived from this.
3. A key part of the project involved designing and using planning tools. These made it possible to not only estimate compressed air consumption in body shop facilities, but also design compressed air generation and distribution systems intended to optimise consumption.

This planning guide represents one outcome of the project. For facility planning purposes, it is designed to provide a transparent depiction of how energy flows between pneumatic components. Where existing facilities are concerned, its intention is to describe energy optimisation measures in depth and outline recommended action points.

## 1.2 Project partners



Project partners and fields of activity

The companies and institutes who participated in the project were selected on the basis of their expertise in compressed air technology. Boge, Festo and VW all possess a profound knowledge of ways in which compressed air can be used efficiently. The specialist experience offered by each of these individual project players ensured that enough

expertise was available at every stage of the compressed air functional chain (compressed air generation, preparation, distribution and application). The Fraunhofer IWU, meanwhile, adopted an umbrella role by categorising the results of the project within the overall context of the innovation alliance and providing corroborating scientific evidence.





### Volkswagen AG

Volkswagen AG, headquartered in the German city of Wolfsburg, is one of the world's leading car manufacturers as well as the biggest automotive producer in Europe. The group supplied 9.3 million vehicles to customers around the world in 2012 – a million more than the previous year. This equates to a 12.8 percent share of the global car market. In the group, Volkswagen AG is the parent company of the brands Audi, Bentley, Bugatti, Ducati, Lamborghini, MAN, Porsche, Scania, Seat, Škoda, Volkswagen and Volkswagen Commercial Vehicles.

Each brand has its own distinct character and operates independently in the market. The range of cars available stretches from compact vehicles that offer optimum fuel consumption all the way through to the luxury category, while the commercial vehicles arm offers everything from pick-up vehicles to buses and heavy goods vehicles.

The group operates 100 production sites across 19 countries within Europe as well as eight countries in America, Asia and Africa, employing more than half a million people. Worldwide, approximately 37 700 vehicles are produced every single day.

VW files around 2000 patent applications each year, 60% of which are on the German market.

[www.volkswagen.de](http://www.volkswagen.de)



### Festo AG & Co. KG

Festo is one of the world's leading suppliers of pneumatic and electric automation technology. As an independent, family-owned business with headquarters in Esslingen, Germany, Festo has become the global market leader in its sector over the past 50 years thanks to innovation and problem solving expertise in the field of pneumatics and electric drive technology, as well as a unique range of industrial training and vocational education programmes. Festo offers a wide range of products for both industrial automation and process automation tasks.

The Festo group has around 15 500 employees worldwide. Approximately 9% of its turnover is invested in research and development, primarily in the area of energy efficiency. Festo AG & Co. KG has around 3000 patents across the globe and files in the region of 100 new applications every year.

[www.festo.com](http://www.festo.com)



### **BOGE KOMPRESSOREN Otto Boge GmbH & Co. KG**

BOGE is a medium-sized mechanical engineering company based in Bielefeld, a city in Germany's Ostwestfalen-Lippe region.

It holds a position as one of the leaders on the German market in the area of compressed air supplies and compressor manufacturing. With more than a century of experience behind it, BOGE is one of Germany's oldest compressor manufacturers. Together with the management team, the company's 550 highly qualified employees believe that one of their responsibilities is ensuring that products are developed in line with the latest scientific findings. In addition to piston compressors and screw compressors, the current range of products includes complete compressed air systems and installations. BOGE compressors and compressed air systems can be found in more than 120 countries across the globe. As well as this, special filters and drying units – plus custom-built condensate management equipment – also form part of the product range.

[www.boge.de](http://www.boge.de)



### **Fraunhofer IWU**

The Fraunhofer Institute for Machine Tools and Forming Technology, or Fraunhofer IWU for short, is part of Germany's Fraunhofer Society (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.). Based in the city of Chemnitz, it also has a branch in Dresden. With a budget of 29 million euros and more than 500 employees, as well as laboratories for adaptronics/mechatronics, machine tools, forming technology, cutting technology, joining technology and assembly systems, as well as micro-manufacturing and virtual reality, the Fraunhofer IWU is one of the world's most important research and development institutes in the area of production technology.

Within this context, it focuses on application-specific research and development in the field of production engineering for the automotive and mechanical engineering sector.

[www.iwu.fraunhofer.de](http://www.iwu.fraunhofer.de)



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Bottom row:

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Dr. Jan Bredau (Festo)

Not pictured:

Nico Schikade (Boge)  
Sören Lorenz (IWU)  
Andreas Schlegel (IWU)

## 2.1 Why energy efficiency?

# 2

### Climate protection and energy efficiency

have long been express aims defined by policy in Germany. As early as 1995, the country undertook to reduce greenhouse gas emissions by 25 per cent over the subsequent ten years. It was hoped that meeting these aims would not only guarantee long-term protective measures for the world's climate, but also establish sustainable, considerate methods of handling the finite energy and raw material resources the globe has to offer.

As far as industry is concerned, dependable power supplies are an absolute must. Given that industrial current consumption accounts for almost half of Germany's total consumption figure, however, there is also a need for the industrial sphere – and, therefore, automation technology – to play its part in introducing the necessary steps towards the sustainable, economical use of energy and raw materials.

In many companies, there is an urgent need for action due mainly to rising energy prices and an increased sense of environmental awareness. Here, simple measures are often all that are needed to bring about significant reductions in energy consumption and costs.

In many cases, the planning phase of industrial production involves choosing from a range of different technologies and operating methods. Identifying exactly the right combination of technology

(effectiveness) and operating methods (efficiency) is key to creating a process that offers the best possible use of both energy and financial resources.

The systematic increase in energy efficiency that industrial facilities aim to achieve is a complex area and requires a broad range of technical and organisational issues to be addressed. In body manufacturing facilities, the central elements are pneumatically operated systems such as welding guns, clamping fixtures and pin pulling cylinders. Against this backdrop, the purpose of this guide is to illustrate the basic properties of pneumatic systems and components – specifically those used in body shops – before offering pointers for planning and optimising facilities as a means of improving energy efficiency.

During the project, it became clear that issues relating to achieving an increase in energy efficiency must be viewed in the overall context of the facility concerned.

Furthermore, many cases require detailed records of parameters such as a facility's size, age and type of installation. For that reason, this guide is unable to provide anything more than basic signposting: options and areas where savings could potentially be made must always be discussed based on the circumstances of the individual case.

## 2.2 "Pneumatics" or "compressed air"?

**Compressed air** is a term used to refer to a whole host of different applications: to take some examples, it can be used as operating energy for tools such as mechanical screwdrivers and impact drivers, as well as in air guns or as sealing air. By contrast, **"pneumatics"** refers to compressed air-operated drive technology in a general sense (in valves, linear drives, grippers and so on).

Efficiency and effectiveness of compressed air applications depend on the way of use. Whether compressed air is mainly used in a sense of "pneumatics" or for other purposes comes down to the industry and company concerned. During evaluations of efficiency values and technology comparisons, however, it is often the case that compressed air is viewed as an all-encompassing concept, with no distinctions drawn between the individual purposes for which it is used. This can inevitably lead to distortions and misinterpretations in data relating to pneumatic drive and handling technology.

In order to illustrate the different categories that compressed air falls into, the table below shows a summary of the individual types of compressed air.

Most of the compressed air in industrial applications is used for pneumatic tools as active air or

process air. While there are no verified statistics on the consumption of pneumatic applications within the compressed air technology sector, an average of roughly 20% of total compressed air consumption is assumed to be realistic. However, this value can vary significantly depending on the company, facility and application concerned.

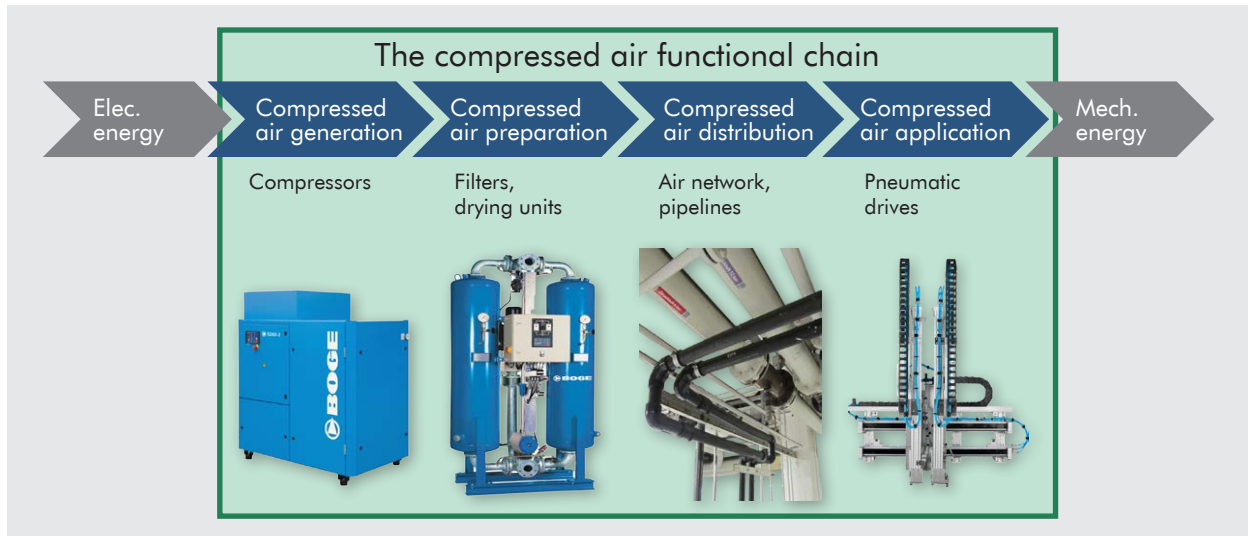
Automotive production is one of the areas in which it is important to distinguish between the various applications. In body shops, a significant proportion of the compressed air generated is used as process air: e.g. for operating cross-jets or for cleaning purposes (removal of chips, smoke or other sources of dirt). Another large proportion of compressed air is used as active air in the paint shop. Supply air, meanwhile, only accounts for a relatively small amount of compressed air in body shops, and is usually used for operating clamping devices, welding guns, pin pulling cylinders or grippers.

This project only considered the potential for optimisation offered by supply air in pneumatic components and systems, as this is the only case in which air acts as the "energy medium"; furthermore, it is only in this context that it is possible to apply energy-saving measures.

Classification of compressed air according to its purpose	
Supply air	Supply air describes air which, as an energy medium, is used to perform mechanical work, such as driving tools and pneumatic machinery. Pilot air (controlling valves, slides, flaps, etc.) is also classified as supply air. When supply air is used for operating valves and cylinders rather than in tools, we refer to <b>"pneumatics"</b> .
Active air	Active air refers to air which is used to transport substances. Active air can be further broken down into conveyor air, which actually transports materials, and active air in a broader sense, where the air is used to blow substances out of a tool or a machine (e.g. for surface treatment).
Process air	Process air refers to air which is used for integration into processes. This also includes use of the air itself, e.g. for drying, cooling or ventilation.
Vacuum air	Vacuum air is air which is used to create underpressure via compressed air, e.g. in vacuum generators.
Test air	Test air is used for testing and checking purposes.



## 2.3 The compressed air functional chain



The compressed air functional chain

Substances and energy flow through compressed air facilities can be divided into four stages:

First, the compressed air that is required is generated in a compressor, normally using an electrically driven motor. The air is subjected to an initial preparation stage (cooling, filtering and drying) to ensure that the compressed air generated meets the requisite quality standards when it enters the air network. This is where the compressed air is distributed and made available to the applications that use pneumatic operation. Before the compressed air can actually be used in an application, however, it normally has to be prepared in an air supply unit so that it will satisfy the requirements of the downstream pneumatic components. In most

cases, air supply units consist of an oil separator, a drying unit, various filters and an adjustable pressure regulator. Finally, when the compressed air reaches the application itself, it is used as an energy medium for mechanical movement tasks (moving, holding, clamping, pivoting and so on).

A complete analysis must be carried out in the planning and sizing phase of all pneumatic systems. The compressor, air preparation equipment, distribution system and application must be carefully designed to work in harmony. In the compressed air functional chain (see figure above), there is no room to overlook anything: the only way to ensure that the entire system will use energy efficiently is to take every single part of it into consideration.

### 2.3.1 Compressed air generation

The compressed air that is required to operate pneumatic systems is provided by a compressor. In most cases, an electrically driven motor generates a mechanical movement that is transferred to pistons or compressor screws. Via suction and exhaust valve first atmospheric air is compressed and then discharged into the compressed air system or an upstream air reservoir.

Different compressor designs are available to cater to the various pressure levels and delivery rates that are required. As an example, multi-stage reciprocating piston compressors are especially suited to generating high levels of output pressure where delivery rates are somewhat low. Screw compressors, on the other hand, are capable of generating lower output pressure at high delivery rates.

The mechanical and thermodynamic processes that occur during air compression produce a large quantity of heat, which has to be diverted away from the compressed air. In many of the older systems that are still installed, this waste heat simply goes unused. However, pneumatic facilities demonstrate far better overall efficiency if they can feed the heat into some kind of useful application, such as heating, process heat (e.g. for generating hot water) or – in the applications that need it – generating a source of cooling for air conditioning purposes (adsorption cooling systems).



### 2.3.2 Compressed air preparation

The compressed air contains all kinds of contaminants, such as solid particles or small amounts of oil that the process of lubricating compressor components introduces into the compressed air. These can, however, be removed by processing the air through various filter stages, bringing its quality up to the required standard. Using fine filters and micro filters, particles measuring as little as  $0.01\ \mu\text{m}$  can be largely eliminated.

Besides filtering, there is also the possibility of reducing the water vapour content of the compressed air in a condensate separator and air dryer, thus lowering the pressure dew point. This stops water drops from forming in the compressed air as a result of pressure and temperature fluctuations in the pneumatic application – a useful option, as these drops can flush out lubricant and lead to corrosion-related damage in individual components.

In pneumatic facilities, filters and drying units can represent sources of pneumatic resistance by causing pressure drops, which in turn lead to a loss of energy. Therefore, this factor has to be taken into consideration when designing and sizing the facility. As a rule of thumb, only as much filtering and drying equipment as is absolutely necessary should be installed.



### 2.3.3 Compressed air distribution

Compressed air is distributed via networks of pipes that come in a range of different topologies. Ring structures and networked topologies are both recommended, though these must be considered in the light of the building layout and the kinds of requirements.

No matter what topology is used, however, the diameter of the pipelines must be adequately sized to allow the flow resistance to remain as low as possible. If the diameter of a pipeline is halved, its flow resistance becomes approximately 32 times higher. What this means is that the resistance of a pipeline increases to the power of 5 when the diameter is reduced.

Changes in the pipeline direction have to be considered separately, particularly in cases where the intention is to use narrow, non-rounded elbows. The flow resistance in pipeline elements of this kind may be far higher than in comparable pipe pieces that are straight.

An exceptionally important part of constructing and maintaining networks is to pinpoint any leakages and eliminate them. Leakages in pneumatic systems only release compressed air to the environment, which means that they are not usually associated with risks to safety or the environment. Anyhow, in some cases they can be a significant contributor to overall energy consumption, and should therefore be removed religiously.



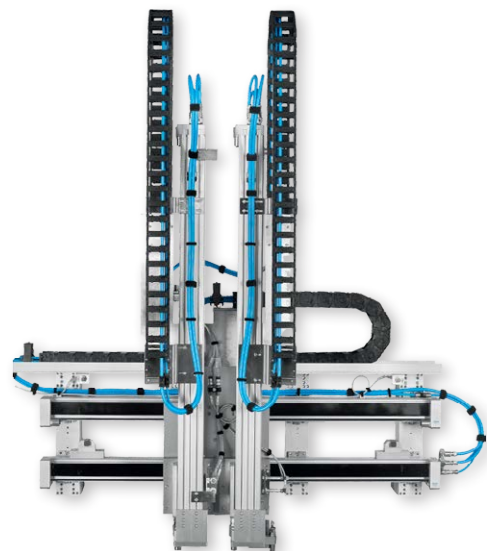
### 2.3.4 Application

The application represents the stage where the pneumatic energy is actually put to use. The operating pressure is pre-set in the air supply unit, and is therefore made available at the same level to the entire application.

The classic example of a pneumatic consumer is a linear drive (pneumatic cylinder) containing a drive piston with or without a piston rod; this piston is set in motion and is able to exert force by means of compressed air in a drive chamber.

An operating pressure of 6 bar rel. is sufficient for the majority of pneumatic applications. The distribution system used in such cases is referred to as the low-pressure system (LP). Some applications, however, may need higher pressure levels: this is especially true if they demand very high contact forces. These, therefore, use a high-pressure system (HP) offering a pressure level of 12 bar in most cases.

The primary applications found in body shops are pneumatic clamping devices, other clamping fixtures and pin pulling cylinders, all of which are generally operated in the low-pressure system. Pneumatic welding guns, on the other hand, often use compressed air from the high-pressure system as they are designed to generate a high level of contact force during welding.



## 2.4 Evaluation principles

### 2.4.1 Air and energy consumption

How much energy pneumatic components consume is largely determined by their air consumption. In most cases, air consumption is specified in normal cubic meters (Nm<sup>3</sup>) or normal liters (NI) per unit of time or motion cycle. A normal liter denotes the volume that a certain mass of air takes in under standard conditions. The ambient pressure and ambient temperature specified by ISO 6358 are usually accepted as standard conditions (air humidity 65%; abs. air pressure 1000 mbar; temperature 20°C). There are, however, other standards that are relevant to compressed air technology too. The table below contains an overview of these.

The standard volume is proportional to the mass of air and is not affected by the pressure at the current time. This is as opposed to the operating volume, which represents the actual physical volume of the compressed air under the current pressure conditions. If, for example, a pneumatic cylinder with a diameter of 32 mm and a length of 0.25 m is filled with compressed air at 6 bar rel., it will then contain approximately 0.2 l of compressed air at the operating volume. Under standard conditions, this equates to 1.4 normal liters.

If a facility's air consumption is known, characteristic values for the compressor system can be used to estimate the electrical energy consumption of the pneumatic components. For the most part, the automotive industry uses large-scale compressor systems that enable compressed air to be generated inexpensively. Generating a normal cubic meter of compressed air for the 6 bar system usually requires an amount of energy between 0.1 kWh and 0.15 kWh depending on how effective the com-

pressors are. Assuming an average electricity price for industrial consumers of 10 ct/kWh, this results in costs for providing compressed air of 1.0 ct to 1.5 ct per normal cubic meter. Later chapters will base their information on defined compressed air costs of 1.33 ct/Nm<sup>3</sup> in the 6 bar system and 1.80 ct/Nm<sup>3</sup> in the 12 bar system, with these values incorporating certain additional expenses for compressor operation (maintenance, depreciation and service, for example) besides the energy costs themselves.

Where supply pressure is higher, both the energy resources and the financial outlay required to generate a normal cubic meter will be greater. This is why it is always important to ensure that the pressure level being used in generation and distribution meets the requirements of the application concerned, and is not too high.

Many people believe that pneumatic energy is a relatively expensive form of energy and seems to be a less favourable option in efficiency evaluations as compared with alternative drive technologies. This conclusion, however, is often based on pneumatic systems that have been inadequately designed and maintained – and not the actual principles behind pneumatic operation. In fact, pneumatic components are often guaranteed to function exactly as they should even despite problematic designs, oversizing, significant leakage and component defects, and this makes pneumatics an exceptionally resilient type of technology. What is true, however, is that air consumption can increase dramatically under these conditions, which is why correct planning and design – as well as error control methods (such as leakage detection) – are absolutely indispensable.

Standard	Pressure	Temp.	Humidity	Density	Comment
<b>DIN 1343-1990-01</b>	1013.25 mbar	0°C 273.15 K	0%	1.292 kg/m <sup>3</sup>	Often referred to as "standard conditions". For flow sensors, e.g. at Festo.
<b>DIN 1871-1999-05</b>	1013.25 mbar	0°C 273.15 K	Not specified	1.292 kg/m <sup>3</sup>	Used for gaseous fuels as well as other gases.
<b>ISO 2533</b>	1013.25 mbar	15°C 288.15 K	0%	1.225 kg/m <sup>3</sup>	Definition of International Standard Atmosphere – troposphere.
<b>ISO 6358</b>	1000.00 mbar	20°C 293.15 K	65%	1.185 kg/m <sup>3</sup>	Test conditions for pneumatic components.

### 2.4.2 Energy and exergy

It is not just the development and implementation of energy efficiency-boosting measures that are gaining ground: the way in which the energetic quality of systems is represented is becoming increasingly important too. Certain system components can only be compared, evaluated or classified according to efficiency specifications, for example, if a consistent and uniform description of the energy interactions within a process is available.

In the compressed air technology field, energy flow diagrams are frequently used for this. Starting from an energy source, they show the energy flows along various stations within a system, which each represent a sub-section of the system (such as the compressor, after cooler, drying unit or network). The width of the arrows is proportional to the flow, which ensures that the diagram is easy to read. In spite of its clarity, this approach does have its weaknesses. In a pneumatics context, the thermodynamic variable of "energy" does not permit any statement to be made on the useable work a pneumatic system can perform. This is particularly due to the fact that the energy content in a given pneumatic condition is a function of the air temperature, but not of the pressure. Neither enthalpy (in the case of open systems) nor the internal energy  $U$  (in the case of closed systems) are affected by pressure levels. For instance, where  $Q$  is the standard volumetric flow rate,  $\rho$  is the standard density,  $c_v$  is the thermal capacity and  $T$  is the temperature, the internal energy  $U$  is calculated as follows:

$$U = Q \cdot \rho \cdot c_v \cdot T$$

The fact that the pressure  $p$  is not required for this calculation shows that these variables are not a useful means of illustrating the benefits of the system. Where pneumatic systems are concerned, it is pressure that is the primary factor in the work they carry out. While high temperatures lead to a high energy content in the system, the energy

cannot be used pneumatically. This shows that it is impossible to make any meaningful statements about the pneumatic effectiveness of a system status based on energy studies.

One method that can help overcome these deficiencies is the use of a different thermodynamic factor: **exergy**. This refers to a part of the energy in a system that is able to bring about work if the system is brought into equilibrium with its environment. Thus, exergy represents the proportion of the total energy that can be used as work; the non-usable proportion is called anergy. Exergy is a status variable, but not a conserved variable, which means that it can be converted into anergy and can be lost as a result.

As an energy gradient in relation to the environment is always required in order for energy to be usable, and this needs to be taken into consideration when calculating exergy, the following information is required to calculate the actual exergy status: the ambient pressure  $p_{atm}$  and ambient temperature  $T_{atm}$ , as well as four variables which describe the current status  $a$ : the supplied electrical energy  $P_a$  (= pure exergy), the absolute pressure  $p_a$ , the temperature  $T_a$  and the corresponding volumetric flow rate  $Q_a$ . These specifications are used to calculate the exergy as demonstrated below.

Exergy can be used to determine all the status changes in the system: consumption of electrical energy by a process, pressure changes, temperature changes and changes in the mass flow, e.g. due to a leakage. Comparing two statuses allows the exergy loss between them to be calculated. When this is expressed as a percentage of the initial exergy, it gives the percentage loss at every station in the functional chain. The exergy illustration on the next page (left side) shows an example of an exergy flow diagram for a pneumatic system. Most

$$E_a = P_a + Q_a \rho_a c_p \cdot (T_a - T_{atm}) + Q_a \rho_a T_{atm} \cdot \left( R \ln \left( \frac{p_a}{p_{atm}} \right) - c_p \ln \left( \frac{T_a}{T_{atm}} \right) \right)$$

Exergy calculation

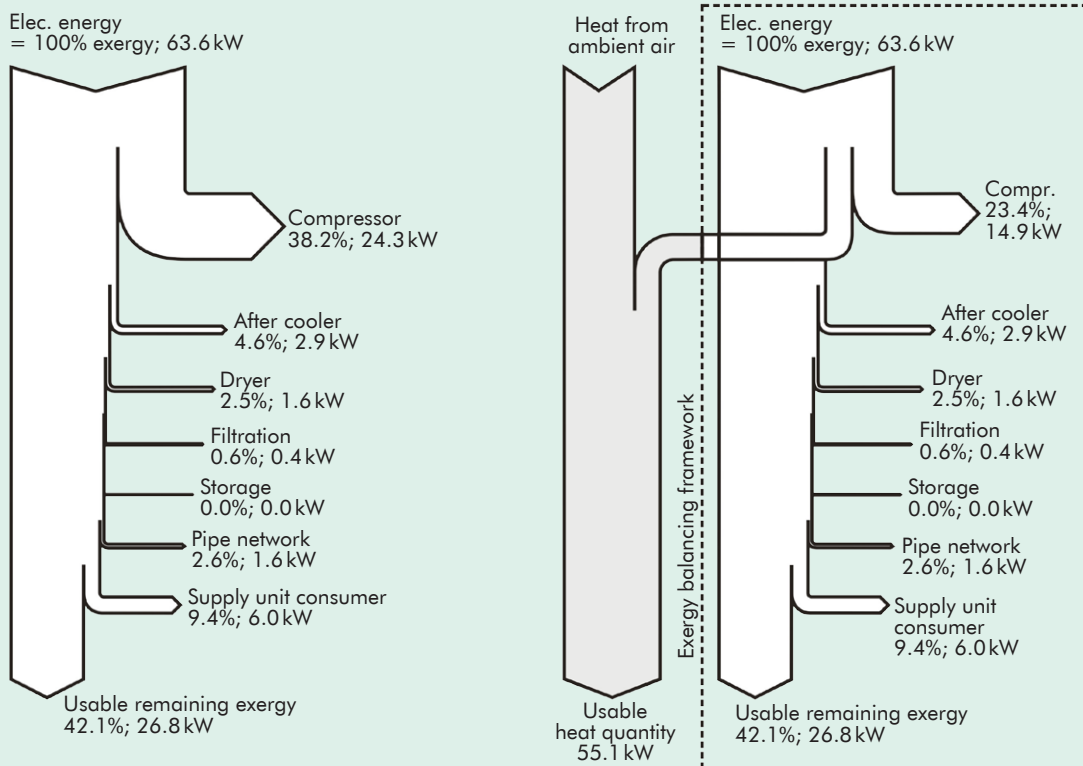


of the exergy is lost on compression – 38.2% in the example shown here. At the end of the functional chain, a remaining exergy amounting to 42.1% of the initial exergy is available for the application.

When the air is compressed, most of the heat development occurs in the compressed air functional chain due to thermodynamics. For this reason, integrating a heat recovery system is a key factor in boosting the energy efficiency of compressed air systems. Exergy and heat can be represented in a single diagram if the usable exergy proportion from heat recovery is routed to the left. This proportion is used to exploit a flow of heat from the compressed ambient air. Physically, this process is the same as a heat pump (figure on right). The example shows a usable amount of heat of 55.1 kW in addition to the usable exergy of 26.8 kW.

The total of the usable amount of heat and the remaining exergy at the end of the functional chain (in this case, 81.9 kW) may exceed the electrical energy applied at the compressor (63.6 kW in this example). While this initially appears to be an inconsistency in the system, this is not actually the case because of the heat which is extracted during the process of compressing the absorbed ambient air, and which also has to be considered in the evaluation (see top of grey arrow).

Exergy flow diagrams of the type shown in the figure here can play an important part in making the efficiency of pneumatics or compressed air applications clearer and easier to compare, including with other technologies.



Exergy flow diagrams – with and without heat recovery

The exergy flow diagram shown here represents some of the outcomes of the "EnEffAH" joint project, which was conducted between October 2008 and June 2012 and was funded by the Federal Ministry for Economic Affairs and Energy. For more information, visit [www.eneffah.de](http://www.eneffah.de)

### 2.4.3 Physical values

To provide a clearer overview of the operands and terminology used in this context, they are summarised in the table below:

Designation	Formula element	Unit	Comment
<b>Standard volume</b>	$V_n$	$\text{Nm}^3$	Volume of air under defined air status conditions (e.g. in accordance with ISO 6358 or, as in Festo's case, in accordance with DIN 1343: $T=273.15\text{K}$ ; $p=1.01325\text{bar abs.}$ )
<b>Standard volumetric flow rate / Nominal flow rate</b>	$Q_n$	$\text{Nm}^3/\text{min}$	Volumetric flow rate of air, referring to the standard volume. Flow sensors generally show the standard volumetric flow rate.
<b>Standard nominal flow rate</b>	$Q_{nN}$	$\text{Nm}^3/\text{min}$	Volumetric flow rate of air with defined pressure parameters: $p_1=6\text{bar rel.}$ and $p_2=5\text{bar rel.}$
<b>Operating volume</b>	$V$	$\text{m}^3$	Actual physical volume, used in thermodynamics
<b>Absolute pressure</b>	$p$	bar	Differential pressure with respect to absolute vacuum, used in thermodynamics
<b>Relative pressure</b>	$p$	bar	Differential pressure with respect to atmosphere, pressure gauge signal
<b>Energy</b>	$U$	kJ	Internal energy; does not shed any light on practical benefits, used in thermodynamics
<b>Enthalpy</b>	$H$	kJ	Energy variable for open systems, effectiveness also questionable, used in thermodynamics
<b>Exergy</b>	$E$	kJ	Maximum work capacity; Statements on practical benefits and usability are possible.

The parameters listed below were determined by analysing the costs and outlay associated with a representative automotive plant. These will be used later in the document for cost estimates and extrapolations. The values are mean values. Some compressed air costs may be even lower in large production locations that use highly efficient compressor stations.

Designation	Unit	Comment
<b>Compressor effectiveness</b>	$\text{kWh}/\text{Nm}^3$	Energy required to generate compressed air (not including investment in compressors) relative to a certain quantity of air ( $1\text{Nm}^3$ ). Here: $0.11\text{kWh}/\text{Nm}^3$ (low-pressure system, 6 bar) $0.15\text{kWh}/\text{Nm}^3$ (high-pressure system, 12 bar)
<b>Compressed air costs</b>	$\text{ct}/\text{Nm}^3$	Costs associated with generating compressed air (including investment in compressors and additional expenses such as maintenance) relative to a certain quantity of air ( $1\text{Nm}^3$ ) (An electricity price of $10\text{ct}/\text{kWh}$ is assumed) Here: $1.33\text{ct}/\text{Nm}^3$ (low-pressure system, 6 bar) $1.80\text{ct}/\text{Nm}^3$ (high-pressure system, 12 bar) $1.50\text{ct}/\text{Nm}^3$ ("average" costs)
<b>Production time</b>	$\text{h/a}$	Number of production hours per year. Here: Full-time operation: 24 h/day and 350 days/year: 8400 h/a Three-shift operation: 24 h/day; 250 days/year: 6000 h/a Two-shift operation: 16 h/day; 250 days/year: 4000 h/a

### 3.1 The role of the body shop in automotive production

3

Automotive plants are generally divided into four large production areas: these are the press shop, the body shop, the paint shop and the assembly area.

The press shop is where sheet metal components are pressed into their required shape. The mechanically or hydraulically driven machines used here are able to produce pressing forces of several thousand tons. In the body shop, the components needed to construct a vehicle (mounting plates, profiles, reinforcements, and so on) are permanently joined together using the processes of spot welding, laser welding, bonding or soldering. The car body then has several coats of paint applied to it in the paint shop before proceeding to the final station: the assembly area, where all the vehicle components are put together.

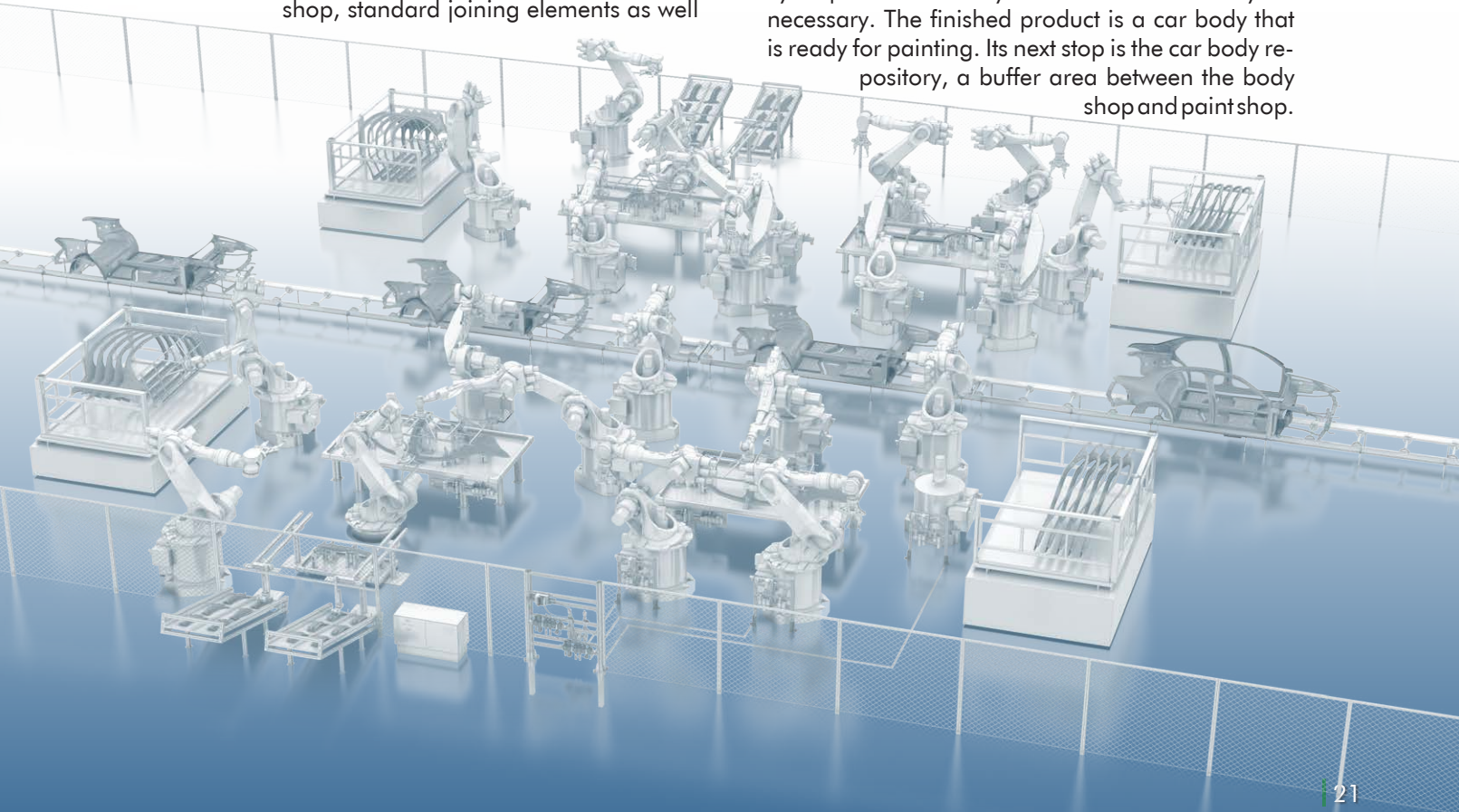
Automotive plant stations usually have buffers between them to provide breaks in the flow of materials. This also provides a way of breaking the system down into separate, more manageable areas if the planning process is a complex one.

Output products of the body shop are the pre-formed sheet metal components from the press shop, standard joining elements as well

as sundry materials like adhesive or solder. In total, the raw materials required for one car body amount to around ten large outer skin panels and several hundred structural pieces installed at various points. The main processes that take place at this station involve joining the subassemblies: the base, roof, side covers, doors and hatches. The assembly line is then where these subassemblies are joined together to form the car body. Once the parts have been fixed into the right shape, the several thousand welding points required to make the structure rigid are applied.

Spot welding is the most common type of joining method. The systems used here are categorised as either geometry stations or finish welding stations, depending on whether they handle parts that need to be positioned with dimensional accuracy or are already tacked together. The other joining methods that are used require system designs that are adapted specifically to suit the tools they use. Both the tools and material flow are guided by industrial robots for the most part.

Once the doors and hatches have been assembled, the structure proceeds to the finishing area for quality inspection and any final touches that may be necessary. The finished product is a car body that is ready for painting. Its next stop is the car body repository, a buffer area between the body shop and paint shop.



## 3.2 Compressed air in the body shop

### 3.2.1 Pneumatic components

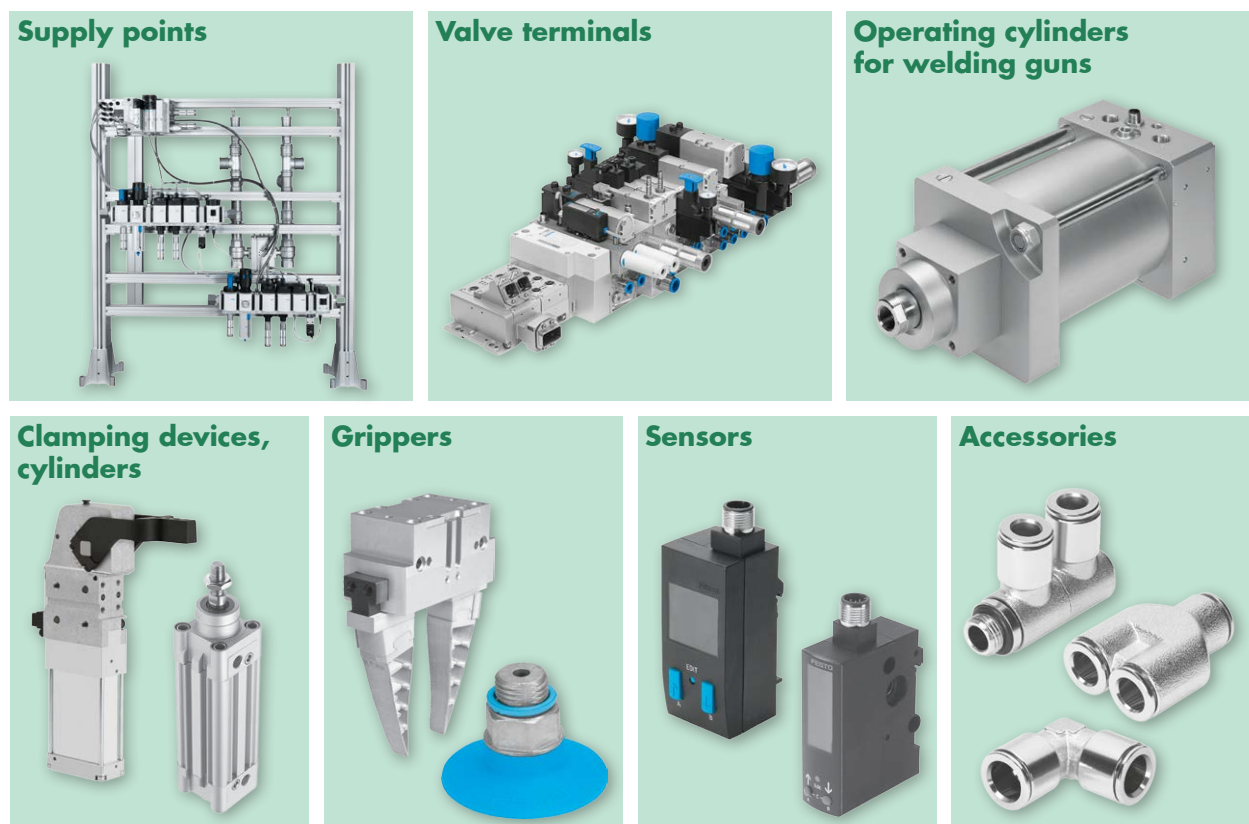
A standard body shop typically involves the intensive use of robotics. Between 1000 and 2000 robots may be in use in a large plant. A standard plant generally has 1-2 body shops, and 500 to 1000 robots with flexible welding guns are typical. Additional robots are used in conjunction with handling and gripper technology. Since the energy they consume accounts for a significant share of the plant's overall consumption, there is now evidence of a trend favouring lightweight technology (lightweight guns, for instance), as this involves lower load weights and thus allows smaller, more economical robots to be used.

Pneumatic drive technology is widely established at individual actuator level. A compressed air system with an operating pressure of 6 bar is used as standard to operate conventional pneumatic components such as valves, clamping devices, pin pulling cylinders, grippers, welding gun drives and other pneumatic components. Clamping devices

make up a very high proportion of these components: up to 20 000 may be found in a large plant.

In addition to the conventional 6 bar compressed air system, in many cases there is also a high-pressure system that provides operating pressure at a higher level (usually around 12 bar). This high-pressure system is responsible for supplying pressured air to components whose functions rely on particularly high contact forces; for example, welding guns used in resistance spot welding. The two systems are referred to as the low-pressure system (LP) and the high-pressure system (HP).

The figure below shows the pneumatic components that body shops use most frequently. The main identifying feature of a body shop is its wide range of drive technology components whose primary task it is to deliver a certain level of force (clamping devices and grippers, for example). In these, positioning movements that are carried out using a long stroke are rare. Therefore, pneumatics represent a useful technology for body shops



Typical body shop components

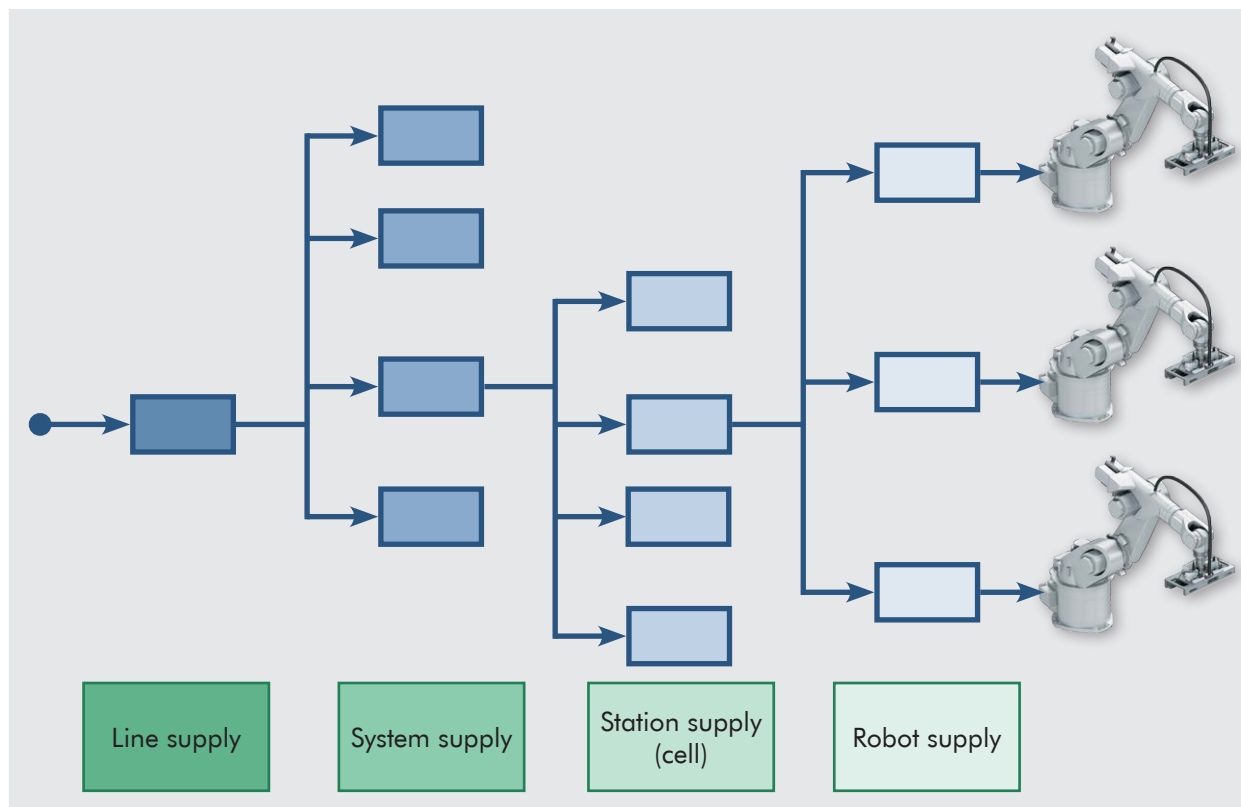
as pneumatic drives allow force to be maintained without extra power over an unlimited period of time (assuming there are no leakages).

What is more, compressed air in body shops has applications beyond simply operating pneumatic components. It can also be used as process air: as a cross-jet in laser welding systems or in a tip dresser for removing chips, for example. When looking at energy efficiency, however, this process air must be disassociated from the consumption of pneumatic components, as there is always a distinction to be drawn between pneumatic drive technology (compressed air acting as the energy medium) and process air (compressed air acting as the flowing medium).

The components used in body manufacturing are put under exceptional levels of strain because of

the sheer frequency of flying sparks. Servopneumatic welding guns do mitigate this by allowing the contact force to be adjusted with greater precision and thus cutting down significantly on sparks and welding spatter, but body manufacturing is still classified as a harsh environment subject to intense strain. Yet despite this, its equipment is still required to offer a long service life: a product life cycle of 10-15 million welding points is expected in the case of welding gun drives.

The figure below shows a typical installation hierarchy of supply points in the body shop. The compressed air is routed to the individual stations (cells) via a line and system supply. Each cell can have multiple supply points. At each robot unit there is also a robot supply point, which supplies the compressed air consumers with air via filters and pressure regulators.

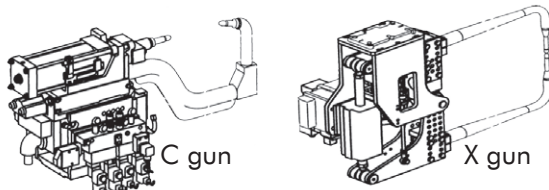


Supply points – transport of compressed air and cooling water (inflow & outflow)



### 3.2.2 Welding gun technology

The individual components of a car body are joined to one another in various systems by applying welding points. Welding guns are used for this purpose, and come in two different designs: the C gun and the X gun. In the case of C guns, the electrode is moved directly by a linear drive; in X guns, meanwhile, a lever mechanism transfers the movement to the electrodes.

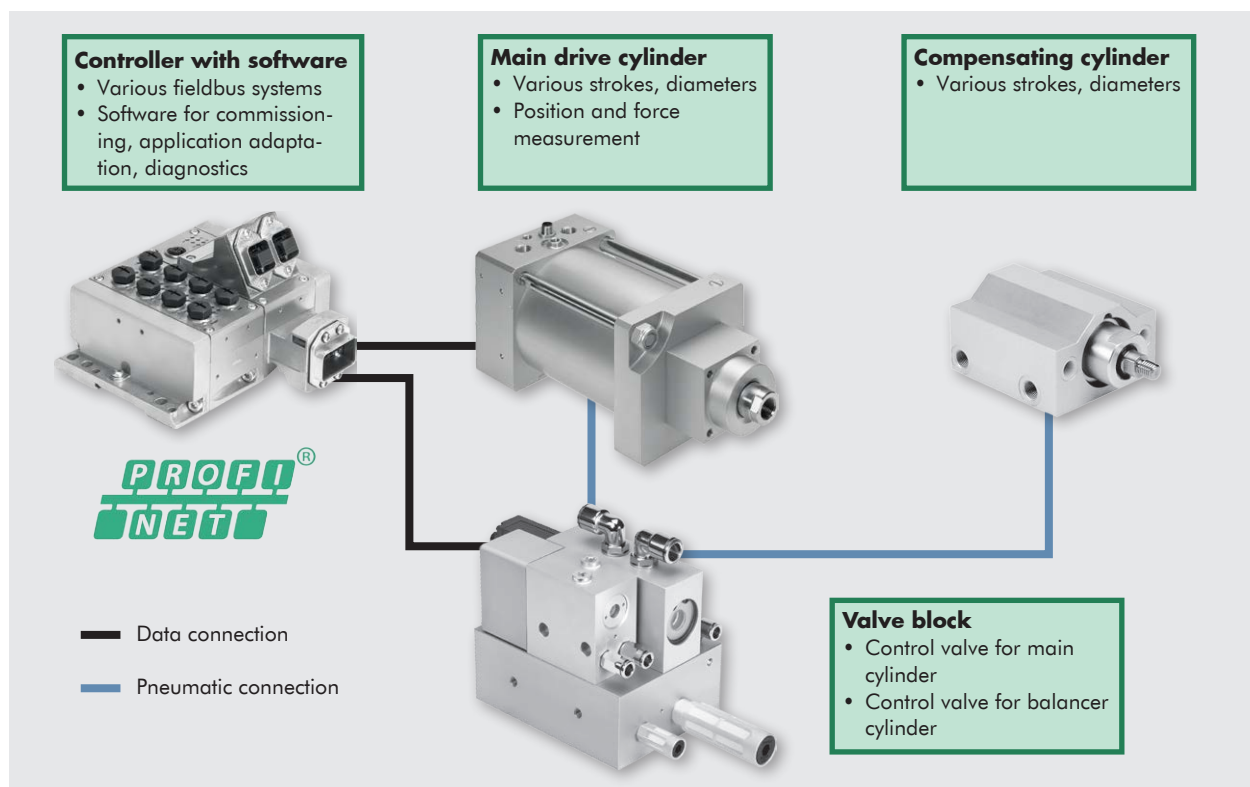


Welding gun designs

As far as drive technology is concerned, there are two basic types: standard drive technology (controlled point-to-point movement) and servo tech-

nology that features position and force control. The latter is gaining an increasingly higher profile, as servo drives enable targeted control of both positioning and force: for example, they can be used to execute shorter positioning operations, which in turn cut down on energy consumption. Not only that, but applying force in a controlled manner also results in higher-quality welding points, enables better control over the process, and produces less noise.

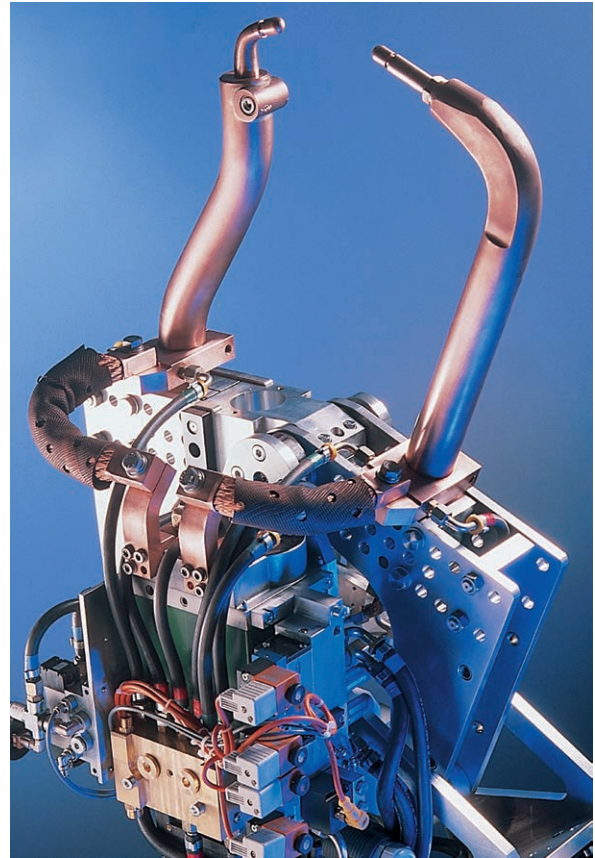
Both electrical and pneumatically driven welding guns can be used for servo technology applications – and both have their own specific advantages and disadvantages. The table on the next page looks at how the technological aspects and economic efficiency of each option measure up to one another. It is, however, generally true that electrical drives demonstrate the lowest energy consumption levels, while servopneumatics offer performance benefits, are a more compact option and incur lower total costs.



Structure of a servopneumatic drive system

Given that this project's main concerns are analysing the efficiency of pneumatic components and optimising them, the information in subsequent chapters will primarily look at pneumatically operated welding guns.

High contact forces are required during the welding process. This is why welding guns are usually operated at 12 bar in a high-pressure system, which is installed as an addition to the conventional compressed air system (generally 6 bar). The expense of operating a second compressed air system may seem too great, so alternative concepts are often considered as a result: for example, using electrical welding guns and discarding the high-pressure system altogether, or reaching a compromise by operating a single compressed air system with an intermediate pressure level (e.g. 8 bar). This is technically a viable option if the level of force that has to be generated at a low level of pressure is similar to the level with a high-pressure system, but it does require the use of pneumatic drives with a large cylinder diameter, thus increasing the weight of the components and impacting negatively on performance. Therefore, taking this approach eliminates one of the key advantages of servopneumatics. Chapter 4.2 explains the options that are available and what makes economic sense.



Pneumatic X welding gun

Feature	Standard pneum.	Servo pneum.	Servo electr.
Price	++	+	0
Weight, size	+	+	-
Commissioning effort	++	+	0
Performance, speed	+	++	+
Achievable force	+	+	++
Energy costs	0	0	+
Noise	-	+	++
Safety, diagnostics	0	+	+
Reliability	-	+	+
Maintenance effort	+	+	0
Training required	++	+	+

## 3.3 Analysing compressed air supply

### 3.3.1 The compressor station

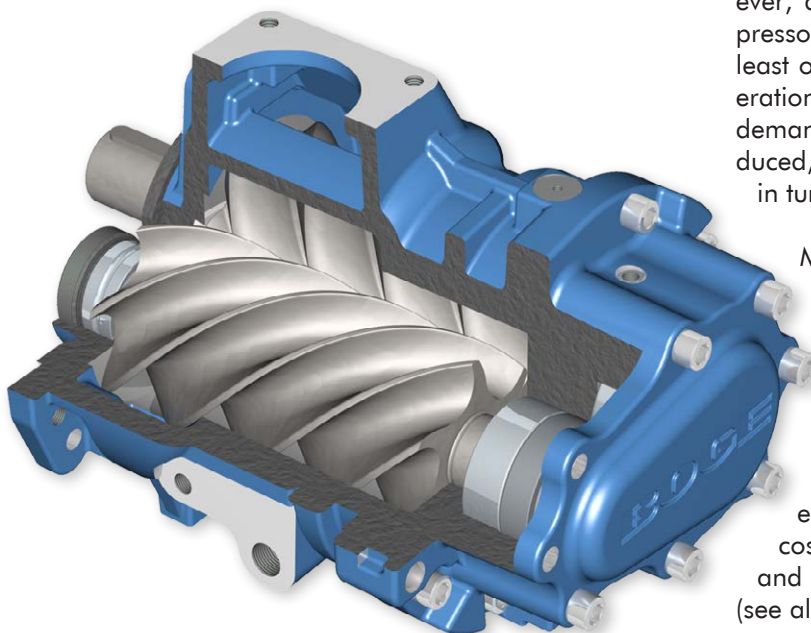
The compressor station is at the heart of a compressed air system. Around 80% of the overall costs associated with a compressor system relate to energy. They therefore have a major influence on the economy of the system.

There is a range of different compressor designs to suit the pressure level and delivery rate requirements of the application concerned. Turbo compressors or oil-free screw compressors are generally the compressors of choice, however: these are ideal in cases involving high levels of compressed air demand and continuous consumption. Turbo compressors are among the dynamic variety of compressors, which have running wheels equipped with blades to accelerate the flow of gas being compressed. Guide vanes that are fixed to the blades convert the velocity energy into pressure energy; these should be used wherever possible in applications involving high delivery rates. Higher pressure stages are achieved by means of multi-stage compression.

Screw compressors belong to the family known as rotating displacement compressors. Two parallel rotary pistons with different profiles work in oppo-

site directions to one another within a single housing, as illustrated in the figure below. The air that is absorbed by the compressor stage is compressed while it is being transported to the pressure joint, until it reaches the ultimate pressure level, and is then discharged. In the case of oil-free screw compressors – where the air being compressed does not come into contact with oil in the pressure chamber – the two rotors are connected by a synchronised gear in a way that prevents the profile surfaces from touching. Plants that require a great deal of compressed air sometimes use multi-stage turbo compressors that feature very high levels of drive power. The power consumption of a single station may reach as much as 2.8 MW in places.

In many cases, compressors also work at a constant rotational speed, which means that it is not possible to adjust the delivery rate. Additionally, because of their sluggish start-up and shut-down characteristics as well as their load limits, compressors cannot simply be switched on and off as often as the operator wishes. The only way to bring about (minor) adjustments in the delivery rate is to change the cross-section at the inlet opening. This also means that conventional compressors do not support a start/stop control method for adjusting the delivery rate to the air consumption. If, however, an application is using several small compressors and the peak load is being covered by at least one speed-regulated compressor, then generation can be adapted flexibly in line with current demand. The station's pressure range can be reduced, and the station will operate more efficiently in turn.



Sectional view of a screw compressor

Measurements have been taken to show the compressed air consumption of production facilities in a factory area that is typical of a body shop environment. Consumption in the high-pressure system measures around 4800 Nm<sup>3</sup>/h, while in the low-pressure system it is somewhat lower, at roughly 3900 Nm<sup>3</sup>/h. If we assume a three-shift operation scenario, this will lead to generation costs of approximately 830 000 euros per year and production hall during productive periods (see also Appendix 8.2 on page 66).

It is possible to determine the idle consumption of a factory area during idle times (weekends, for instance). This may equate to as much as 35% of the compressed air consumption that takes place during production – a figure that may seem excessive, but is in fact very realistic for older installations with complex topologies. If nothing is put in place to combat this, plants could encounter a worst-case scenario where idle air consumption incurs costs beyond 100 000 euros per hall and year.

However, let us now consider the alternative: an idle consumption level of around 15% in a modern, well-maintained system. Reducing total air consumption by roughly 20% would be feasible in this case, even if it would involve a great deal of technical work. Taking this approach would reduce air consumption during both idle periods and production, and would therefore result in cost savings of approximately 200 000 euros annually in a typical production hall.

Due to thermodynamics, a large amount of heat is produced during the compression process. It can be recovered centrally at the compressor station via heat exchangers and put to good use. For example, waste heat can be used for heating the building or process water, which saves heating energy elsewhere and increases the energy efficiency of the entire production system.

Many older production facilities have no integrated heat recovery system. Instead, the heat is simply dissipated by means of water cooling and escapes into the environment unused. Measurements have revealed that the amount of heat produced in a typical plant can reach around 40 000 kWh per day. If we assume that as much as 90% of this heat could be used in a recovery system, this results in potential cost savings of 350 000 euros annually even when compared to a district heating network (3 ct/kWh) – a system that is seen as very economical. What is more, the fact that less strain is being put on the conventional water cooling system allows further savings to be made.

### 3.3.2 Pipe network topology

The structure of a plant is a crucial factor in deciding which topology to use. Older plants that have undergone continuous expansion over a long period are particularly likely to have less-than-ideal topologies, as these will often have grown with the plant, creating a complex picture – and making them even more difficult to understand if parts of them are underground.

Large plants frequently use multiple generator stations that can be installed separately with large distances between them. While this creates a more reliable compressed air supply, it also makes it more difficult to coordinate the individual compressors in an appropriate way that makes optimum use of energy. Not only this, but the quantity of air that is generated cannot be explicitly allocated to particular consumers either. For these reasons, installing a flow sensor at the supply point of a production hall, for example, is recommended.

### 3.3.3 Conclusions

It is an unfortunate truth that inadequate volumetric flow rate control, unused heat and relatively high idle air consumption are all typical features of the systems installed today. Deficient operating statuses and high energy losses are usually down to a lack of transparency, itself the result of a failure to provide measured data. Despite this, compressed air generation and distribution cannot be consigned to an ultimate verdict of inefficiency. If the right measures are put in place, energy losses are largely preventable.

Using a heat recovery system opens up a great deal of potential for optimisation. Generating compressed air according to need – in other words, avoiding idling time – preventing leakages and having professional maintenance work done are all encouraging methods that can be applied to the majority of stations and production plants.



## 3.4 Analysing consumers

Analyses of compressed air applications in the automotive industry have revealed that demand for compressed air can occupy a considerable proportion of a plant's energy expenditure. A typical automotive plant may require approximately 15000Nm<sup>3</sup>/h of compressed air during periods of production. Assuming three-shift operation and with idle consumption taken into account, this results in annual consumption of 100 million Nm<sup>3</sup>.

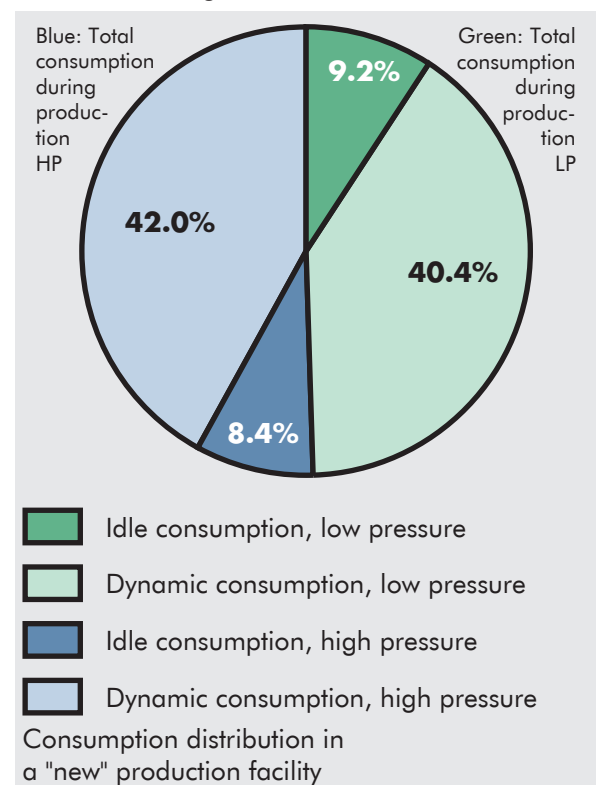
At an average generation cost of 1.5ct/Nm<sup>3</sup>, it takes 1.6 million euros annually to generate the required compressed air.

Most of the compressed air required in the automotive industry is not being used in pneumatic applications to carry out mechanical work, however, but instead as active air (in the paint shop, for example) or for other purposes. Although no solid investigations in this area have been conducted as yet, we can assume that around 30% of the total compressed air is being used to operate pneumatic actuators (such as valves, drives, clamping devices, welding guns and pin pulling cylinders). In a representative plant, this proportion of compressed air consumption would equate to a financial outlay of around 480 000 euros.

### 3.4.1 Pneumatic consumers

With the aim of building up a picture of the energy consumption within individual production facilities in a body shop, extensive measurements were performed in several selected facilities. By evaluating these measures, it was hoped that the primary consumers could be identified and, as a result, appropriate measures could be pinpointed as a means of reducing consumption in future facilities. The first step in this process was to look at the air consumption of the facility as a whole (both low pressure and high pressure) at the supply point, before taking detailed measurements at individual components in order to refine the results. This analysis has made it possible to learn more about consumption during production and idle phases in both the high-pressure and low-pressure elements of a facility.

A modern production facility was the first to go under the microscope: this had only recently been put into operation and was therefore still relatively new. It contained 345 actuators and had servopneumatically operated welding guns installed rather than conventional versions of this tool. The chart below provides a visual overview of consumption distribution here. It shows that around half of the air consumption occurred during the production phases due to components in the low-pressure system (green), while the other half was due to high-pressure components (blue). When the facility was idle, air consumption dropped to around one-fifth of the consumption recorded during the production phases. This idle consumption was due to leakage as well as consumers such as air blast nozzles not being switched off.

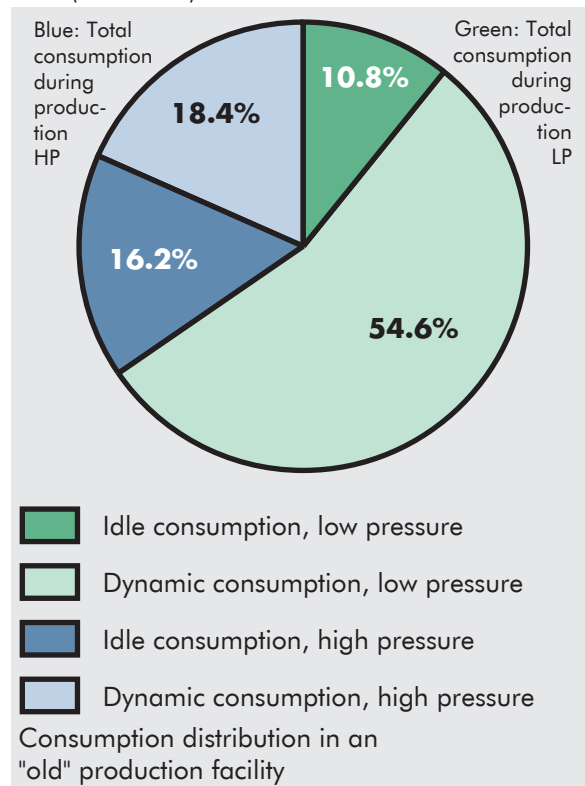


The total idle consumption amounts to 17.6%, a value that is relatively low for a typical facility. It is therefore possible to say with confidence that the facility only has a few leakage points, and this in turn allows us to conclude that the pneumatic installation is of a high standard.



However, experience has shown that the results of this process cannot be applied globally to all facilities. The investigations also looked at a second, somewhat older facility containing 72 actuators in a low-pressure system and 8 conventional welding guns in a high-pressure system. This facility did not have any servopneumatic welding guns.

The chart below shows the distribution of the air consumption in this case. Here, the proportion of low-pressure consumption was somewhat higher at approximately 65% (green area), while the high-pressure system accounted for the remaining 35% (blue area).



Air consumption during facility downtime amounted to roughly 27% of the total air consumption. Something that also stood out was the relatively high proportion of idle consumption among high-pressure consumers – specifically, this was almost half as high as consumption during production. This was a sign of a large number of leakages in this part of the facility. In this one specific area, it was possible to reduce the facility's air consumption by 12% in no time at all simply by performing an inspection, then eliminating the leakages.

Besides investigating the compressed air consumption of body manufacturing facilities, it is also possible to analyse individual pneumatic components to get a detailed picture of consumption behaviour. Not only can this method verify facility consumption values, but the results can also be used to create a data base for extrapolating consumption figures in comparable facilities.

Generally speaking, most pneumatic components are clamping cylinders, pin pulling cylinders or welding guns. In the high-pressure system, it is pneumatic welding guns that account for all consumption.

The dynamic high-pressure consumption of the facility can be used to calculate the compressed air demand per welding point if the number of welding points per part and the system output per hour are known. In the facility under analysis, it was determined that a conventional welding gun results in air consumption of 20NI to 35NI per welding point depending on the type, size and force of the gun. Therefore, the energy costs associated with 1000 welding points fall between 36 ct and 63 ct.

Shorter strokes can be executed with servopneumatic welding guns if required, which has a positive effect on air consumption: between 7NI and 20NI per welding point, depending on the type of gun. In this case the energy costs associated with 1000 welding points fall between 13 ct and 36 ct. Individual measurements taken directly on the servo welding guns confirm these results.

It should, however, be mentioned that servopneumatic welding guns have a certain idle consumption, which can be a significant contributor to air consumption during lengthy downtimes. This idle consumption is 10NI/min to 20NI/min depending on the type of gun. In facilities that experience lengthy downtimes, switching off the air supply is therefore a useful energy-saving measure, particularly when using servopneumatic welding guns.

Appendices 8.3 and 8.4 on page 66 contain a detailed summary of the data presented here.

## 4.1 Factory planning in body shop areas

Compressed air technology is a typical example of a field where companies possess this kind of expertise: there is a multitude of suppliers whose standard product range covers items used specifically in body shops, such as clamping and positioning units, tubes, and valves. The equipment bills of materials containing these purchased parts are drawn up at the same time as the design drawings, as are the installation diagrams. In the case of compressed air technology, this means pneumatic diagrams; these also tie in with the control technology as they specify exactly which signals will trigger switching of the pneumatic valves (see figure at the bottom of page 30).

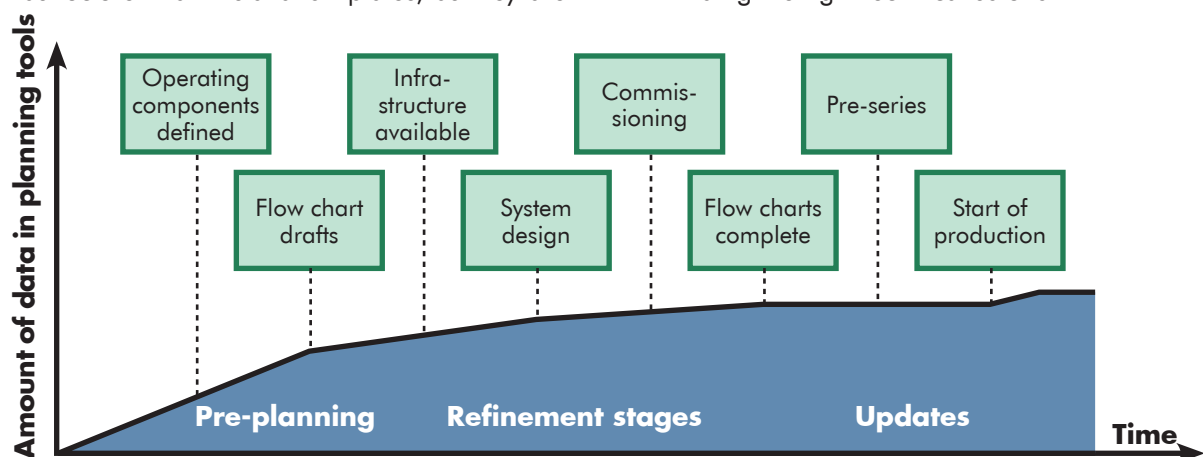
Once the processes and equipment are known, it is then possible to develop the system layout. This defines where the items of equipment are positioned in relation to one another, and thus also determines the shape and size of each space required for them. It goes without saying that they should take up as little space as possible, with the parts arranged in a way that makes the most logical sense – and with the applicable safety requirements adhered to as well. The intended location in the actual factory hall may pose additional restrictions such as the column grid specifications, supply connection points for operating media and routes for logistics activities. What is more, the system layout has to take into account any internal supply lines and robot changeover concepts. The compressed air components in the system are usually supplied by a small number of connection terminals that may also accommodate pressure reducers and filters. Before this point, the compressed air technology is dealt with as part of the factory infrastructure. Hall installation plates, as they are

known, establish a link between the factory and the system; as such, they are also a key tool in helping infrastructure and system planners coordinate their activities.

The main outcomes of system planning that require documentation are:

- Process plans
- Equipment bill of materials
- Design data for fixtures and tools
- Control technology concept
- System layout
- Connection diagrams for establishing links to the operational infrastructure

Special software is used to create these documents. Pinpointing exactly the right solutions relies on something different, however: creative ability and the benefit of experience, and there is no software that can provide these particular skills as yet. A digital factory program is used to integrate the infrastructure and consumer planning for the compressed air technology into the Product-Process-Resource model. As this tool tends to focus on simply describing information rather than active planning, however, it is also important to establish a more structured, proactive process (which may also be aided by software) that starts as early as the technology sizing stage. This allows system and infrastructure planners to identify safety factors, for example, and thus avoid being faced with a sudden glut of them further on in the process. The information in the next sections of this document will show how scenarios can serve as a basis for systematic sizing, and what role software can play in finding the right technical solution.



Procedure and amount of data in the factory planning process



#### 4.1.2 The InnoCaT reference factory

In the InnoCaT alliance consortium, data and parameters were gathered for a typical car factory and coordinated between the partners from the different areas. This led to the creation of a fictional InnoCaT reference factory, which reflects the typical characteristics of car factories as a benchmark model.

The information from the factory as a whole can be used to demonstrate elements of energy usage that add value, as well as areas where it is only playing an auxiliary role or is not productive (e.g. in lighting, ventilation, idle consumption or stand-by facilities). In each case, the consumption is extrapolated to reflect the extent of a typical car body and the production volume of a standard plant. This is carried out by linking operation-specific or part-specific energy demands to product features.

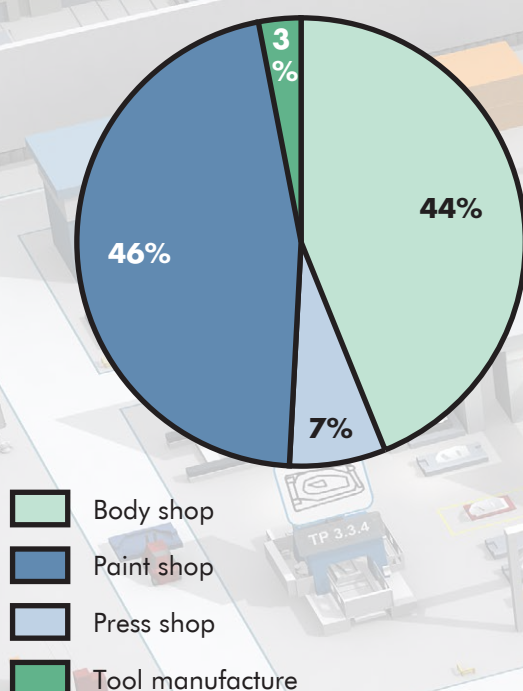
First and foremost, determining energy demand makes it possible to identify how energy consumers in a standard plant are distributed in percentage terms, and gives an impression of the proportions in which different types of energy are consumed. It

also demonstrates areas where savings could be made through facility optimisation and efficient process control: for example, reducing power consumption during stand-by operation or running systems in an energy-efficient way.

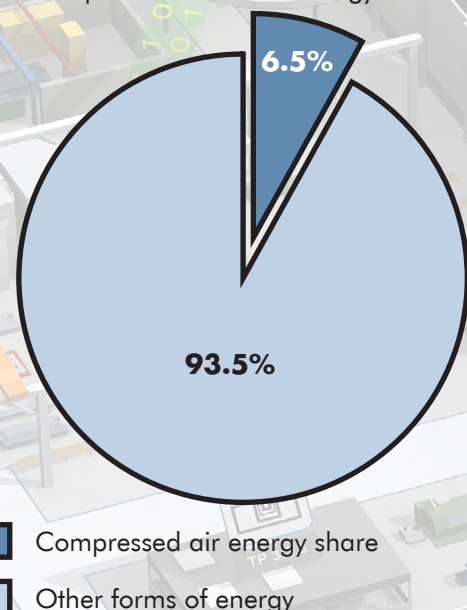
The annual production volume of the reference factory is 250 000 painted car bodies. The reference factory also houses a full tool manufacturing facility whose annual production capacity covers the manufacturing of tools for all outer skin components and special-function structural parts of 1.5 vehicle models.

The total energy consumption analysis yields information on the shares of energy demand attributable to the individual production stations, as shown in the chart on the bottom left. Here it can be seen that the highest energy consumption values are in the body shop (44%) and paint shop (46%). The press shop and tool manufacturing area play only a minor role. Since a great deal of the pneumatic drive technology is found in the body shop, it is this area especially that offers potential for energy-saving measures.

However, it has also been possible to determine that compressed air generation accounts for a share of just 6.5% of total energy consumption



Total energy consumption in the reference factory, distributed among individual production areas



Compressed air accounts for around 6.5% of the total energy consumption in the reference factory



for the reference factory (see second chart). The majority of energy consumption is due to electricity demand in the production stations – mainly in order to operate electric motors in equipment such as industrial robots.

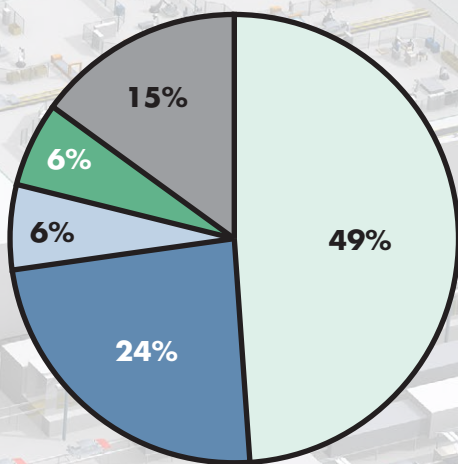
During the course of these analyses, total consumption of approximately 100 million Nm<sup>3</sup> or

400 Nm<sup>3</sup> per car body produced was calculated. Most of this resulted from the use of compressed air in the body shop (49% or 196Nm<sup>3</sup>). Around a quarter (24%) of the compressed air was attributable to the paint shop, while the press shop and tool manufacturing area were each responsible for 6%. The remaining compressed air consumption (15%) took place in other production areas (see chart on the left).

If we assume that standard quantities of energy are being expended in order to generate compressed air, this results in a whole-plant electricity demand for compressed air generation of around 13 million kWh per year or 52 kWh per car body.

Focusing once again on the body shop, local compressed air demand equates to roughly 26 kWh of energy demand per car body. In total, around 6.4 million kWh of electrical energy are used every year to generate compressed air in the body shop, as compared with 7.2 million kWh/a for other indirect processes (e.g. central cooling water supply), 26.3 million kWh/a for direct processes (electricity demand from robots and other systems) as well as 34.0 million kWh/a of electrical energy required to supply peripheral systems like ventilation, lighting and logistics.

The table below, plus Appendix 8.1 on page 66, contain a summary of the key data from the reference factory.



- Body shop
- Paint shop
- Press shop
- Tool manufacture
- Other areas

Proportional compressed air consumption of the different production stations in the reference factory

	Reference factory	Reference car body
Output	250000 vehicles/a	
Number of welding points	1037 million/a	4150
Electricity demand in production areas	131.4 million kWh/a	512kWh
Total electricity demand incl. infrastructure	206.5 million kWh/a	810kWh
Compressed air demand	100.1 million Nm <sup>3</sup> /a	400Nm <sup>3</sup>
Compressed air demand, body shop only	49 million Nm <sup>3</sup> /a	196Nm <sup>3</sup>
Electricity demand for compressed air in the body shop	6.4 million kWh/a	26kWh



## 4.2 Considering possible system topologies

How efficiently a body shop can use energy is in many ways dictated by the properties of an infrastructure at both plant and hall level. Does this need both a high-pressure and a low-pressure system? Would one single system be enough? These are examples of questions that have to be raised when planning a new plant. What is more, they have to be answered at an early stage of planning, long before the details of the production systems and their components are filled in.

Planning a production site and its infrastructure brings with it a range of conceivable scenarios, which the next sections will explore and evaluate systematically. As part of this, they will focus on high-pressure systems and the welding guns supplied by these. The scenarios presented here have already been verified with the input of various car manufacturers as well as the "Green Carbody" innovation alliance. This means that they represent typical scenarios, although it should be noted that the calculations are still just examples. Therefore, the scenarios and their values will need to be adapted to the specific conditions of the application concerned.

The primary purpose of comparing different scenarios is to determine how best to coordinate compressed air generation, distribution and consumption in a new plant from the perspective of energy costs and total cost of ownership (TCO).

**Scenario 1:** The plant is intended to have both a low-pressure system (6 bar) and a second, high-pressure compressed air system (12 bar). The conventional pneumatic drives (clamping devices, pin pulling cylinders) will be supplied from the low-pressure system, whilst all the welding gun drives will be supplied from the high-pressure system.

**Scenario 2:** Only one compressed air system is planned, with a pressure level of 8 bar – a compromise between low pressure and high pressure. All the pneumatic components (welding gun drives and standard consumers) will be supplied from this system. If the pressure level is not sufficient for some welding gun drives, these will be modified (e.g. using drives with a larger cylinder diameter). The investment costs associated with these components may be higher.

**Scenario 3:** Only a 6 bar low-pressure system will be used. All components will be supplied from this system. If the pressure force is not sufficient for operating the welding gun drives, these will need to increase in size.

**Scenario 4:** As with scenario 3, only a 6 bar low-pressure system will be used. All conventional pneumatic components will be supplied from this system. Any welding guns whose pressure force is insufficient during pneumatic operation will be replaced with electric drive technology.

**Scenario 5:** As with scenario 4, only a 6 bar low-pressure system will be used. All conventional pneumatic components will be supplied from this system. The welding guns will be entirely electrically operated.

The calculations below assume a new planning case rather than retrofitting or conversion. The following parameters apply to the scenario evaluation:

1. A typical new plant has 2 to 3 body shop halls operating a total of around 500 welding guns. Larger plants may contain up to 1000 welding guns.
2. Equal proportions of X guns and C guns are used. It is assumed that 60% of the pneumatic welding guns could be operated with a standard pressure of 6 bar, while a higher pressure level of 8 bar would be required for 20% of them and the remaining 20% would use a supply pressure of 10 bar.
3. The C guns and X guns have drives of different sizes as well as different travel cycles. For this reason, detailed consumption measurements were taken on different C and X guns using various reference cycles, and the data was calculated on this basis.
4. Welding gun drives have a service life of approximately 10-15 million welding points.
5. They are typically used in three-shift operation.
6. One welding gun can apply around 500 welding points per hour. Assuming three-shift operation, this equates to 12000 welding points each day.
7. 4150 welding points are applied in a typical car.

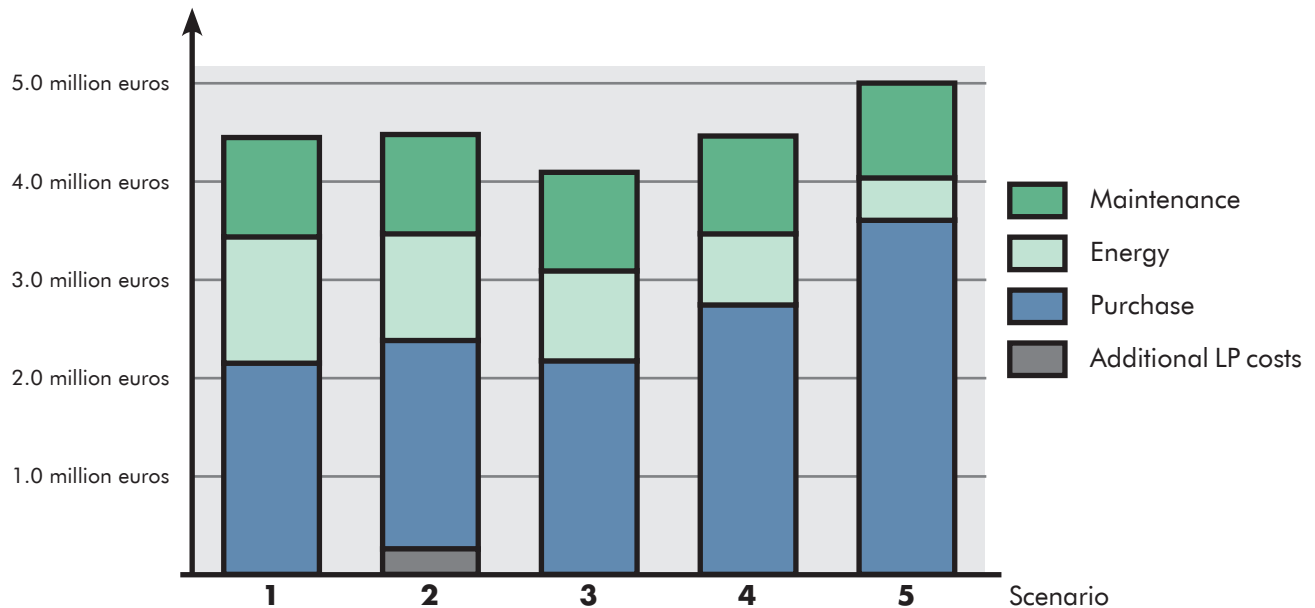
8. The total cost of ownership has to consider maintenance costs as well as costs associated with investing in replacement guns, which usually account for 20% to 40% of the total requirements nowadays.
9. Maintenance costs include the outlay required for updating and servicing the infrastructure (compressors, for example) as well as an estimated amount for the maintenance costs of the drives themselves.
10. To account for energy costs and compressed air costs (in the form of electricity demand), values that are typical for German industry were used. As German car makers invest large amounts in Asia and America, energy costs will need to be adapted to regional conditions in such cases.
11. The costs for operating the low-pressure system are the same in all the scenarios, which means that only the part of the installation required for operating the welding gun technology is considered.

The table below contains an overview of the scenarios that have been investigated.

In the information that follows, the total cost of ownership (TCO) incurred over a typical service life of 5 years is compared in the various scenarios. The TCO is made up of the investment costs, energy costs and maintenance costs. To ensure the point of comparison is kept simple, all the costs are relative to the drive technology only. The investment costs associated with the mechanical system, peripheral welding gun equipment and welding control technology are not considered to be linked to the drive technology. Energy costs for the welding process, water cooling and so on are also disassociated from the drive technology, which is why they are not listed.

The figure on the next page contains a comparison of the total cost of ownership relative to each of the scenarios. All five scenarios use a conventional low-pressure system; therefore, no explicit consideration has been given to the system type. As the pressure level of the low-pressure system in scenario 2 is different (8 bar instead of 6 bar) and this factor also affects the conventional low-pressure components (such as clamping devices and pin pulling cylinders), this particular costing starts with a proportion attributed to additional low-pressure costs.

Scenario	Structure of compressed air system	Components
1	12 bar system 6 bar system	100% pneumatic welding gun drives (12 bar) Low-pressure components in the 6 bar system
2	8 bar system	80% pneumatic welding gun drives (8 bar) 20% modified pneumatic welding guns (8 bar) Low-pressure components in the 8 bar system
3	6 bar system	60% pneumatic welding gun drives (6 bar) 40% modified pneumatic welding guns (6 bar) Low-pressure components in the 6 bar system
4	6 bar system	60% pneumatic welding gun drives (6 bar) 40% electric welding guns Low-pressure components in the 6 bar system
5	6 bar system	100% electric welding gun drives Low-pressure components in the 6 bar system



Total cost of ownership associated with welding in a standard plant after 5 years

It is clear that the proportion of energy attributable to the high-pressure system in the case of pneumatic drives (scenario 1) is around 3 times higher than in the case of servoelectric drives (scenario 5). In total, however, servopneumatic drives incur lower investment and energy costs than servoelectric drives, even after 5 years.

The energy costs associated with operating welding guns in scenarios 2, 3 and 4 are relatively low, but scenario 2 also incurs higher costs for operating the low-pressure system (8 bar instead of 6 bar), which makes the total cost of ownership after 5 years comparatively high.

Scenario 3 proves to be the least expensive option overall as it only uses low-pressure components at a pressure level of 6 bar, which in turn keeps both energy costs and purchase costs low. That said, this is only a feasible option in cases where using a low-pressure network alone will not cause any technical problems when operating any of the pneumatic welding gun drives. Drives that demand a high level of force would have to be modified in such a way that they can be operated reliably even at 6 bar; for example, by using drives with a larger diameter. This, however, would require more space and heavier components, something which

would have a negative impact on the load weight and, therefore, the electrical energy consumption and dynamic response of the robots being used. Given this, it is clear that scenarios have to be considered on a case-by-case basis to ensure that they really are a viable option.

Generally speaking, it is evident that the cost differences between scenarios 1 to 4 are – at no more than 400 000 euros over 5 years – reasonably low. Even using two pressure systems (as in scenario 1) does not bring with it any remarkably high costs. Therefore, there is nothing to suggest that simply discarding the option of a high-pressure system across the board would result in low-cost, optimised operation over the long term.

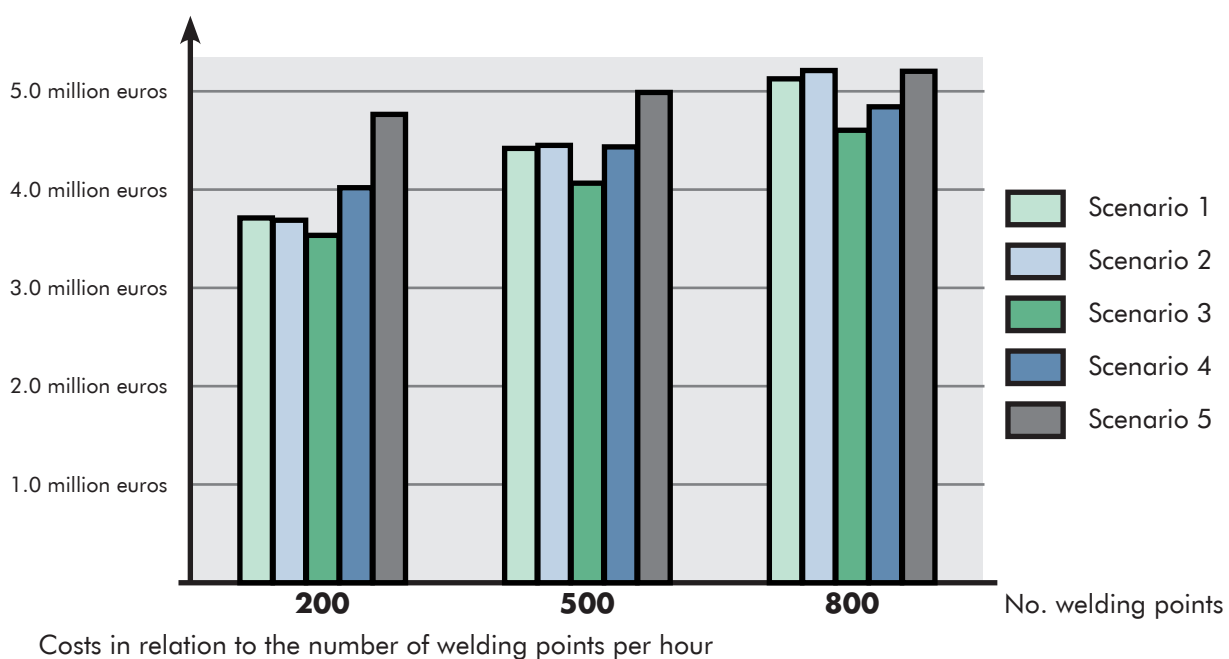
The conclusions we can draw from comparing these scenarios depend on how heavy a workload the components are expected to bear. So far it has been assumed that a welding gun demonstrates a typical cycle rate of 500 welding points per hour. The figure on the right illustrates how the total cost of ownership changes if the number of welding points is varied, however. If it is reduced to 200, the differences between the total cost of ownership associated with scenarios 1 and 4 become more stark because the investment costs start to domi-

nate. This means that a servoelectric system is not an economical choice in this case. If the number is increased to 800, on the other hand, this improves the economic efficiency of the servoelectric system.

These scenarios illustrate that, from an energy perspective, a servoelectric system is the most ideal choice. If we consider total cost of ownership, however, a pneumatic solution is more economical – even where this includes investment in a high-pressure system. This costing already allows for idle consumption in the pneumatic drives (which could be prevented by energy-saving switching operations). It is also assumed that the high-pressure system is being used exclusively for the welding gun drives, not for any other consumers. Additionally, it should be considered that regular maintenance would be required in this case to prevent leakages.

Compared with investments in pneumatic drives, the purchase costs associated with a compressor station are virtually insignificant: this much is clear from the minor differences between purchase costs in scenarios 1 to 4. As a general rule, a compressed air system's efficiency will decline as the pressure level rises but increase if the system grows in size.

An alternative to two compressed air systems would be to use a single low-pressure system and install local pressure boosters as a means of increasing the pressure level as required at selected points in certain systems. In this case a pressure booster acts as a further compressor that is electrically operated and compresses the compressed air from the low-pressure network until it reaches a higher pressure level. The specific power consumption of local pressure boosters (including the energy expended in order to generate the required low-pressure air) is comparable with the power consumption of a central high-pressure compressor. From an energy perspective, therefore, no savings would be made by using decentralised compressed air generation. This option has the drawback of higher investment costs, however (because there are several individual systems); additionally, it does not allow the compressed air generation system to be linked to a central heat recovery system. Generating compressed air in a central compressor station allows as much as 94% of the electrical energy expended to be recovered as usable process heat in a heat recovery system. This can compensate for much of the heating costs incurred at the plant. Using decentralised compressors eliminates this option and, in turn, has a negative effect on the efficiency of the installation as a whole.



## 4.3 Where it all starts: Consumer planning

At first glance, planning compressed air systems may seem to be a reasonably straightforward exercise: simply identify the right compressor station based on an estimate of the application's air consumption and install the appropriate distribution system.

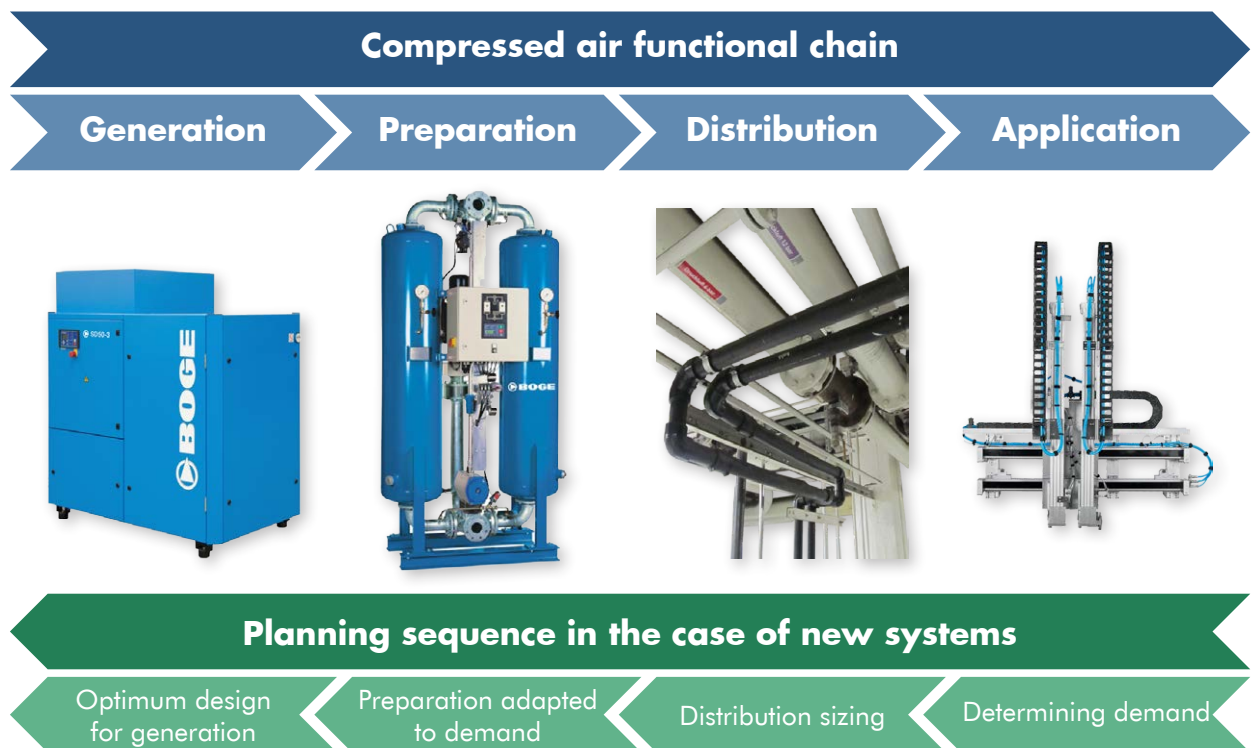
In many cases it is easy to determine the system pressure requirements and compressed air quality on the basis of operational data from production facilities. Compressed air demand, on the other hand, cannot usually be determined in any specific way, only estimated using rough empirical values; this often involves extrapolation based on the demand of existing facilities.

This method can pose a not inconsiderable risk to the planning process if it is coupled with a lack of experience or a failure to take certain factors into account. At worst, the actual demand may outstrip the planned values and significant financial resources may have to be ploughed in to compensate.

This is why very high safety factors are frequently built into the process at various points. While this measure does reduce the risk of undersupply, it also inevitably leads to oversized systems that are often highly inefficient. As a result, much of the potential for creating an efficient compressed air system can simply be wasted early on through a failure to align generation with consumption.

Ideally, planning should be carried out with due consideration given to the actual compressed air functional chain. This requires a bottom-up approach that enables the distribution system and compressed air generation system being installed to be sized on the basis of detailed planning around consumers.

With this in mind, a sufficiently detailed consumer plan should be drawn up as the starting point for creating an efficient compressed air system. For this to happen, the required production resources have to be examined in advance and a media requirements plan drawn up at component and system level. This is the only way to ensure that all the links in the compressed air functional chain have the most ideal sizing.



Planning sequence



This requirements planning also makes it possible to determine which points in the factory require certain media and adapt the required infrastructure to demand in the best way possible. This makes it possible to avoid undersupplies and impermissible pressure drops in areas with high levels of air demand. What is more, ensuring that the distribution system and the local media demands are coordinated early on has the advantage of enabling pipelines, valves and fittings to be sized exactly as required in many areas, making immediate savings in investment costs.

When planning the compressor station too, it is absolutely essential to have a sufficiently precise idea of the compressed air demand, as this is the only way to ensure that the right number, performance grading and type of compressors will be used, and that the compressed air for them can be prepared as required. Here the aim is to maximise operational time under load and keep idling time to a minimum. If the control systems and compressed air reservoirs are working in harmony, this will allow the delivery rate to adapt to fluctuating compressed air demand.

Furthermore, if compressed air distribution plans are already in place, the compressor station can be positioned in exactly the right place and linked to the compressed air system to maximum effect. This also opens up the opportunity of making better use of the heat that is produced (heat recovery) by feeding it into the hot air heating system or hot water system, for example, or even using it as process heat. If heat recovery is not possible – or not required – then appropriate ventilation measures have to be put in place to ensure that the heat is dissipated reliably.

The work involved in designing the compressor station might come right at the end of the planning process, but it is actually where the compressed air functional chain starts. This means that any steps taken to optimise compressed air generation will have a knock-on effect on the entire compressed air system. Therefore, this work sets the stage for creating an efficient compressed air system. Precision planning is the only way to ensure that all the links in the compressed air functional chain have the most ideal sizing and are working in harmony.

### 4.3.1 Automotive production

Compressed air consumption in automotive production is relatively high compared with other industries. The majority of compressed air is used as active air: in paint shops, for instance, this acts as the carrier medium for the paint particles being distributed.

Process air, too, accounts for a large share of air consumption: to take some examples, it can be used as sealing air to prevent contamination, or in cross-jets to protect focussing optics during laser welding. In this case, the compressed air jet is directed onto the welding point by a nozzle, with the flow direction at right angles to the laser beam, thus efficiently deflecting any spatters of molten metal or other particles that are produced during the welding process.

The degree of automation in automotive production is also relatively high. For this reason, much of the compressed air consumption relates to pneumatic drive components as well as gripping and clamping technology. Besides these automated production processes, there is some manual work performed using pneumatic tools, although it is difficult to build up a full picture of the consumption figures for this – and difficult to plan accordingly.

As some systems demonstrate exceptionally high air consumption levels during production, the consumption figures are subject to significant fluctuations in places. Therefore, breaking down consumption into base, medium and peak load consumption is a useful way of selecting suitable compressors as well as planning the compressor station and integrated control system.

## 5.1 Compressed air generation

# 5

This chapter will look at measures for boosting energy efficiency throughout the compressed air functional chain, covering everything from compressed air generation, preparation and distribution all the way through to application. Compressed air generation is right at the start of the functional chain; therefore, developing the right plans at this stage will lay the foundations for an installation that is efficient through and through. This work involves setting out specifications for compressor and drying unit types, their control systems and interconnections with one another, as well as the installation as a whole. As almost every compressed air station is subject to different conditions, it is essential to consider all the requirements and influences on the system. This creates a very complex task for the compressed air expert.

As an initial step, several basic parameters have to be determined so that appropriate compressors, compressed air preparation systems and reservoir systems can be selected. Once the compressed air generation requirements have been clarified (the delivery rate, pressure level, compressed air quality and consumption profile, for instance), there are yet more questions to be answered: what is the required availability of the compressors and drying units? Will the system use oil-free or oil-lubricated generation? Is heat recovery an option, and if so, what are the temperature requirements? Are there areas that may occasionally require no compressed air and could therefore be switched off? How realistic are the load profiles? Given this glut of information, there is the risk of even experienced compressed air experts inadvertently letting errors creep in. This is why there are various checklists, expert programs and guides that allow every influential factor to be included in the deliberations and plans.

Achieving maximum availability whilst consuming the least possible energy per generated quantity of compressed air, and ensuring the best possible heat recovery, is the ultimate goal in all this.

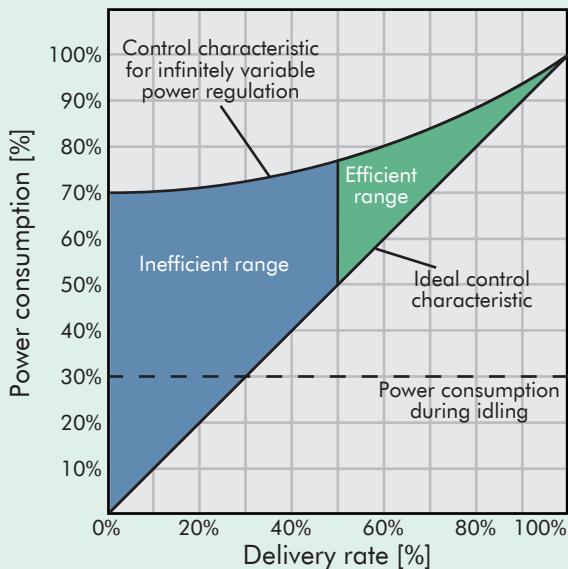
### 5.1.1 Speed regulation

Conventional compressors are operated at a fixed speed. This means that the compressed air delivery rate is largely defined as well. If there are fluctuations in the air consumption, the compressors are first switched to idle operation and then turned off entirely after a certain period. There are two reasons for this. First, like a power station network, a compressor system has to react quickly to fluctuating energy consumption in a compressed air system to prevent the system pressure from dropping. It can do this more efficiently if the compressor is able to switch rapidly from idling to active and there are no lengthy starting times. Second, excessively frequent switch-on and switch-off operations must be avoided: large electric motors, in particular, are prone to overheating if they are simply switched on and off as often as desired. Idle operation, however, still needs a reasonably large amount of electrical energy, and this will go unused if compressed air is not generated accordingly. This has a negative effect on both the energy balance and the compressor station efficiency.

Regulating the motor speed in the compressor allows compressed air to be generated in line with consumption – so idle phases can be largely avoided. The smaller a compressor, the more efficiently it tends to use a speed regulation mechanism. Under ideal conditions, it is possible to keep the system pressure constant at the required level up to 0.1 bar. This prevents the overcompression caused by the difference between switch-on and switch-off pressure in compressors without speed regulation. In turn, it is generally possible to save around 10% energy per 1 bar of excess compression avoided.

Speed is normally regulated using a frequency converter. However, the losses associated with this mean that frequency-regulated compressors are approximately 3 to 5% less efficient at full load than a comparable fixed compressor. With this in mind, regulated compressors should primarily be used to cover fluctuating load ranges, whereas fixed machinery should be used to cover the basic load.

### Facts and figures

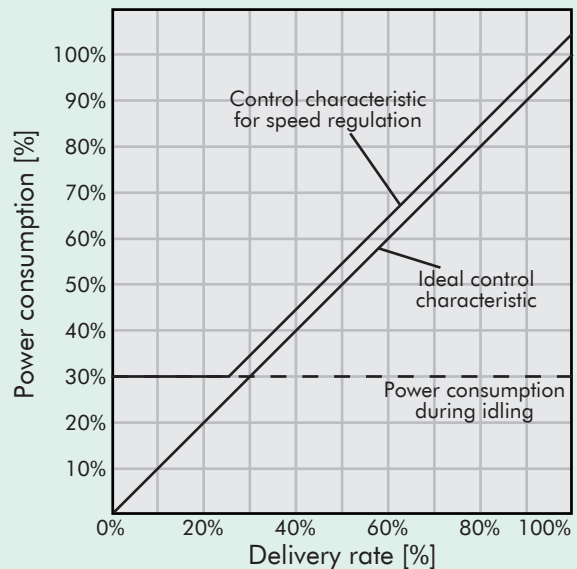


#### Infinitely variable power regulation

Some compressors are equipped with **infinitely variable power regulation**. This regulation method does not change the speed of the electric motor in the compressor, but instead intervenes in the intake regulator processes and operates according to the interphase transformer principle. This enables the actual delivery rate to be adjusted in line with the current pressure demand (see figure at top left).

It makes sense to operate these compressors in a range between 50% and 100% of the maximum delivery rate. At lower delivery rates, the relative power consumption will be too high, which means that compressor will either be switched off or continue to run idle for a certain time.

This method of regulation allows the system pressure to be kept relatively constant, as only what is actually needed is delivered. The equipment for regulating the delivery rate in this way is also comparatively inexpensive and is mainly used for small compressed air containers and situations with significant fluctuations in compressed air demand. When it comes to regulating peak load in a compressor network, however, speed-regulated compressors are a better choice.



#### Speed regulation

**Speed regulation** enables regulation of a very wide range of delivery rates, from 25% up to 100% of the maximum rate (top right-hand figure). However, this case does not quite match up with the ideal line passing through the origin. The converter consumption results in losses of 3% to 5%, with the power consumption higher than the delivery rate by this value. With an efficient regulation system in place, the power consumption lower limit is around 30% as a certain amount of electrical power is required during idling too (without delivery).

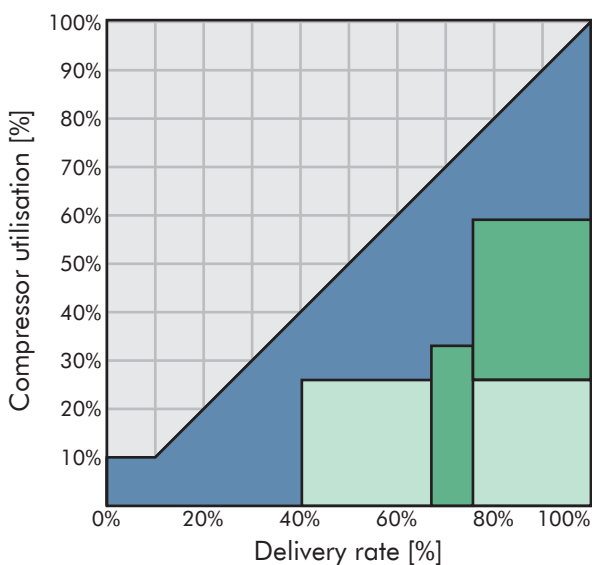
When planning a station, it is essential to consider all aspects of the characteristic in order to avoid any statuses that deviate significantly from the ideal scenario when operating the station.

Using speed regulation can result in considerable energy savings if the right initial conditions are in place. Minimising idling time, reducing losses caused by switching cycles, and adapting the power consumption to the actual delivery rate that is required and supplied are all ways of tapping into potential savings.

### 5.1.2 Optimised compressor control

Sizing a compressor station to suit the application's needs can help prevent unnecessary energy consumption. A compressor station should be designed to allow a range of compressors to operate at basic load and peak load. What this means is that there must not be any gaps in the characteristic curve of the compressor station in which the application is not being regulated properly. Connecting speed-regulated peak load systems avoids consumption caused by the use of larger systems in partial load operation – a situation where energy is not used efficiently. A control system that uses energy in the most efficient way possible can also be used for load distribution in the compressor station. This system has the task of activating or deactivating the appropriate compressors at the correct time and ensuring that the right machines are in operation at all times. This considerably reduces the number of switching operations and the amount of idling losses. Since a well-designed station is essential to an efficient control system, using a station planning tool to identify the most ideal configuration is recommended.

The figure below contains graphical representations of results yielded by different compressor station designs. The X-axis shows the required delivery rate, while the Y-axis uses colour-coding to indicate the compressors that have to be activated

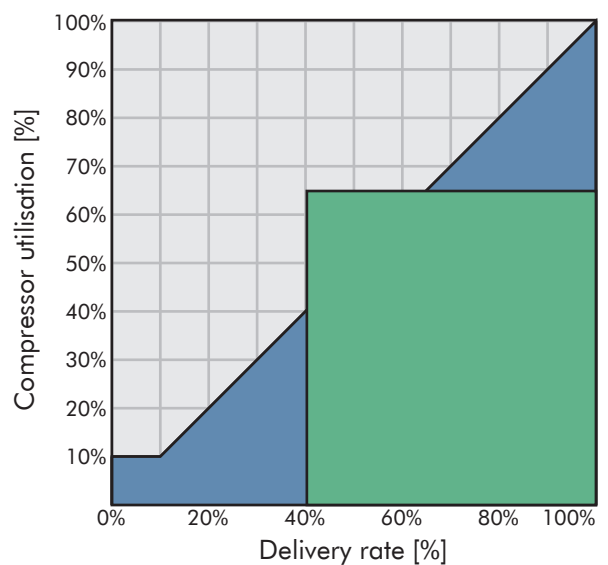


Two designs with different compressors

in each case and their proportional utilisation. The station on the left consists of a regulated compressor (blue) and two smaller fixed compressors (green). In this case it is evident that the higher-order controller is able to select the right configuration so that everything is regulated correctly at all times. The regulated machine (blue) covers the peak load in each case. Compare this setup with the figure on the right, showing a combination of a regulated (blue) and a fixed (green) machine. In the middle load range it is not possible to identify a combination that would cover the required delivery rate precisely. This leads to inadequate regulation, which in turn causes switch-on and switch-off processes that use energy inefficiently, as well as excess compression.

Another advantage of a higher-order controller is that it enables considerably better monitoring. For example, by determining and displaying consumption it is possible to identify the extent of idle consumption caused by leakages – and, therefore, the potential for savings in this area – and take steps to rectify this.

Ideally, a higher-order controller should be installed whenever there are more than two compressors in a station. An optimum design for the station should also be created using planning software as early as the planning phase so that the control system can be implemented to best effect.



### 5.1.3 The compressed air reservoir

The various systems used in a production hall may demand significantly different levels of compressed air. If multiple consumers are active at the same time and conditions become unfavourable, the system pressure may temporarily experience a sharp slump, creating a negative impact on other components.

If there are then attempts to compensate for this by increasing the generation pressure at the compressor station or purchasing additional compressors to adapt the delivery rate, energy demand will rise and the system will become inefficient.

Another way of compensating for pressure fluctuations is to use an adequately sized compressed air container that adopts the role of a reservoir between the compressor station and distribution system. This container covers momentary consumption peaks and creates a smoothing effect. Depending on the structure of the distribution system, it may also make sense to provide a container for smoothing local pressure fluctuations in the case of applications with highly fluctuating air consumption.



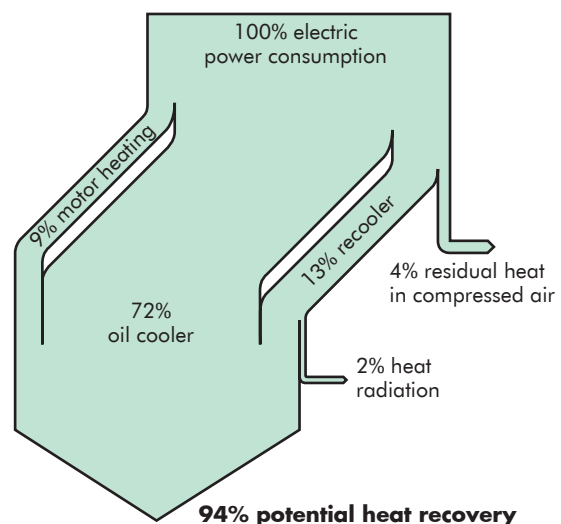
Calculating the dynamic behaviour of the system pressure and consumption is a complicated task whose solutions cannot usually be produced using simple calculation templates or empirical formulae. Ideally, and if the topology and consumption behaviour are known, an appropriate software tool should be used to plan the size of a suitable container and where the buffers should be located.

### 5.1.4 Heat recovery

When air is compressed, a lot of the heat development occurs in the compressed air chain due to thermodynamics. For this reason, integrating a heat recovery system is a key factor in boosting the energy efficiency of compressed air systems. As the diagram at the bottom shows, as much as 94% of expended electrical energy can be recovered as heat and put to good use.

Particularly in larger facilities, waste heat can go on to be useful heat for heating rooms or industrial water, for instance, or acting as process heat. Heat that is produced can also be used to generate a source of cooling in adsorption refrigeration machines; for example, to provide rooms with air conditioning in summer. Consistently using waste heat in this way goes a long way towards improving overall efficiency.

In the scenario calculation demonstrated in Chapter 4.2, heat recovery was not specifically considered as it is not possible to make good use of heat that is produced in every plant. It should, however, be taken into account whenever a new production facility is being planned. Assuming the investment costs associated with the basic parameters referred to earlier (40 000 to 60 000 euros), savings of around 35 000 euros stand to be made, with an amortisation time of 1 to 2 years.





## 5.2 Compressed air preparation

### 5.2.1 Effect of compressed air quality

As there is so often a failure to choose the right preparation components and size them correctly, vast amounts of potential savings are being lost in this area. Ensuring the necessary compressed air quality is extremely important in this context.

Compressed air quality is divided into nine quality classes according to ISO 8573-1:2010. The lower the class number, the higher the quality level. There is also a distinction between three types of contamination: particles, water and oil content. The table below shows the maximum contamination levels permitted for each of the individual quality classes.

It is important to ensure that compressed air meets the requisite quality as contamination in the air used in the application can affect how the pneumatic components perform, and can even lead to permanent damage. In most facilities, compressed air is prepared at two different locations. The central area where it is prepared is located close to the compressor station, at a point before the compressed air is conveyed into the distribution system. There is also decentralised preparation, which

takes place immediately before the air is used in the application. This is carried out in air supply units and ensures that the air quality required by each component is met.

Appropriate filter systems are used to eliminate contamination consisting of solid matter. Refrigeration dryers or membrane air dryers extract water from the compressed air, reducing the dew point as a result. This ensures that, despite falling temperatures in media that is flowing quickly, no water vapour condensates and thus damages the surfaces of the components.

Filters, drying units and pressure-reducing valves create flow resistance in the pneumatic system. This results in a pressure drop when media flows through the system, something which is especially likely to reach significant levels if the filters are not cleaned regularly. A pressure drop always has a negative impact on the energy balance of the compressed air system and should therefore be prevented wherever possible. This is why only as much filtering and drying equipment as is absolutely necessary should be installed as a rule.

Class	Solid particles				Water		Oil
	Max. number of particles per m <sup>3</sup>			Quantity	PDP *)	Quantity	Quantity
	0.1-0.5 µm	0.5-1.0 µm	1.0-5.0 µm	[mg/m <sup>3</sup> ]	[°C]	[g/m <sup>3</sup> ]	[mg/m <sup>3</sup> ]
1	< 20 000	< 400	< 10	-	-70	-	0.01
2	< 400 000	< 6000	< 100	-	-40	-	0.1
3	-	-	< 1000	-	-20	-	1.0
4	-	-	< 10 000	-	+3	-	5.0
5	-	-	< 100 000	-	+7	-	-
6	-	-	-	5.0	+10	-	-
7	-	-	-	10.0	-	0.5	-
8	-	-	-	-	-	5.0	-
9	-	-	-	-	-	10.0	-

Compressed air quality classes to ISO 8573-1:2010

\*) Pressure dew point

## 5.3 Compressed air distribution

A pipe system is made up of individual sections. By identifying the optimum design for each section, it is possible to create a connection between the compressor and consumers that works as efficiently as possible.

The pneumatic distribution system is generally a welded or clamped network made from stainless steel, plastic, copper or aluminium. As it only has a few connecting components as compared with the compressed air application, it should usually contain only a small number of leakages.

It should be possible to shut off certain parts of the network (using strategically positioned valves, for instance). This facilitates maintenance work and, where various shifts are in place, can even help to keep leakage losses in temporarily unused system components to a minimum.

It is also necessary to consider whether pressure and flow sensors for monitoring the compressed air system and flows can be incorporated into the system, and at what points.

### 5.3.1 Topology

Compressed air systems can have star-shaped, ring-shaped and bus-type structures; depending on the application and associated usage profile, it may even make sense to use a range of structures. In every case, however, there are three different line sections:

The **main line** links the compressor station to the compressed air preparation system and the compressed air container. The distributor lines are connected to this main line. Its sizing must enable the total delivery rate of the compressor station to be transmitted with as little drop in pressure as possible: the pressure drop  $\Delta p$  in the main line should not exceed 0.04 bar.

The **distributor lines** are installed throughout the system and transport compressed air to within the vicinity of the consumers. Generally, there are two different topologies that can be used in this case: a ring circuit and a system with branch lines. If branch lines are preferable, these do allow relatively little material to be used, although they have

the disadvantage that the system must be bigger than a ring circuit to prevent any excessive pressure drops. They also afford relatively little operational reliability, as no alternative supply routes are available if one of the line sections fails.

If a ring circuit structure is used instead of a system with branch lines, this will result in better economic efficiency and operational reliability in the pipe system. In this case it is possible to shut off individual sections of the pipe system without interrupting the compressed air supply in other areas. As a result, there is always a guaranteed supply of compressed air for the majority of consumers – even during maintenance, repair and extension work. Another advantage of this topology is that the compressed air in a distribution ring has to cover a smaller distance than in the case of branch lines. This results in a lower pressure drop  $\Delta p$ .

The **connecting lines** start from the distributor lines and supply the compressed air consumers with compressed air. As the consumers are operated at different pressure levels, an air supply unit with a pressure-reducing valve usually has to be installed upstream of the consumer concerned. This pressure-reducing valve reduces system pressure to the working pressure of the consumer. There is no need for an air supply unit (made up of a filter, separator, regulator and lubricator) at some locations if there is already adequate compressed air preparation.

A size of DN 25 (1") is recommended for connecting lines used in industrial contexts. This almost always guarantees a reliable supply of compressed air with virtually no cost disadvantages compared with smaller dimensions. Consumers with a compressed air demand of up to 1800 NI/min can receive their supply from a line length of up to 10 m with no pressure losses to speak of.

When planning a new compressed air system, it is essential to ensure that all the line sections are coordinated with one another so that they do not encounter pressure and energy losses at any point.

### 5.3.2 Pipeline resistance

As far as flowing compressed air is concerned, every pipeline that conveys air presents some resistance. The reason for this is the internal friction that occurs in all liquid and gaseous media flows, both between the flowing media molecules themselves and between the molecules and the pipeline wall. This is what causes the pressure drop in pipelines, which in turn leads to losses of pneumatically useful energy. As a result, it is important that all lines are sized sufficiently to allow pressure drops to be kept to a minimum even in spite of a high throughput.

#### Facts and figures

The internal pipe diameter  $d_i$  can be sized using the approximation formula below. This is based on the maximum operating pressure  $p_{max}$  (i.e. the compressor switch-off pressure), the maximum volumetric flow rate  $Q_n$  (i.e. the required delivery rate in  $Nm^3/s$ ) and the fluidic pipe length  $L$  (in m). The targeted pressure drop is defined by  $\Delta p$ . The internal diameter  $d_i$  is also calculated in meters.

$$d_i = \sqrt[5]{\frac{1,6 \cdot 10^3 \cdot Q_n^{1,85} \cdot L}{10^{10} \cdot \Delta p \cdot p_{max}}}$$

If the pressure drop with a given internal diameter needs to be determined, this can also be calculated using an approximation formula, shown below.

$$\Delta p = \frac{1,6 \cdot 10^3 \cdot Q_n^{1,85} \cdot L}{10^{10} \cdot d_i^5 \cdot p_{max}}$$

From this it is clear that the pressure drop is a linear function of the pipeline length, but depends on the internal diameter to the power of 5. If the diameter is halved, the pressure drop becomes 32 times higher. This shows how important it is to ensure that pipe cross-sections are sized correctly.

The flow resistance of straight pipe pieces is easy to calculate, but these are not the only components of pipelines. Any quadrant pipes, valves and other fittings that are also installed will significantly increase the flow resistance in the pipelines. This is why it is essential to calculate the fluidic pipe length  $L$  in the case of valves, fittings and quadrant pipes. To simplify this process, the flow resistance levels of various valves, fittings and quadrant pipes are converted into the equivalent pipe lengths. The table below shows the equivalent pipe lengths (in m) of some valves and fittings in relation to the nominal pipe diameter:

	DN 25	DN 40	DN 80
Shut-off valve	8.0	10	25
Diaphragm valve	1.2	2.0	4.5
Knife gate valve	0.3	0.5	1.0
Elbow bend	1.5	2.5	5.0
90° bend	0.3	0.5	1.0

These values then have to be added to the actual pipe length in order to obtain the fluidic pipe length  $L$ . When the process of planning a system begins, not all the information about the valves, fittings and quadrant pipes will be available in most cases. To compensate for this, the fluidic pipe length  $L$  is often calculated by multiplying the straight pipe length by the standard value of 1.6.

The pressure drop  $\Delta p$  in a pipeline with a maximum pressure of 8 bar (6 bar system) should not exceed a certain total pressure loss up to the point where the consumer is reached.  $\Delta p$  should be less than 0.1 bar for the entire pipe system; the following values are recommended for the individual pipe system sections:

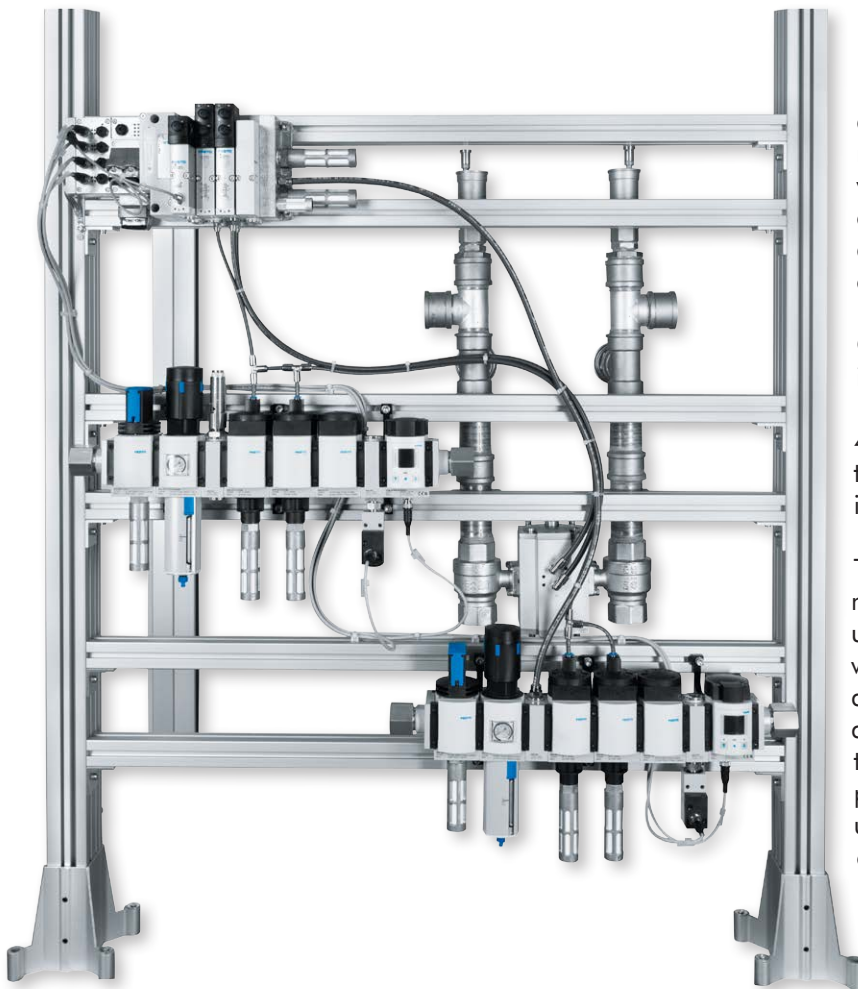
Main line	$\Delta p < 0.04$ bar
Distributor line	$\Delta p < 0.04$ bar
Connecting line	$\Delta p < 0.03$ bar

Using appropriate planning software can stop the pressure drop from getting too high in any section of the pipe system.

## 5.4 Pneumatic application

The application itself comes at the very end of the compressed air functional chain. It starts with local air preparation (decentralised filtration, pressure regulation and so on), which usually involves one supply point. This is followed by local compressed air distribution (generally via tubing lines), valves and various pneumatic drives or other components in the application.

The focus of this analysis is pneumatic drive and handling technology, which means it will not give any further consideration to other compressed air applications such as compressed air guns, process air (like sealing air) or pneumatic tools that also use a certain amount of compressed air. As these may account for a considerable share of compressed air consumption, however, they should always be taken into account when looking at efficiency.



### 5.4.1 Supply points

The compressed air for the production facility is provided at supply points, sometimes also referred to as hall installation plates or robot installation plates. These supply points therefore represent the interface between the compressed air distribution system and the facility itself.

Filters and pressure-reducing valves are used to pre-select the required air quality and pressure level in the facility. Since each of the components creates flow resistance and the pressure drop results in a loss of energy, sizing must be carried out in line with the requirements of the application.

#### I. Correct sizing

The compressed air generated in the compressor has already been filtered in a central filter system. However, damage to the lines and pipes in the distribution system may lead to corrosion and wear on the interior pipe walls, creating contamination in the compressed air again; therefore, an additional filter in the vicinity of the consumer is also recommended.

Compressed air quality is divided into nine quality classes according to ISO 8573-1:2010. The table on page 44 shows the maximum contamination levels permitted for each of the individual quality classes.

The compressed air quality is determined by combining the three values for the number of particles, the water and the oil content. Normally, a range of different compressed air quality standards is needed to satisfy the requirements of the various applications. An average quality class is usually sufficient for pneumatic applications; for instance: (7:4:4). Servopneumatic components, meanwhile, are more sensitive and therefore make more stringent demands on the permissible particle contami-

nation (6:4:4). When using (oils that are based on synthetic ester or native ester, such as rapeseed oil methyl ester), the residual oil content should not exceed 0.1 mg/m<sup>3</sup>. This equates to quality class 2. The requirements for these pneumatic components are therefore (7:4:2) or (6:4:2).

The air quality only has to be as good as is absolutely necessary. Due to the pressure drop associated with the flow resistance of filter components, increasing the compressed air class will lead to higher energy losses. In cases where air is being prepared in an air supply unit at the location of the relevant consumer, not all the pneumatic components necessarily have to be operated with high-quality prepared air: components for which a lower air quality (such as blast air) will suffice can be supplied with air that is channelled off before the preparation stage.

It is also important to remember that fine and ultra-fine filter components in particular have to undergo regular maintenance and cleaning. Soiled filters can cause a pressure drop in the region of 0.5 bar and account for a significant proportion of pressure losses that could otherwise be avoided.

Activated carbon filters, for example, have to be replaced after around 1000 operating hours for this reason. State-of-the-art filter components enable the pressure drop to be monitored using a colour chart or signalling from a pair of pressure sensors, which means that maintenance measures can be launched as and when required.

### Automotive industry

In the automotive industry, a compressed air quality level of (7:4:4) is sufficient for operating clamping devices, pin pulling cylinders and conventional welding guns. Servopneumatic welding guns must be operated at a compressed air quality level of (6:4:4).

## II. Pressure reduction at the pressure regulator



The pressure in the distribution system is usually greater than the pressure required in the application, as pressure variations and supply bottlenecks must not be allowed to have an adverse effect on the application. To reduce the pressure, therefore, the supply point uses a pressure regulator that limits the supply pressure level in conventional pneumatic components to 6 bar, as an example.

In existing facilities, pneumatic drives are often oversized and consume more energy than required for their function. In this instance, the pressure level can be reduced without impairing the function. The components will then consume less compressed air as the air mass for filling to a certain volume is proportional to the supply pressure. By consequence, it is possible to achieve energy savings of around 10% per 1 bar drop in pressure, depending on the pressure level.

A side benefit of reducing pressure is that leakage losses also decrease at lower supply pressure levels, as the pressure drop gets lower at the leakage points and this makes the impetus of the leakage flow weaker.

However, it should be noted that a general pressure decrease in a facility with energy-efficient drives will result in performance deteriorations, and may therefore cause problems during operation. As such, the minimum pressure required must be tested individually and with caution on every machine.

Some pneumatic cylinders are equipped with pneumatic cushioning that decelerates the speed of the payload before the end position is reached,



in order to prevent damage to the cylinder. This system uses a pressure pad that inflates just before the end position is reached in the exhaust chamber, and generates braking force. If the system pressure is significantly reduced, there is the risk of this cushioning failing to work as it should. Therefore, as an initial step it is necessary to check the pressure range in which the pneumatic drives are permitted to operate; otherwise, there is likely to be damage to the components.

#### Automotive industry

Depending on the required dynamic response and load of the individual pneumatic components in a production facility, it is often possible to reduce the supply pressure from 6 bar to 5 bar without any negative impact on the component functions. In fact, there have even been cases where pressure has been successfully lowered to below 5 bar.

### III. Switching off the air supply

During downtimes (at weekends or overnight, for instance), very often there is no automatic facility for switching off the compressed air supply. If any idle consumption takes place in the system, this will rack up significant energy losses over an extended period, mostly as a result of leakages – which, depending on how good the installation is, can account for as much as 35% of a pneumatic system's total consumption. To prevent these losses, a shut-off valve can be installed at the compressed air supply point. This interrupts the system's air supply during downtimes.

Since intelligent functions and the sensors required to execute these are increasingly being integrated into components, it is relatively simple to set up switch-off functions of this kind. With pressure and flow sensors in place, an autonomous monitoring system can be created for the system's behaviour.

With this information, the system's stand-by status can then be identified on the basis of the consumption profile. Under ideal conditions, the compressed air supply will be interrupted as a means of inhibiting unnecessary air consumption. There is the option of monitoring the system behaviour during operation too: if an unusually high level of air consumption is detected during production, a service message indicating this irregularity in the system can be generated and maintenance measures can be introduced if necessary.

If the air supply is being switched off during stand-by, however, it is essential that all pneumatic components can be switched to a pressure-free state without any problems and will not perform any uncontrollable movements without a compressed air supply. A controlled switch-on procedure also has to be defined so that the system can switch back to production from its pressureless idle status quickly and reliably.

#### Automotive industry

The project being discussed here explored the idle consumption of several production facilities. The results showed different measured levels of idle consumption according to the age of the facility and its structure. This may be attributable to leakage, but another reason may be consumers (such as air blast nozzles) not being switched off. On average, idle consumption accounts for approximately 25% of total consumption. This means that, in an average-sized facility with an air consumption level of around 100 Nm<sup>3</sup>/h, 25 Nm<sup>3</sup>/h is due to idle consumption.

Switching off the air supply selectively during system downtimes can at least prevent this consumption while the facility is not in production. Assuming three-shift operation and downtime at the weekends, there are 2400 hours of downtime per year. If the facility's air consumption were completely cut off during these times, the result would be financial savings in the region of 1000 euros per year and facility.

### 5.4.2 Compressed air distribution

Compressed air in an application is usually distributed to the individual pneumatic components via tubing lines and connecting components. Depending on how complex the application is, this may also involve a wide range of screw and plug connectors.

#### 1. Preventing leakages

Practically every system has leakages: there is no such thing as a system that is sealed to absolute perfection. In a compressed air system that is reasonably well maintained, leakages can be expected to account for 8% to 10% of total air consumption. Findings from practice have shown that as much as 30% of compressed air can be lost through leakages in the average system. For this reason, leakages present a significant opportunity to increase the energy efficiency of a compressed air system.

Every connecting component represents a potential leakage point through which compressed air can escape into the environment unused. Major leakages are generally easy to detect and remedy, but most small leakages – which are responsible for the largest losses overall – can only be found by experts with special devices for locating leakages and defining measures to eliminate them.

Older systems with very worn components are frequently susceptible to leakage-related losses. Yet their pneumatic components are usually still guaranteed to work correctly despite this, so there is often no real incentive to introduce measures specifically designed to eliminate leakage points. If, however, the aim is to keep a system's energy efficiency at a satisfactory level, it is not enough to simply ignore the leakages until a function eventually fails. By installing a condition monitoring system, the air consumption can be monitored continuously. This allows changes in consumption due to increasing leakages to be detected and eliminated at an early stage. There is also the option of other functions that offer much more than just leakage detection, such as system diagnostics, rapid error location and even process monitoring.

A variety of measures are available for eliminating leakages in pneumatic systems with as much precision as possible:

#### During the planning phase

Poorly attached connecting components (screw or plug connectors) are often a source of leakages. It is important to ensure that as few connecting components as possible have the potential to create a problem.



#### During operation

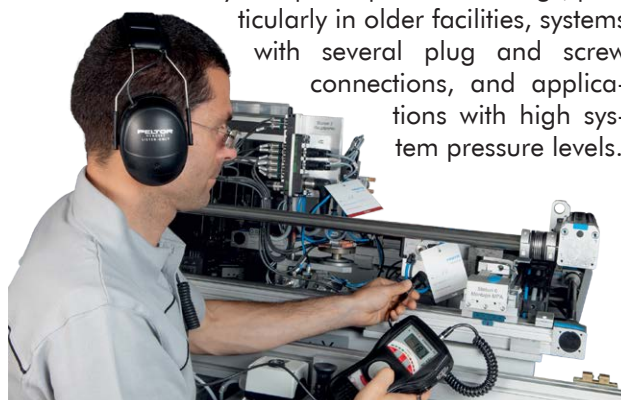
Selectively switching off the air supply during periods of downtime will eliminate leakage losses during these times at least (it must be possible to restart the system rapidly and reliably).



#### Service & maintenance

Measures for targeted leakage minimisation and achieving a low level of leakage can be either introduced by trained staff or purchased as a service from external service providers. The first step in the process should be to identify the potential for savings by measuring the air consumption attributable to leakages. The leakage points can then be pinpointed and eliminated. At the end of the process, a final measurement should be taken to determine whether the measures have been successful. Installing a monitoring system and performing regular checks can then ensure that the requisite system quality is being maintained.

Consistently locating and eliminating leakages is an excellent way to tap into potential savings, particularly in older facilities, systems with several plug and screw connections, and applications with high system pressure levels.



### Facts and figures

Since leakage points are usually associated with a large pressure drop, it is assumed that the flow conditions can be represented using a flow equation for supercritical flow. Therefore, the volumetric leakage flow rate is made up of the following:

$$Q_n = p_1 \cdot C \cdot \sqrt{\frac{T_n}{T_1}}$$

$Q_n$  - Leakage flow [NI/s]

$p_1$  - Supply pressure [bar abs.]

$C$  - Reference value for leakage point [l/(s bar)]

$T_n$  - Standard temperature [K]

$T_1$  - Supply temperature [K]

The volumetric leakage flow rate is thus proportional to the absolute supply pressure value; in other words, leakages have a particularly significant effect in systems with high pressure levels.

From empirical observations, reference value  $C$  can be calculated as follows with leakage surface  $A$  in [mm<sup>2</sup>]:

$$C = 0.19864 \cdot A \cdot \left[ \frac{l}{s \cdot \text{bar} \cdot \text{mm}^2} \right]$$

The volumetric leakage flow rate is proportional to the leakage surface. The volumetric leakage flow rate increases with the square of the effective leakage diameter.

The **volumetric leakage flow rate in [NI/min]** in relation to the supply pressure can be determined from the table below.

Supply p [bar rel.]	Leakage diameter [mm]				
	0.50	1.00	1.50	2.00	3.00
4	11.7	46.8	105	187	421
6	16.4	65.5	147	262	590
8	21.1	84.3	189	337	758
10	25.7	103	232	412	927
12	30.4	122	274	487	1095

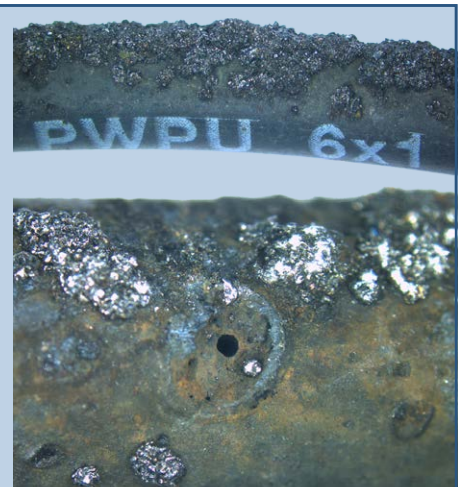
The associated **costs per year in [€]** are listed in the table below.

Supply p [bar rel.]	Leakage diameter [mm]				
	0.50	1.00	1.50	2.00	3.00
4	70	278	626	1113	2505
6	110	439	988	1757	3953
8	157	628	1414	2513	5656
10	213	851	1915	3404	7660
12	276	1104	2484	4416	9936

### Automotive industry

Automotive production often uses welding guns, which may cause significant quantities of flying sparks during the welding process. Even where compatible pneumatic tubes are used, liquid metal spatter can in many cases result in damage that remains undiscovered for a long time.

The figure on the right shows an example of a pneumatic tube exhibiting typical damage of this kind. At a supply pressure level of 6 bar, this hole will create a permanent volumetric leakage flow rate of around 20 NI/min. While this may seem relatively low, over the course of a year it will amount to a handsome air consumption value of roughly 10 000 Nm<sup>3</sup>, as well as 150 euros in costs.



## II. Dead volume reduction

Particularly in bigger facilities that use valve terminals, there are often large distances between the valves and cylinders. The tubes connecting them represent a dead volume for every switching operation, as they must be filled and emptied every time. The compressed air needed for this is lost unused. Minimising dead volumes between the cylinder and valve is therefore an essential part of optimising energy efficiency. The dead volume between the valve and cylinder can be reduced by:

### Using thinner tubes

Reducing the tube diameter will reduce dead volume and, in turn, losses. It is, however, important to note that the flow resistance will rise with smaller tube diameters. As outlined on page 46 (green box), the flow resistance is relative to the line diameter to the power of 5. If the tube diameter selected is too small, this may have a negative impact on the dynamic response of the downstream application. For this reason, reducing the diameter is a step to be taken with caution.

### Using shorter tubes

In line with the principle that valves should be as close to the cylinder as possible, ideally the valve should be attached directly to the cylinder, as illustrated below. This makes the dead volume very low. However, the disadvantage of this is that the equipment is harder to maintain, as the valves can no longer be arranged in a way that allows them to be accessed centrally in the system.

Reducing the dead volume between valves and cylinders opens up considerable potential for savings, particularly in the case of short cylinders, long tubing lines and high cycle rates.



Valve mounted directly on the drive

### Facts and figures

The air consumption of a pneumatic component in [NI] can be calculated as follows in the case of a double stroke:

Pneumatic cylinder:

$$V_{N\_cyl} = \frac{p_{abs}}{p_{atm}} \cdot \frac{\pi}{4} (2d_{cyl}^2 - d_{rod}^2) \cdot l_{cyl}$$

Tube:

$$V_{N\_tube} = \frac{p_{rel}}{p_{atm}} \cdot \frac{\pi}{4} (2d_{tube}^2) \cdot l_{tube}$$

$V_{N\_cyl}$	- Cylinder air consumption
$V_{N\_tube}$	- Tube air consumption
$p_{abs}$	- Absolute pressure
$p_{rel}$	- Relative pressure
$p_{atm}$	- Atmospheric pressure
$d_{cyl}$	- Cylinder diameter
$d_{rod}$	- Rod diameter
$l_{cyl}$	- Cylinder length
$d_{tube}$	- Tube diameter
$l_{tube}$	- Tube length

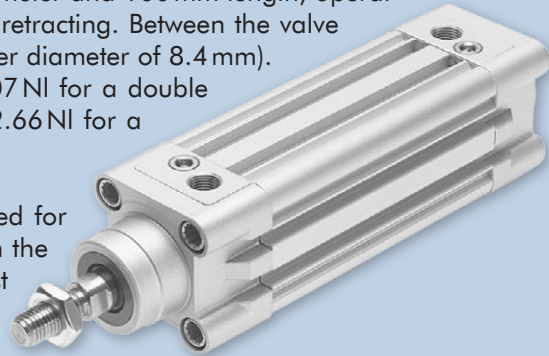
It is important to note that the standard consumption of a tube volume is calculated using the ratio of relative pressure to atmospheric pressure, for reasons inherent in the system. In a pneumatic cylinder, meanwhile, the ratio between absolute pressure and atmospheric pressure applies. This is because a certain quantity of air remains in the tube following venting, but does not remain in the cylinder chamber as this reduces its volume to a minimum.

To ensure a low dead volume, the ratio of the tube volume to the cylinder volume should be as low as possible.

### Automotive industry

Let us take the example of a cylinder with a 32 mm diameter and 100 mm length, operating at a supply pressure of 6 bar, and advancing and retracting. Between the valve and cylinder there is a distance of 4 meters (tubing inner diameter of 8.4 mm). In this case the cylinder requires an air volume of 1.07 NI for a double stroke. The process of filling the tubing line requires 2.66 NI for a double stroke.

Consequently, a total air quantity of 3.73 NI is required for a double stroke. However, just about 30% of the air in the application is used for the cylinder movement; the rest is lost in the dead volume. With a double stroke every 5 seconds, the dead volume will result in air consumption of 32 NI/min and around 170 euros of compressed air costs per year (assuming three-shift operation).



Various production facilities were considered when analysing dead volume conditions in body shops. The average cylinder volume in this area of the facility was around 0.25 NI, while the average tube volume was 0.1 NI. The share of consumption attributable to dead volume was therefore approximately 30%.

Large dead volumes are usually the result of the chosen system topology. If the valves are in a central position outside the system and connected to the pneumatic cylinders using relatively long tubes, this does make them easier to maintain, but also requires media to circumnavigate significant distances between the valve and the cylinder. Adjusting the topology could reduce the dead volume's share of consumption to around 10%. As such, this would allow approximately 20% of the air consumption in the associated pneumatic components to be saved.

### 5.4.3 Valve terminals

If an application requires several valves, then valve terminals – which group the valves together in one place on a shared plate – are a useful option. This not only saves space during installation, but also makes the system easy to maintain, as all the valves can be accessed from a single central location.

The air is supplied by a shared supply line, which keeps the installation work required for the tubing lines to a minimum. The exhaust air from all the valves, too, is combined into a single exhaust air line, before being released to the environment via a shared silencer. A shared cable or a bus signal is used to control the valves electrically.

Some valve terminals offer additional functions that can help pneumatic applications run energy-efficiently: for example, integrated pressure-reducing valves for adjusting the pressure level in line with demand, or the option of switching off individual parts of the system during downtimes.



Valve terminal



## I. Pressure zones

With the aid of separator plates or valves with integrated duct separation, it is possible to create multiple pressure zones in modular valve terminals. This results in pressure reductions at certain locations in the system. The low-pressure air that is generated can be used specifically at those points that do not require a high level of pressure potential (e.g. for the return stroke of a pneumatic cylinder, which needs less force). This enables only as much operating pressure as is actually required to be provided for each valve and each actuator, in turn ensuring that air consumption – being proportional to pressure – is in line with demand.

The figure below shows a valve terminal with multiple valves, on which the required output pressure is set manually and displayed on a pressure gauge.

### Automotive industry

Clamping cylinders are used to clamp components and require a high level of force to be applied in one of the drive's two directions of movement. Similarly, injection cylinders must exert a high degree of force in their advancing movement. In both cases, the conventional supply pressure of 6 bar is only required in one direction of movement. The return stroke can be carried out using reduced force, thus saving energy.

## II. Switching off system components

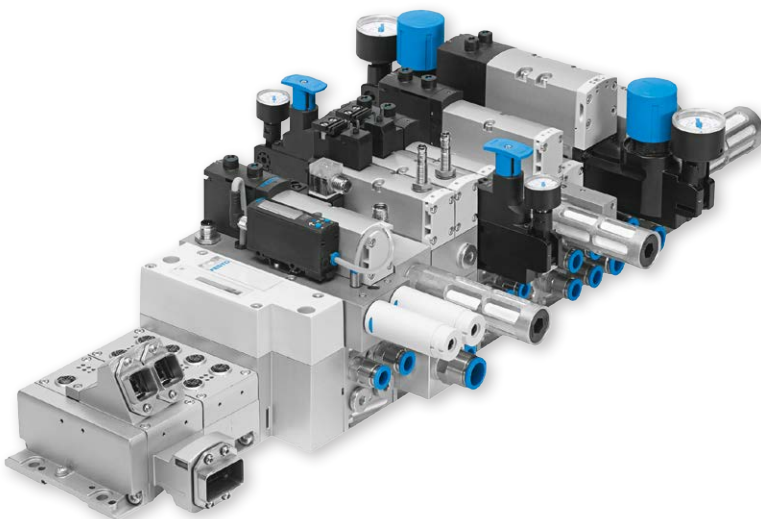
As well as the energy efficiency module referred to on page 49 and the option of switching off a system manually during downtimes, it is possible to switch off decentralised units (such as valve terminals and welding guns) during operational pauses too. This can be done manually or automatically and various standards have been developed for it. One example is the PROFlenergy protocol:

based on the PROFINET communication protocol, this standard enables activated components to be switched off flexibly or switched to special energy-saving or stand-by modes. A device description file (GSDML) contains standardised information about which modes the component in question supports and how much time is needed to move back into an operational status from stand-by. This allows the control system to respond flexibly to both planned and unplanned periods of downtime. Depending on the timings and function range associated with the components, it may be possible to carry out operations that go further by switching off entire system sections, although safety-related functions will be handled in line with safety regulations. The component reactivation process will then follow a certain sequence to ensure that the system can get back up and running safely.



### Automotive industry

A modular valve terminal equipped with PROFINET fieldbus nodes and the PROFlenergy standard is able to evaluate the start/stop instructions of a production pause; the system can then be configured accordingly to ensure that a fail-safe position is adopted for each output (digital or analogue) and solenoid coil. This can also be applied to servopneumatic welding guns while they are paused (that is, outside the contact zone).



#### 5.4.4 Clamping devices and pin pulling cylinders

Most conventional pneumatic drives in body shops are used to fasten the metal sheets being processed. As part of this, pin pulling cylinders align the component precisely and clamping cylinders clamp the metal sheet with a high level of force to prevent the possibility of any unintended movements during processing.

If conventional welding guns without regulated servo operation are used, these are also included in the category of conventional pneumatic drives.

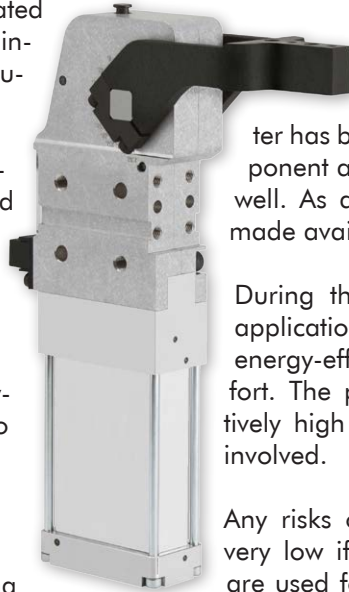
Pneumatic drives generate the required mechanical movement or necessary force and the pneumatic energy is converted into mechanical energy within them, making this stage accountable for the majority of air consumption. Energy-saving measures in pneumatic drives therefore open up much potential for savings: ultimately, anything that is not consumed does not have to be generated and distributed.

#### I. Correct sizing

Pneumatic drives are often oversized during the planning phase. The drive force is generally far greater than is actually necessary for the application. Experience shows that, on average, half of all the pneumatic consumers in an application-specific, energy-efficient design could be one size smaller.

Below is a list of reasons why oversizing may happen:

- Excessive safety factors for operational reliability
- No requirements data, or insufficient requirements data, available
- Design based on permissible guide loads – the drive forces and air consumption can no longer be selected
- Use of whichever drives are currently in stock



If an unnecessarily high drive force is provided in the drive (i.e. too large a cylinder diameter has been selected), this means the component air consumption will be too high as well. As a result, pneumatic energy that is made available will go unused.

During the planning phase, a pneumatic application can be designed correctly and energy-efficiently with reasonably little effort. The potential for savings is thus relatively high considering the amount of work involved.

Any risks of less operational safety will be very low if tried-and-tested simulation tools are used for design purposes. While certain safety factors will still need to be taken into account (as friction in a drive may increase over time, for example, but the component still needs to operate reliably), the right tools will allow this aspect to be reproduced and considered as appropriate as well.

#### Automotive industry

If we assume that 50% of pneumatic drives are one size too large, it would be possible to make compressed air savings of approximately 15% by using the next size down.

In a typical production facility that consumes 100Nm<sup>3</sup>/h of air, we can also assume that around 50% of the compressed air is used to operate pneumatic drives. If 15% compressed air savings were achieved by using the correct sizing, this would equate to savings of 7.5 Nm<sup>3</sup>/h. In three-shift operation, this would mean that 675 euros in costs could be saved each year.

### Facts and figures

The movement characteristics of a pneumatic drive depend on the load, installation position, valves, tubing connection and throttle components used. Accordingly, the only way to optimise dynamic movement characteristics and ensure correct sizing is to use simulation tools. In cases where a drive's movement characteristics are not relevant, the dynamic response will play a lesser role, meaning that the available force  $F_{cyl}$  can be calculated using the pressure and the cylinder diameter. This information enables static sizing of the drive:

#### Cylinder known, load mass sought:

$$F_{cyl} = d^2 \cdot \frac{\pi}{4} \cdot p_{rel}$$

Empirical values have made it possible to determine that, during horizontal movement, the load mass may be up to 1.5 times ( $F_{cyl}/g$ ). During vertical operation, the load mass may be 0.75 times this.

$$\text{Horizontal: } m_{load} \leq 1.5 \cdot \frac{F_{cyl}}{g}$$

$$\text{Vertical: } m_{load} \leq 0.75 \cdot \frac{F_{cyl}}{g}$$

If the load mass  $m_{load}$  is considerably lower, the drive is oversized.

#### Load mass known, cylinder sought:

$$d_{load} = \sqrt{\frac{4}{\pi} \cdot \frac{m_{load} \cdot g}{p_{rel}}}$$

In this case too, empirical values have shown that the cylinder diameter to be used can be determined using a fixed factor from the load diameter. During horizontal movement, the cylinder diameter must be at least 0.82 times the load diameter. During vertical operation, it should be 1.16 times this.

$$\text{Horizontal: } d_{cyl} \geq 0.82 \cdot d_{load}$$

$$\text{Vertical: } d_{cyl} \geq 1.16 \cdot d_{load}$$

If the diameter  $d_{cyl}$  is considerably larger, the drive is oversized.

## II. Reduced return stroke force

Many pneumatic applications only require a high level of drive force in one of the two directions of movement. Movement in the other direction takes place with virtually no force. This also applies to clamping cylinders, for example, which use a great deal of force to hold a component in place when they are closed, but open with almost no force.

If less drive force is required in one of the two directions of movement, the corresponding valve chamber can be supplied with compressed air at a lower level (for example, 3 bar instead of the usual 6 bar). The compressed air required for this can be generated either using an additional pressure regulator at the supply point or in the valve terminal with a pressure-reducing valve.

### Automotive industry

In a typical production facility, clamping cylinder operation accounts for approximately 30% of air consumption. It is assumed that all the associated components can be operated with a reduced return stroke force in cases where a pressure level of 3 bar is enough to generate this force. Therefore, the air consumption of these components could be reduced by 25%.

As a result, savings of 7.5Nm<sup>3</sup>/h are feasible in systems with a total air consumption of 100Nm<sup>3</sup>/h. This equates to 675 euros in costs being saved each year (in three-shift operation).

### 5.4.5 Welding gun drives

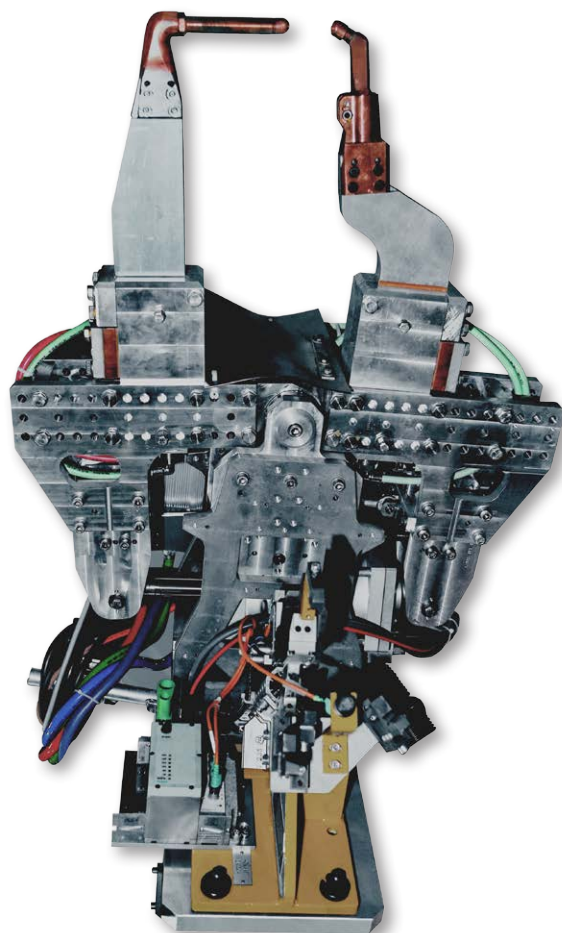
Welding guns must be able to generate a high level of contact force during the welding process, so they are usually supplied with compressed air from the high-pressure system. The pressure level is in the region of 12 bar.

The energy content of the compressed air is higher as compared with the conventional low-pressure system, which in turn makes the amount of work and the costs required to generate the compressed air reasonably high. Therefore, welding gun drives are an application where it makes particular sense to implement an energy-saving drive concept.

#### I. Switching off idle consumption

The structure of the proportional valves used in servopneumatic welding guns results in a certain level of air consumption – one that is comparable with a permanent leakage – even during downtimes. If, however, the air supply is switched off at the relevant supply point during downtimes, it is possible to curtail these losses.

Measurements have shown that the air consumption of servopneumatic welding guns is around 1.6 Nm<sup>3</sup>/h during downtimes.



#### Automotive industry

A typical production facility with a total air consumption of around 100 Nm<sup>3</sup>/h uses around 10 servopneumatic welding guns. Assuming three-shift operation and downtime at the weekends, there are 2400 hours of downtime per year.

If the air consumption of the welding guns were completely cut off during these times, the result would be financial savings in the region of 700 euros per year.

## II. Optimised motion profile

The motion profile has a significant impact on the energy consumption of welding guns. For example, many applications have no need to open the welding gun completely after each welding point, reposition it and then close it again. If the welding points are positioned in a convenient line, it is enough to perform a small opening stroke of a few millimeters in order to change the welding gun position – something which can reduce air consumption significantly as well as cut down on processing time. Conventional welding gun systems are unable to take up intermediate positions, and consume vast amounts of energy when processing several welding points in succession, as the gun has to be opened fully each time.

Servopneumatic welding guns, on the other hand, allow an alternative motion profile to be used, where the opening stroke is selected on a case-by-case basis after each welding process. Thus, using servopneumatic welding guns allows for relatively energy-efficient operation.

Despite this, servopneumatic welding guns demonstrate a certain amount of idle consumption during downtimes. Where welding is performed only occasionally (on single points) and there are long periods of downtime, conventional pneumatic drive technology therefore does have its benefits as it involves no idle consumption to speak of.

Servoelectric systems incur lower energy costs than pneumatic ones, which can have a significant effect particularly where long stroke lengths are required – although the investment costs are much higher (see Chapter 4.2). Generally, the type of application will determine which welding gun system offers the best use of energy and financial resources.

Air consumption is not the only aspect that matters from an energy perspective. The gun weight (welding gun and drive technology) is also an important application-specific factor to be taken into account. In the case of mobile welding guns that are mounted on a robot, for example, this weight will constantly need to be moved and held in place, sometimes resulting in significant electrical energy consumption in the robot's drive technology. If the weight of the components is kept low, this will have a positive impact on the system's energy consumption. High levels of energy density are a defining feature of pneumatic drive technology; accordingly, pneumatic components are usually smaller and lighter than electrical drives even where they demonstrate similar performance data. Particularly in mobile applications, pneumatic welding guns are therefore recommended as a means of keeping the moving mass as low as possible.

### Automotive industry

Each complete opening and closing operation of a welding gun results in air consumption of around 20 NI to 35 NI per welding point, depending on the type of gun used and the drive diameter. If, on the other hand, the motion profile means that the welding gun only has to open by 20% after each welding point, and does not have to open all the way until 10 points have been processed, the consumption per welding point will be around 7 NI to 13 NI. This means a reduction in air consumption per welding point of 60%.

A motion profile that reaches a compromise between these two extremes has to be developed to suit each component processed and the welding point configuration. If we assume an average opening of around 50%, this will result in average air consumption in the region of 15 NI per welding point. The compressed air costs for one welding point will therefore be around 0.03 cents. On average, approximately 4150 welding points are applied when manufacturing a car body. Therefore, operating the welding guns generates air consumption of 62 Nm<sup>3</sup> per car body. This equates to a financial outlay of around 1.10 euros.



## 6. Planning tools

Even as early as the planning phase for a new plant or system, ensuring accurate sizing and an appropriate design is an essential part of creating a concept that optimises the use of energy throughout. If technical solutions for boosting energy are not sought out until later on, they are likely to involve much more expense.

Investigations have shown, however, that there are often no attempts to introduce a systematic approach to energy-efficiency when designing a large compressed air system, and empirical values that are supposedly reliable are used instead. What this in fact creates in most cases are components that are significantly oversized. This is due to an overemphasis on operational reliability, the principle being that it is better to have extra capacity and not use it than to need it and not have it. In some cases there is not enough time to carry out calculations accurately, and this leads to deficiencies in the planning process. Planning tools may be helpful in such cases.

As part of the "Green Carbody Technologies" innovation alliance, three key areas in which software tools can be used for planning compressed air systems were identified:

- 1. Determining compressed air demand** for estimating the necessary delivery quantity and for calculating the total cost of ownership (TCO) and life cycle costs over the complete life cycle of the system.
- 2. Planning the compressed air system itself**, including tubing diameters and lengths, as well as the positioning of compressor stations and compressed air reservoirs, in order to prevent pressure drops resulting from lengthy

distances, leakages and undersized pipes. With the consumption values determined from (1.), an optimised system topology for minimising losses can be created. Infrastructure aspects can also be taken into account.

- 3. Sizing compressors** in order to create a machine configuration that is adapted perfectly to consumption.

The interaction between the tools allows optimum planning of the entire compressed air functional chain. In a best-case scenario, the software tools will have suitable interfaces to allow data exchange between the individual tools in a higher-level data model.

The compressed air demand (1.) in the application, including an analysis of the life cycle costs, can be determined thanks to a Festo tool called the "Life Cycle Cost Calculator (L3C)". This makes it possible to calculate the required delivery rate of a facility and provide it via a defined interface. In turn, then, the compressed air system can be planned and the compressors required for operating the facility can be sized.

Boge provides two modules that are able to perform the tasks described in (2.) and (3.). The two are also linked, so that the parameters determined when sizing a system can be directly transferred to the module for sizing a compressor station.

The optimum design for each individual automation function is not being discussed here; for this purpose, the various component manufacturers may offer selection or simulation tools for their particular solutions or perform design work for customers.



## 6.1 Determining compressed air demand

Determining compressed air demand plays a crucial role in planning new production facilities, as the outcome of this process then allows media supplies to be designed and installed. So far, however, demand values have only ever been estimated – a practice that usually results in oversized compressed air generation and distribution systems. In a worst-case scenario, a poor estimate can even cause undersupply, something that can only be remedied with a considerable amount of extra effort and expense.

The process of determining media demand takes place up to 18 months before a facility enters production, which means that the plans for the facility have not yet been made in final detail. For this reason, Festo has developed a planning tool and designed software to enable compressed air demand to be estimated at an early stage of planning, without requiring significant modelling work and with no bias towards any one manufacturer. This is called the "Life Cycle Cost Calculator" and is

able to map an entire facility over three hierarchy levels. Consumers are mapped in a plug-in using automation functions. The tool has been designed to make adding extra functions exceptionally simple.

The figure below shows an example of modelling a production cell in a body shop: the left-hand side contains the project tree with the three hierarchy levels, while the right-hand side describes a clamping cylinder (a typical pneumatic drive used in body shop contexts).

This tool ultimately enables users to estimate costs over the entire product life cycle; these consist of the purchase costs, energy costs (operating costs) and maintenance costs. It does not take disposal costs into consideration.

Certain information is required to map the functions. For example, the following is required for the "pneumatic movement" function:

**Karosseriebau**

- Fertigungszelle 1
  - Roboter A
    - Spanner 50 / 135°
    - Spanner 50 / 135°
    - Spanner 50 / 135°
    - Spanner 50 / 135°
    - Spanner 50 / 135°
  - Roboter B
    - Spanner 40 / 135°
    - Spanner 40 / 135°
    - Spanner 40 / 135°
    - Spanner 40 / 135°
    - Spanner 40 / 135°
- Fertigungszelle 2
- Fertigungszelle 3
- Fertigungszelle 4
- Fertigungszelle 5
- Fertigungszelle 6

**Referenz** Spanner 40 / 135° 1x

Funktionszyklen / Roboterzyklus 2 1x  
Dauer Funktionszyklus 20 s 1x  
2x

☐ Zelle ☐ Roboter ☒ Funktion

**Doppelwirkender Zylinder**

Kolben-Ø 40 32 mm mehr ...  
Max. Hub x 75.6 mm = ☒ = ausgeführt 75.6 mm

Schlauch

1 = ☒ = 3  
Innen-Ø x 6 mm Innen-Ø x 6 mm  
Länge 20 mm Länge 20 mm

2 = ☒ = 4  
Innen-Ø x 6 mm Innen-Ø x 6 mm  
Länge 1500 mm Länge 1500 mm

Zusätzl. Leckage ... 0 l/h ?  
☐ Betriebsdruck 6 bar ?  
☐ Druckverstärkerverhältnis 1: 1 ?

Pneumatisch Bewegen

Beschaffungskosten Automatisierungsfunktion ... 200 Euro ?

	Funktionszyklus	Roboterzyklus	Zellzyklus	Beobachtungsperiode
Verbrauch	1.94 l	3.87 l	3.87 l	12548 m³
Energiekosten [Euro]	3.49E-5	6.97E-5	6.97E-5	226

Kopieren Einfügen Löschen Mehr

Determining compressed air demand using the "Life Cycle Cost Calculator"

- Drive diameter and stroke
- Tubing inner diameter and length
- Number of function activations per higher-level cycle

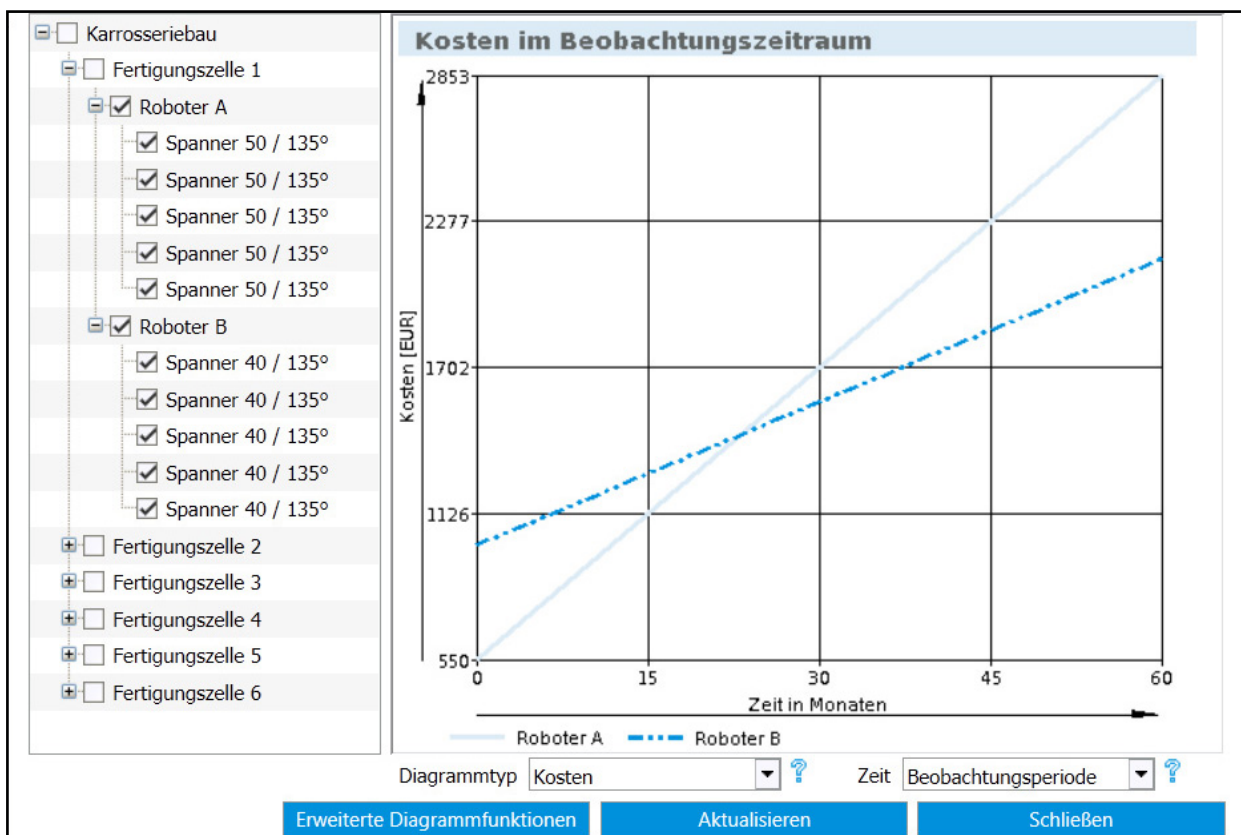
Using the input parameters (operating pressure, compressed air generation costs, observation period), the consumption of the individual components is aggregated automatically and evaluated over the observation period. In addition to the energy costs for the components, the purchase and maintenance costs can be taken into account.

Following the modelling process, the energy requirements of the system can be evaluated both numerically and graphically. The tool also offers the option of creating a range of different models that may, for example, reflect different designs and sizes for individual drives. Specific aspects of these can then be analysed and compared in order to

determine the most economically efficient solution for the observation period.

The figure below shows two differently configured variants of a handling robot with the same functionality. For the energy-optimised robot B, special clamping devices were used. These generate the same contact pressure for a smaller drive diameter thanks to special kinematics, but are much more expensive to buy. Using a break-even point diagram, the planner can decide on the most efficient variant over the long term without having to perform time-consuming calculations.

If a facility is fully mapped in this tool, the model that is created makes it possible to draw conclusions about compressed air demand. Using an interface, this information can then be made available for other purposes later on.



Break-even point diagram for two robot variants

## 6.2 Compressed air network planning

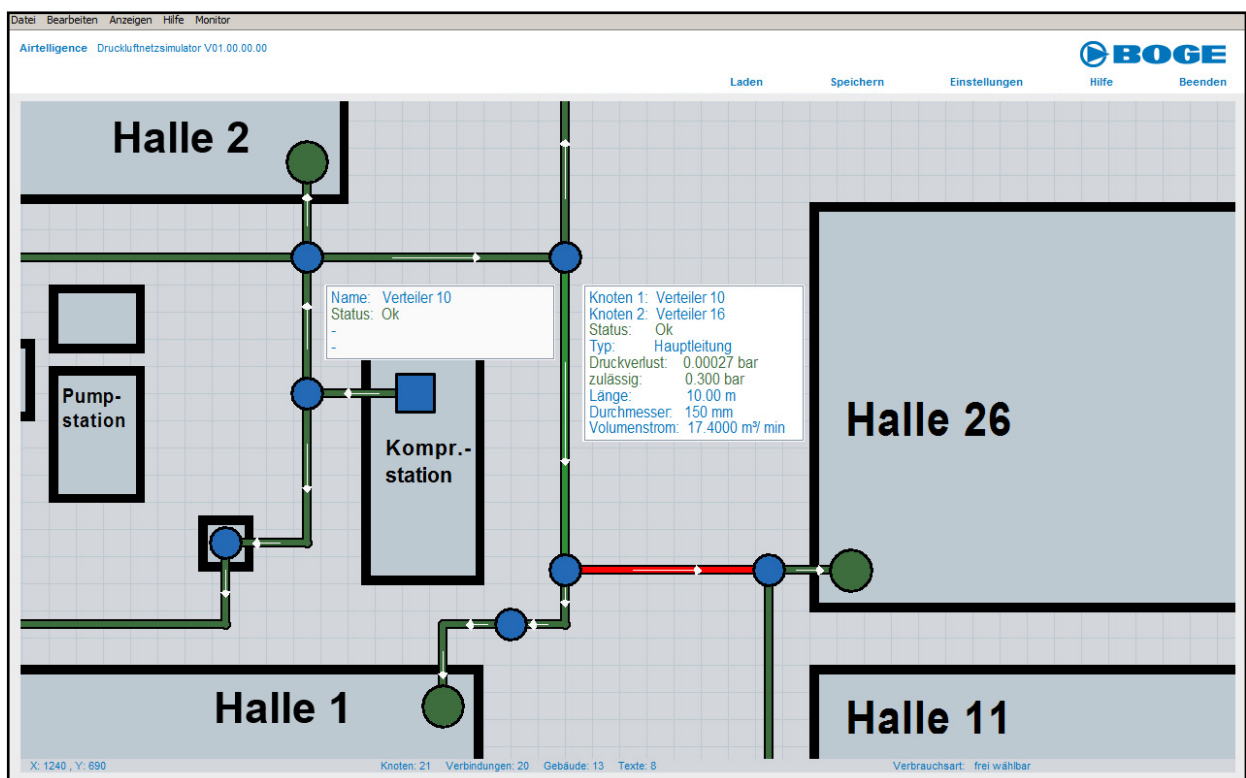
Complex flow simulation programs have been in use for decades now. However, they require extensive computer hardware and trained staff – and are relatively costly. Creating compressed air system models with this kind of software takes up a great deal of time and financial resources in most cases. Because of the complexity of the calculations, it can also take anywhere from a matter of minutes to a few hours – and all the way up to a few days – to create a simulation. All these factors make flow simulation programs unsuitable for planning compressed air systems.

With this in mind, a challenge was set: to develop a less cumbersome tool that could run on a standard desktop PC and yet still identify and display bottlenecks or oversized pipelines. Unlike flow simulations, in this case a calculation with specific parameters would be enough to achieve a result, as turbulence and flow conditions would not necessarily have to be mapped in detail.

An example of an application for the module that arose out of this task is shown in the figure below. This simulation contains nodes and connections, where connections are usually pipes and nodes may be consumers, generators or distributors. This depiction is based on actual pipeline plans used in the design for the factory concerned.

The tool provides immediate feedback about the flow conditions in the pipe segments and consumers/generators, and allows changes to be made in real time. For example, in this configuration it has identified an inadequately sized pipe segment and highlighted it in red. At this point it would be possible to adapt the pipe or position a small decentralised generator next to the consumer. The effects of these steps could then be observed and evaluated instantly.

This process enables users to design the most ideal system possible, as well as preventing excessively large or small pipe segments and the use of pipes that would have very little impact on the flow characteristics.



Planning a compressed air system

## 6.3 Compressor station planning

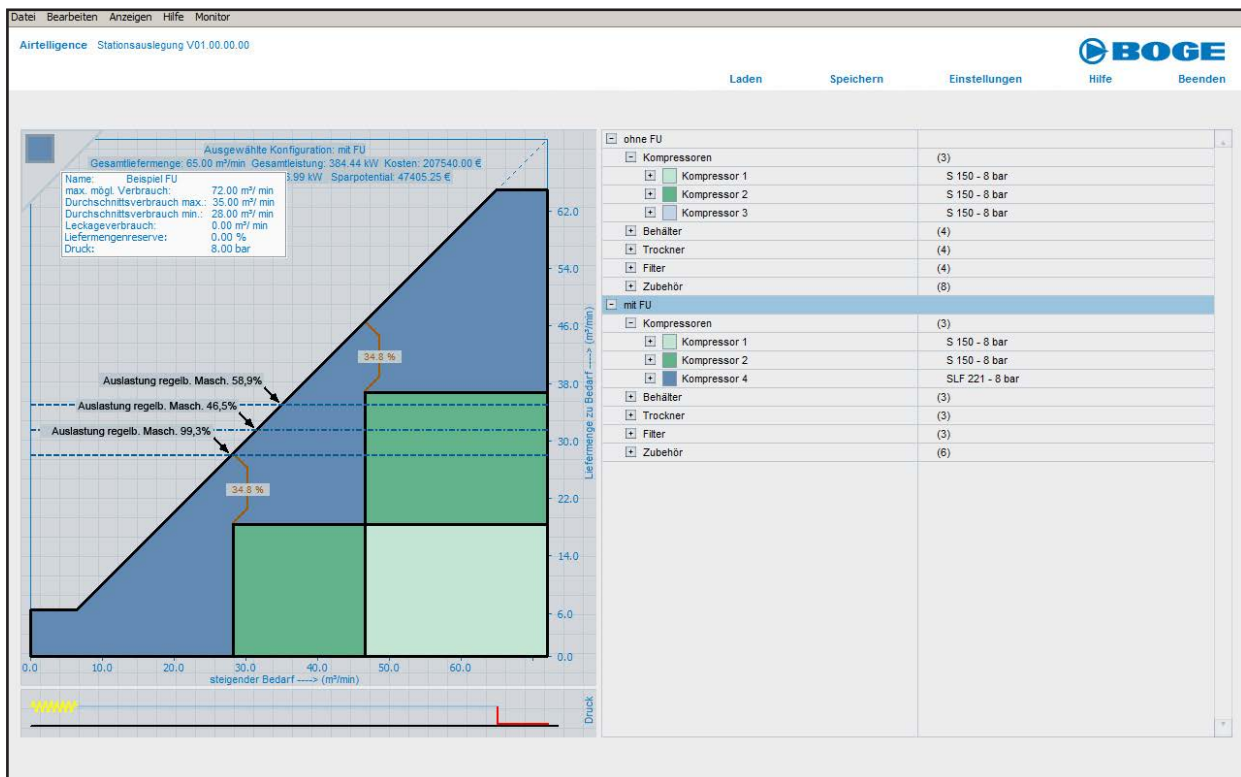
Up to now, stations have often been designed on the basis of data sheets whose information allows compressors with the right delivery rate to be selected. However, this approach can result in unfavourable machinery combinations if the user does not have sufficiently in-depth knowledge. In some cases, compressor stations can be designed by external service providers such as the compressor manufacturers themselves. While this method usually leads to considerably better results, it can take several days for the service provider to produce a solution. The process of optimising the design then often has to be repeated several times until a finalised version can be identified, something which can trigger further delays in the schedule.

With the aim of offering a better alternative, a tool that designs an entire compressor station for the user was developed: this includes all compressors and accessory components that are necessary for highly efficient compressed air production. Additionally, the process of entering the parameters was made as simple as possible – allowing a result to be produced in a matter of minutes.

The compressed air system's average consumption is specified as an input parameter. The tool then uses an intuitive graphic to depict the efficiency at key points, as illustrated in the figure below. This allows the user to distinguish a "bad" station from a "good" one at a glance. Removing or adding components triggers an immediate change in the results.

In the simplest scenarios, only the average and maximum consumption plus the required pressure are needed to design an entire station complete with all accessories (drying units, filters, reservoirs and so on). Of course, the tool supports other parameters too, such as the compressed air quality, ambient temperature and leakage.

It also contains a comprehensive data base that supports a whole range of different compressors and accessories, without favouring any one specific manufacturer. This allows the tool to examine and visualise every existing station in order to determine the effect that individual components have on the result.



Planning a compressor station

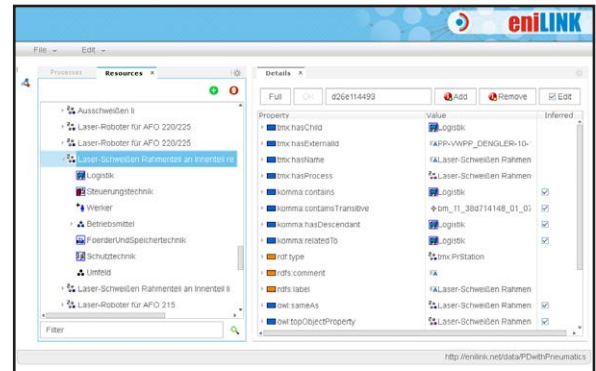


## 6.4 Combining all the tools

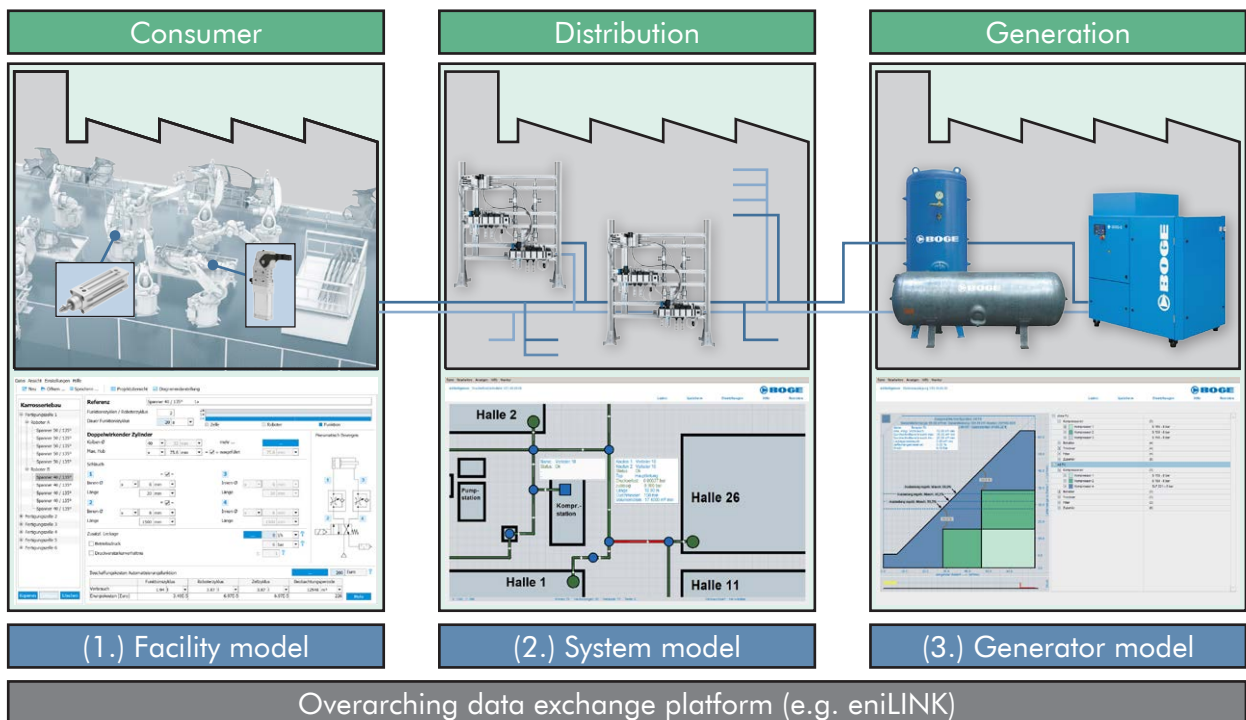
The figures below show an integrated approach to the planning tools. The facility model (left) provides a comprehensive overview of a compressed air consumption plan. Once this information is known, another tool can be used to generate a system model (middle) so that a suitable system topology, adapted to the application concerned, can be identified. Finally, a generator model (right) can be used to plan the structure of the compressor station.

It is essential for the individual software modules to exchange data if the planning process is to run smoothly. This is the only way to enable several people to work on the planning process at the same time, to incorporate specialists as they are required, and to ensure that the planning work stays within certain boundaries. This requires an agreed framework for data exchange between the planning partners, which is also accepted across the various planning phases.

To enable this in the project being discussed here, a web-based planning software prototype was developed. This involved the use of a software plat-



form called "eniLINK", which allows applications to be created on the basis of linked data technology. A typical piece of planning software was used to export the model of a production facility and prepare it in a way that would allow compressed air components to be added via eniLINK. As an example, the compressed air demand of pneumatic clamping elements was calculated in relation to their required opening angle. The intention is for future versions of the software to include catalogue data for additional components, which will enable calculations and analyses to be performed automatically for these.



Chain of tools for planning compressed air generation, distribution and consumption

## 7. Summary

### 7. Summary

This guide presents selected results from the project "Planning the efficient use of compressed air in the body shop" performed by the "Green Carbody Technologies" innovation alliance. The overall objective of the alliance is to achieve energy savings of around 30% across the entire body manufacture value chain. With this objective in mind, the project examined the pneumatics used in body shop, analysed drive technology and addressed issues faced by planning processes today.

The energy efficiency that various technologies offer, particularly in body shops, is currently the subject of often **heated debate**, and compressed air technology is very much included in this. These discussions are often fuelled by the subject of losses that these technologies are known to be associated with – such as leakages – as well as the lack of transparency and data concerning costs that are actually incurred. In most cases there are no reliable, representative measurements indicating the compressed air consumption of production facilities in body shops. This means that measures such as omitting high-pressure systems when planning new production facilities, and even entirely compressed air-free production, are being considered and discussed without access to reliable information about energy costs and total cost of ownership. Technical advantages such as high power density, long service life and the robustness of pneumatic drive technology are often underrated.

A key aim of this project was to achieve **transparency** when addressing the issues it raises – by taking measurements, comparing technologies and scenarios with actual values, and illustrating practical ways in which energy savings can be generated in just a short time.

The results of the measurements showed that pneumatics are a **cost-effective, energy-efficient** option for body shops. Meanwhile, the measurements performed in a range of typical production facilities illustrated the actual consumption costs associated with them, with sometimes surprising results: the exceptionally high levels of consumption and loss that were feared at the outset of the project proved to be much lower when the analyses themselves were performed. The reason was

that, although large pneumatic drive components were present in the clamping, gripping and welding technology in question, their air consumption stayed within certain limits because of the relatively low number of motion cycles.

For planners, there is now **transparent data** available at body shop, cell and component level. The numerical values and statements have been compared with the experiences of various car manufacturers and verified. One welding point of a servopneumatically driven C gun, for example, costs around 0.013 ct (7 Nl air consumption). A complete facility with a throughput of 80 components per hour consumes approximately 50 to 200 Nm<sup>3</sup>/h (70 ct/h to 300 ct/h), depending on its size. The costs for the share of compressed air that is required from an energy perspective during the production of a car body amount to roughly 6 euros (all stations, including paint shop). The share of the body shop, which contains extensive drive technology, is around 3 euros. Around half is attributed to the high-pressure system, which accounts for an investment of approximately 350 000 to 500 000 euros in a typical factory. The scenarios and TCO examinations illustrated in this guide demonstrate that high-pressure systems undoubtedly pay off.

**Energy savings of 30%** are a feasible goal. This guide outlines the energy-saving measures required to achieve this – from switch-off systems, to eliminating leakages, all the way through to diagnostic systems. There is significant potential in efficient generation design, the use of heat recovery and correct pneumatic drive technology design.

Thanks to the **software tools** that have been developed, it has been possible to demonstrate for the first time how the entire functional chain – from compressed air generation to application – can be exploited and scrutinised with TCO aspects taken into account. This approach will need to be integrated into higher-level planning tools used by car manufacturers to ensure that this kind of holistic perspective can be maintained in the future too.

The project discussed in this guide has shown that the pneumatics used in body shop contexts are ideal for use as drive technology if designed correctly, and will remain an economically efficient technology in the future.



## 8. Appendix

# 8

### 8.1 Data from the InnoCaT reference factory

	Reference factory	Reference car body
Output	250 000 vehicles/a	
Number of welding points	1 036 million/a	4 150
Electricity demand in production stations	131.4 million kWh/a	512 kWh
Total electricity demand incl. infrastructure	206.5 million kWh/a	810 kWh
Factory compressed air demand	100.1 million Nm <sup>3</sup> /a	400 Nm <sup>3</sup>
Electricity demand for compressed air in the factory	13.0 million kWh/a	52 kWh
Costs for compressed air in the factory	1.6 million euros/a	6.36 euros
Compressed air demand in body shop only	49.0 million Nm <sup>3</sup> /a	196 Nm <sup>3</sup>
Electricity demand for compressed air in the body shop	6.4 million kWh/a	26 kWh
Costs for compressed air in the body shop	780 000 euros/a	3.11 euros

### 8.2 Measured data from an analysed body shop

	Per hour	Per year
Consumption during the production phase (three-shift operation, 6000 h/a)	4800 Nm <sup>3</sup> /h HP 3900 Nm <sup>3</sup> /h LP 8700 Nm <sup>3</sup> /h total	28.8 million Nm <sup>3</sup> /a HP 23.4 million Nm <sup>3</sup> /a LP 52.2 million Nm <sup>3</sup> /a total
Consumption during the idle phase (three-shift operation, 2400 h/a)	1680 Nm <sup>3</sup> /h HP 1365 Nm <sup>3</sup> /h LP 3045 Nm <sup>3</sup> /h total	4.0 million Nm <sup>3</sup> /a HP 3.3 million Nm <sup>3</sup> /a LP 7.3 million Nm <sup>3</sup> /a total

### 8.3 Measured data from two typical body shop facilities

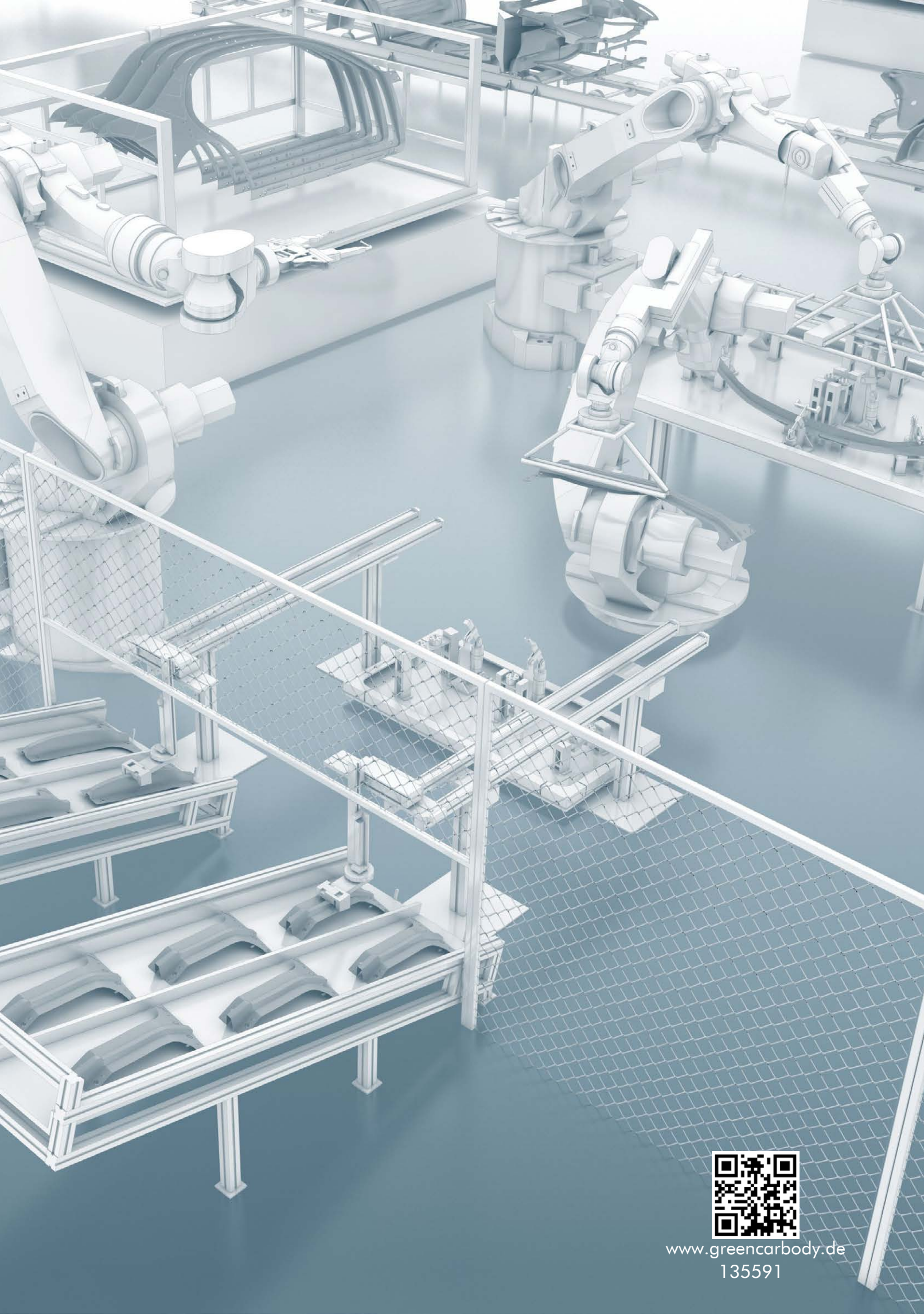
	"Old" facility	"New" facility
Number of actuators	72	345
Number of conventional welding guns	8	0
Number of servopneumatic welding guns	0	22
Output of components	78 pc./h	80 pc./h
Idle consumption, low pressure	5.1 Nm <sup>3</sup> /h	18 Nm <sup>3</sup> /h
Dynamic consumption, low pressure	25.7 Nm <sup>3</sup> /h	79 Nm <sup>3</sup> /h
Idle consumption, high pressure	7.6 Nm <sup>3</sup> /h	16 Nm <sup>3</sup> /h
Dynamic consumption, high pressure	8.7 Nm <sup>3</sup> /h	82 Nm <sup>3</sup> /h
Total air consumption	47.1 Nm <sup>3</sup> /h	195 Nm <sup>3</sup> /h
Compressed air costs	70 cents/h	3.05 euro/h

### 8.4 Air consumption and energy costs of pneumatic components

	Air for 1000 cycles	Costs for 1000 cycles
Toggle clamp	6 Nm <sup>3</sup> to 10 Nm <sup>3</sup>	8 cents to 13 cents
Conventional welding gun	20 Nm <sup>3</sup> to 35 Nm <sup>3</sup>	36 cents to 63 cents
Servopneumatic welding gun	7 Nm <sup>3</sup> to 20 Nm <sup>3</sup>	13 cents to 36 cents







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