

Chapter 9

Approach for Achieving Transparency in the Use of Compressed Air in Manufacturing as a Basis for Systematic Energy Saving



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Abstract The increase in energy efficiency in manufacturing and in particular in the area of compressed air is becoming a top issue in the context of factory planning and operation. Facing this development, the European Commission entrusted the Seventh Framework Program, Horizon 2020, to strengthen the research efforts to hit the proclaimed environmental, energetic and economic objectives of the European Union. In this paper, the authors present selected results on how to re-engineer brownfield factories to become clean and competitive factories of the future. Furthermore, the focus is put on energy-efficient generation, preparation, distribution and utilization of compressed air. It provides a systematic and practical approach to re-engineer existing compressed air systems to become eco-efficient. In European industries, around 10% of the final energy utilized is converted into compressed air as a factory internal energy source and hence plays a vital role for various applications such as handling and assembly of parts. When generating compressed air, it is important to use efficient compressor stations with optimized compressed air preparation and appropriately designed compressed air systems for distributing and utilizing the compressed air. However, due to a lack of transparency and knowledge in terms of actual demands and technical dependencies, compressed air systems are

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often operated inefficiently. The holistic approach described in this article suggests specific improvement strategies and innovative technology solutions based on profound evaluations in industrial cases.

9.1 Introduction and Scope

A look at the power demand of industry in Europe emphasizes the role of compressed air. In 2009, the industry sector accounted for a total energy demand of around 970 billion kWh (Eurostat 2009). Especially, the area of actuators and drive technology is relevant, and more than 60% of the industrial electricity demand is attributable to the provision of mechanical power, including about 63 billion kWh alone for the compressed air supply (IEA 2009). Many companies nowadays see a need for immediate action, especially in regard to rising energy prices and increased environmental awareness. Already, simple measures help to reduce the energy demand and significantly reduce energy costs. However, existing potentials are often unused.

In order to improve an existing compressed air system in terms of energy efficiency, the identification of most relevant energy losses and the selection of suitable improvement strategies are major tasks. In Fig. 9.1, the schematic sketch of a compressed air facility and their roughly estimated saving potentials within four main areas (air generation, air preparation, air distribution and air utilization) is shown. This holistic perspective is necessary since losses such as leakages and pressure drops within the upstream infrastructure mainly influence the efficiency of the overall compressed air system. Therefore, this article summarizes identification and improvement strategies for the overall compressed air infrastructure following a systematic approach.

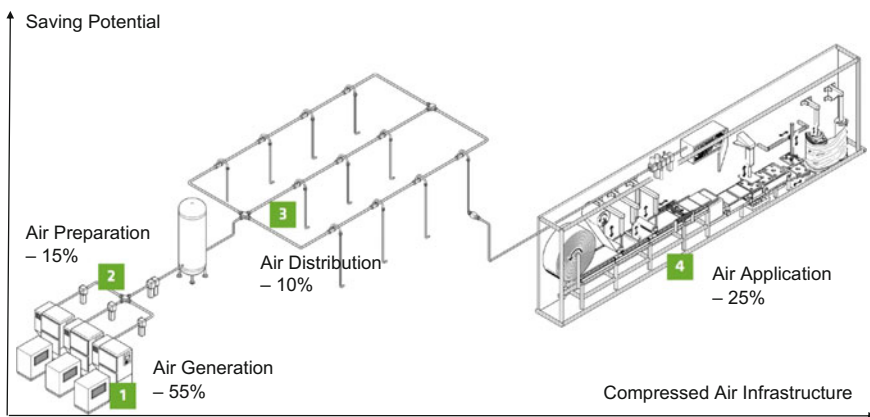


Fig. 9.1 Distribution of saving potentials within the compressed air infrastructure (Hirzel and Köpschall 2012)

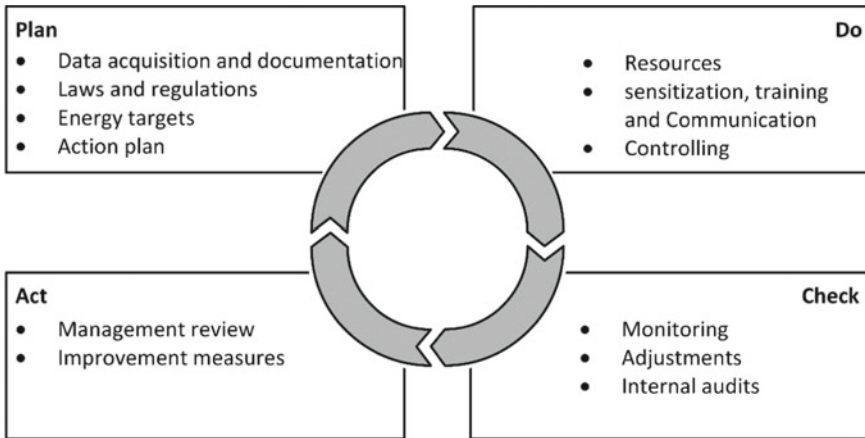


Fig. 9.2 PDCA—process with the four basic tasks and their key activities Adapted from (BMU 2012)

9.2 State of the Art in Energy Auditing in the Field of Compressed Air

Within facility management and the operation of factories, energy management gained importance during the last decades. In the meantime, systematic and normed processes like described in the ISO 50001 are more and more common in the industry. It is used for the systematic increase in energy efficiency in industrial production environments. The EN 15900 on energy efficiency services (DIN 2010) is another systematic approach, which aims at increasing the energy efficiency within the industry. The basis of both approaches is depicted in Fig. 9.2 as an improvement process which can be divided into four basic tasks.

The process starts with the identification of typical energy wastes, followed by the derivation of improvement strategies and the implementation of appropriate measures. Finally, the verification and sustaining of suitable measures guarantee long-term saving effects.

As the given approaches within ISO 50001 and EN 15900 focus on a general management level respectively consider energy efficiency as a whole, important aspects for the applicability within compressed air systems are not described in detail.

9.3 Approach

The nucleus of the developed approach follows a continuous improvement process and can therefore be aligned with processes like proposed in ISO 50001 and EN 15900. Combined the approach includes four steps. The first step targets the identification of energy wastes in compressed air systems. Referring to the identification, improvement strategies are shown. Subsequent the implementation of measures and their verification are described.

9.3.1 Identification of Energy Wastes

Table 9.1 highlights typical losses. The identification of sources for energy losses is explained in the following subsections, where additional strategies for avoiding the detected losses are presented.

Each loss is related to either surplus flow rate or surplus pressure level and can be directly converted into the energy demand at the compressor station. Leakages as flow rate losses have to be compensated by more compressed air generation whereas pressure losses have to be compensated by increasing the pressure level at the compressor station. As a rule of thumb, it can be stated that the increase in 1 bar at the compressor station leads to an increase in energy demand about 6%.

9.3.2 Compressed Air Generation

Compressors are the first element in compressed air systems. Losses in terms of surplus electricity demand are often resulting from wrong dimensioning of compressor stations and from wrong or inefficient supervisory control algorithms.

A suitable strategy for identifying losses within existing compressor stations is the measurement of the demand profile. The measurement has to happen over a sufficient long period of time, i.e. several days for capturing downtime and weekends with basic and peak loads as well as fluctuations in demand. Parameters which need to be

Table 9.1 Main loss sources within the compressed air infrastructure

Air generation	Air preparation	Air distribution	Air utilization
<ul style="list-style-type: none"> • Supervisory control of compressors • Dimensioning of compressors • Pressure level in compressor station 	<ul style="list-style-type: none"> • Level of air quality • Pressure drops in filters, dryers • Choice of components, e.g. drying equipment 	<ul style="list-style-type: none"> • Pressure drops in pipes • Leakages 	<ul style="list-style-type: none"> • Dimensioning of components • Leakages • Use of sealing air, blow air

captured for further loss detection are as follows: compressor operating times, energy demand measurements (current and voltage of each compressor), compressed air flow measurement (with analogous flow sensor) and pressure levels within compressor stations as well as required range of pressure for control at compressors.

The conduction of measurements helps to improve:

- **Costs transparency of compressed air demand:** With the measurements of energy demand of compressors and preparation equipment as well as the measurement of supplied compressed air volume with analogous sensors, the costs of compressed air demand can be calculated with *energy intensity of produced compressed air* [kWh/Nm^3] = *total electrical energy demand* [kWh]/*supplied air volume* [Nm^3] and the prices for electrical energy. As average values 2.0–2.5 cent/ Nm^3 are given in practice, but values have in general to be checked and determined for each individual industrial set-up. As further reference, the energy intensity should be at about 0.1 kWh/ Nm^3 at a given pressure level of 8 bar (Gloor 2000).
- **Transparency of energy demand of the entire system:** The measurement of compressor operating times and the pressure bandwidth at the centralized storage offer possibilities to put transparency into the process of compressing air. Several things can be detected such as performance of control of compressors (ratio between idle time and run-time of each compressor and overall station, degree of capacity utilization of compressors, matching of compressor power to required flow output). Furthermore, information about output reserves of the system is available.

9.3.3 Compressed Air Preparation

Compressed air preparation must be capable of supplying compressed air at precisely defined quality. Since oil, water or particles in compressed air have a negative effect on the service life span of pneumatic components, the air quality needs to be considered. They cause washout of lifetime lubrication and increased wear and damage to gaskets. Energy and operating costs rise; in worst case, it can lead to unexpected production downtime. Losses are often resulting from excessive requirements regarding the air quality or the use of outworn equipment.

A suggested strategy for identifying losses within existing air preparation facilities is measurement for compressed air quality. Parameters like the pressure dew point and oil concentration are needed to be captured for further loss detection and should be measured centralized and decentralized.

This strategy aims at keeping the quality of compressed air at an optimum level: the frequent inspection of centralized air preparation equipment helps keeping the quality of compressed air at an optimum level. Maintenance engineers often install surplus filters and dryers just to keep the air as clean as possible. If high quality of air is not required for the application, surplus equipment needs to be removed to reduce pressure drops (filters) and the usage of cleaning air (dryers).

9.3.4 Compressed Air Distribution

Optimal leakage management radically lowers the cost of compressed air, as leaky components are a great waste of energy and money. According to Radgen and Blaustein, about 16% of the total potential savings can be achieved in this area with the largest potential efficiency gain by just a single type of measure (Radgen and Blaustein 2001, p. 52). In contrast, in the EnEffAH study, Hirzel and Köpschall estimate the saving from regular leakage reduction measures with a 5% contribution to the total efficiency gain (Hirzel and Köpschall 2012, p. 34). In fact, leakages do not occur within widespread compressed air piping systems but within the tubing of the compressed air applications. The losses that are to be identified within the compressed air distribution are air flow losses due to outworn tubing or fittings as well as not properly closed tube endings and pressure drops¹ due to wrong dimensioning of pipes and tubes.

The following strategies for identifying losses within the distribution network are suggested:

- (1) Measurement of leaks in the entire plant by either using hand-held ultrasound detectors for manual leakage detection or installing an intelligent leakage detection system.
- (2) Centralized and decentralized measurement of pressure, e.g. at centralized storage as well as spot tests at supply units of applications with analogous pressure sensors.

The conduction of measurements helps to improve:

- Categorization and recording of leakages: With the help of ultrasound detection devices, leakages can be detected during operation that means no production downtime is required. Leaks can be rapidly identified and clearly categorized through marking. The classification of leaks helps the calculation of air losses in [Nm^3] or [€] for further cost-benefit analysis.
- Check for complete compressed air system, from compressor to pneumatic application: Test spot measurements of pressure within the overall compressed air infrastructure help the recording of information needed for repairs and improvements. As a rule of thumb, the pressure drop within the main piping system should be less than 0.01 bar (between storage and main piping system) and 0.03 bar (between main piping system and connecting pipe to application).

¹Pressure drops will only influence the energy efficiency of a compressed air system negatively if they occur between the centralized storage and the valve at the pneumatic cylinder that means within the piping part that is constantly ventilated with compressed air. The pressure drops have to be compensated by an increased pressure level at the generation unit in order to guarantee a minimum supply pressure at the application. This results in higher costs for air generation. The pressure drops within tubing between valve and actuator are similar to resistances and influence the dynamic behaviour significantly.

9.3.5 *Compressed Air Utilization*

Knowing the air demand of each machine is a vital prerequisite for optimal sizing of the compressed air supply and distribution as well as for determining leakage losses. But the application's demand profile is not only required for the dimensioning of the generation part. It can and should be used additionally to optimize the performance of the application itself—according to the saying “if it's not used, it doesn't have to be generated”.

The following strategies for identifying losses within existing applications are suggested:

1. Measurement of compressed air flow profile with the help of analogous flow sensors in supply unit as well as pressure measurements. The air demand profile should be captured over several hours depending on the production sequence in order to measure all the effects.
2. Measurement of air quality in decentralized supply unit based on the measurement of the parameters such as pressure dew point as well as visual inspection of air preparation units.
3. Measurement of leaks in individual machine with the help of manual ultrasound detectors.

The conduction of measurements helps to improve:

- Identification of inappropriate compressed air usage: The information about potential savings within the compressed air application has to be gained from analysing various characteristics such as: demand per machine cycle and per minute, average and max./min. pressure and max./min. rate of air flow. Therefore, the exact demand during both downtime and operation has to be captured. With the correct information on actual air demand, unnecessary energy demand due to oversupply as well as undesired pressure drops due to undersupply can be identified. The detection of leaks with ultrasound is a possibility to detect small leakages during operation.
- Optimal configuration of compressed air supply to the machine: Continuous maintenance of compressed air preparation favours the efficiency of the overall system, such as an increased service life of pneumatic components due to adjusted air quality. Similar to the optimization of centralized filters and dryers, the proper equipment has to be chosen for the decentralized air preparation in order to avoid surplus pressure drops and reduce demand.

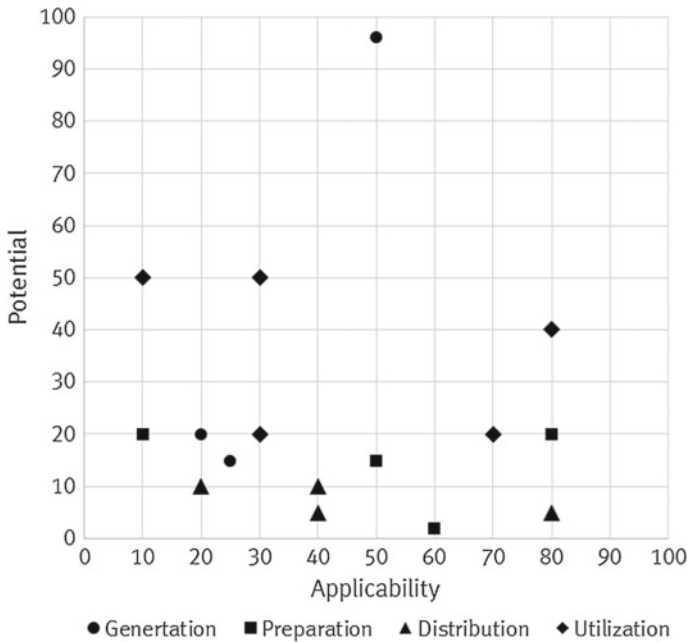


Fig. 9.3 Overview over improvement strategies with typical applicability and saving potentials

9.4 Improvement Strategies

In the following, suggested improvement strategies² are summarized for the four main areas of air generation, preparation, distribution and utilization. Figure 9.3 shows a portfolio of all improvement strategies with typical values for their applicability and saving potentials.

9.4.1 Compressed Air Generation

Current, voltage, pressure and flow rate measurements in centralized compressor stations are used to locate loss sources during the process of generating compressed air. Four main improvement strategies are suggested in the following.

- **Dimensioning of compressors adjusted to the demand profile (app. 20%, pot. 20%):** Optimized compressor stations are controlled by an overall control unit which accounts for changes within the demand profile. Several smaller compres-

²The improvement strategies are result of the research project EnEffAH (Hirzel and Köpschall 2012). The abbreviation “app.” defines the degree of applicability of the shown improvement method; “pot.” shows the possible saving potentials. Both values are rough approximations.

sors as well as a mix of frequency-controlled and fixed compressors add to the flexibility of modern stations.

- **Centralized heat recovery (app. 50%, pot. 96%)**: The usage of centralized heat recovery is one of the most promising improvement strategies for compressed air installation. The amount of energy used for generating compressed air is not lowered, but the emitted heat is recovered and used as process heat (water, air) within the company and to support traditional heating.
- **Use of frequency-controlled compressors (app. 25%, pot. 15%)**: The use of frequency-controlled compressors should be always combined with fixed compressor (no speed control). They can be perfectly used for balancing peaks within demand profiles. It should be mentioned that the efficiency of frequency-controlled compressors drops significantly beyond their operation point.
- **Reduction of main pressure level (app. 50%, pot. 15%)**: The reduction of main pressure level offers high saving potentials since it directly relates to the energy demand at the compressors. A reduction is often possible as soon as surplus pressure drops have been avoided.

9.4.2 Compressed Air Preparation

Within the area of compressed air preparation, high pressure drops in outworn components or the too restrictive air quality requirements are offering high saving potentials. Three main improvement strategies are suggested in the following.

- **Choice of drying technology (app. 50%, pot. 15%)**: The choice of technology for drying the compressed air up to a defined dew point influences possible saving potentials. Since refrigerant-type dryer (minimum dew point 3 °C) requires only 2% of the overall energy for generating compressed air, adsorption dryers (minimum dew point –80 °C) use 30%.
- **Dimensioning of air preparation unit (refrigerant-type dryer: app. 60%, pot. 2% and adsorption dryer: app. 10%, pot. 20%)**: Often, too restrictive requirements on the air quality add up to an over-dimensioning of air preparation equipment. This fact results in surplus pressure drops—main pressure level has to be increased to compensate these pressure drops.
- **Regular check of air preparation equipment (app. 80%, pot. 20%)**: The regular check of air preparation equipment is a relevant factor for guaranteeing the efficiency of the overall system. There can be high and surplus pressure drops in filters that are blocked by oil and dirt. A half-yearly check of filters can end up in a reduction of the main pressure level by 1 bar. This results in a reduced energy demand of approximately 6% due to the reduced pressure level at the compressors.

9.4.3 Compressed Air Distribution

The correct dimensioning of the piping system influences the overall efficiency and is mainly dependent on two loss sources—pressure drops due to wrong dimensioning and leakages due to missing maintenance. Hence, four improvement strategies are suggested:

- **Optimized dimensioning of piping infrastructure (app. 20%, pot. 10%)**: Piping systems are often undersized. The reduced pressure level at the compressed air utilization has to be compensated by increasing the main pressure level at the generation unit. The pipes should better be oversized than undersized.
- **Optimization of network topology (app. 40%, pot. 5%)**: The choice of network topology decreases or increases the performance of the piping infrastructure. Whereas branched networks suffer from constantly increasing pressure drops, networks with closed circuits pressure drops can be balanced and the absolute pressure level stabilized.
- **Placement of decentralized storages (app. 40%, pot. 10%)**: Decentralized storages are a cost-efficient way of stabilizing pressure oscillations in piping networks. They are frequently used close to consumers with high dynamics and huge demand.
- **Reduction of leakages (app. 80%, pot. 5%)**: Leakages have to be reduced (refer Sect. 9.5).

9.4.4 Compressed Air Application

Typical machinery for automation processes consists of several components that are using compressed air in different ways. For a better description of relevant improvement strategies, compressed air utilization is divided into five categories such as vacuum applications (1), use of blow and sealing air (2), grippers (3), pneumatic cylinders (4) and pneumatic pivot drives (5). The following improvement strategies for the aforementioned five application types are highlighted.

- **Reduction of pressure level applicable to types (1) to (5)**: The pressure at the decentralized supply unit (right before each application) should be reduced up to the point where the machinery does not function anymore. This avoids over-dimensioning. In case of modern machines with correct dimensioning, this improvement strategy is not applicable!
- **Replace double-acting cylinders by single-acting ones for types (3) and (4) (app. 10%, pot. 50%)**: A spring is used for realizing the return stroke of the cylinder. Hence, half the amount of air is saved within one stroke.
- **Reduce size of components applicable to type (1) to (5) (app. 80%, pot. 40%)**: The dimensioning of automation systems that means the choice of components in type and size should always be done by experts. There are tools for optimized dimensioning available by component suppliers. The correct dimensioning is the most important step towards an efficient drive system.

- **Reduce pressure level for unproductive return strokes applicable to type (3), (4) and (5):** In case of unproductive return strokes, the pressure level can be reduced.
- **Shorten tubing length applicable to types (1) to (5):** As stated earlier, the size of piping between valve and actuator influences the air demand of the drive system. They represent a dead volume that needs to be filled within each stroke. Hence, tubes should be shortened as much as possible. Additionally, the diameter accounts for the air demand. Tubes with too small diameters function as resistance and influence the dynamics negatively.
- **Air-saving circuits (app. 30%, pot. 50%):** There are several possibilities for the implementation of air-saving circuits, e.g. for usage in vacuum generators. Nevertheless, the shortening of running time of blow and sealing air components is a simple but effective improvement method.
- **Avoidance of dead volume (app. 30%, pot. 20%):** Especially in cylinders and tubing, dead volume should be reduced as much as possible.
- **Elimination of leaks in application (app. 70%, pot. 20%):** Most leakages occur inside machinery and only a few within the overall piping infrastructure. Above all, outworn and leaky fitting cause flow losses.

9.5 Implementing Measures

The implementation of appropriate measures calls for elaborated concepts. In the following, the most relevant measures to improve energy efficiency along the whole compressed air infrastructure are described.

9.5.1 *Optimization of Parameters in Compressed Air Generation and Preparation*

The measurements and correct interpretation of the parameters should be in general done by specialists for compressed air installations. These service providers often offer trainings for customers such that they can do these measurements on their own and/or derive the necessary plans of action.

9.5.2 *Leakage Management System*

The detection of leakages with ultrasound equipment is comparably time-consuming in typical industrial plants. A leakage management system is according to the Plan-Do-Check-Act (PDCA) management cycle supporting the continuous and automatic

monitoring of compressed air systems. There are three different levels of leakage management suggested (dependent on flow volume and power of compressed air installation in factory)—Level 0: One-time manual leakage detection and repair typically done by external service provider, e.g. for smaller outworn compressed air installations; Level 1: Yearly manual leakage detection by trained employees as well as yearly check by maintenance service for compressors; and Level 2: Installation of distributed sensor equipment in piping system (e.g. at storage, junctions in main piping system, at supply unit of each application) and automatic monitoring by overall Supervisory Control and Data Acquisition (SCADA) system with alert function (e.g. changes in demand profile, increase in pressure drops). The leakage management concepts in Level 1 and Level 2 have to be defined as a personal action plan for savings, with systematic documentation of leak elimination. Action plans have to be defined for rapid and lasting leak elimination.

9.5.3 Condition Monitoring and Diagnostic Systems for Application

Condition monitoring and diagnostic systems help to detect changes in pressure and flow rates early and to prevent impending production downtime. If downtime still occurs, they enable rapid detection of the problem. A condition monitoring system has to fulfil the following objectives such as: continuous monitoring of critical machine processes, prevention of unplanned downtime as well as permanent demand monitoring and rapid detection of deviations. It supports the maintenance engineer during the analysis of the process and the identification of the parameters to be monitored. It furthermore saves the parameters. An elaborated condition monitoring system guarantees energy-optimized system operation, transparency of demand, constant production quality, maximum availability and budgeting for repairs.

9.5.4 Improvement of Existing Machinery

Improvement concepts for compressed air applications should obviously go beyond fixing leakages. Further savings by strategically redesigning the compressed air system for the future have to be addressed. This will not only stabilize the processes but also reduce the costs. Based on the previous losses detection and improvement strategies optimization, measures for relevant machines need to be implemented. For the analysis of relevant applications in a machine, two main phases are suggested, namely a general and detailed analysis which are shown in Fig. 9.4. Before starting the analysis, a comprehensive picture about relevant data such as the energy demand and expected cost-effectiveness should be available (initial phase). The main first phase as the general analysis allows a structured analysis of the components to

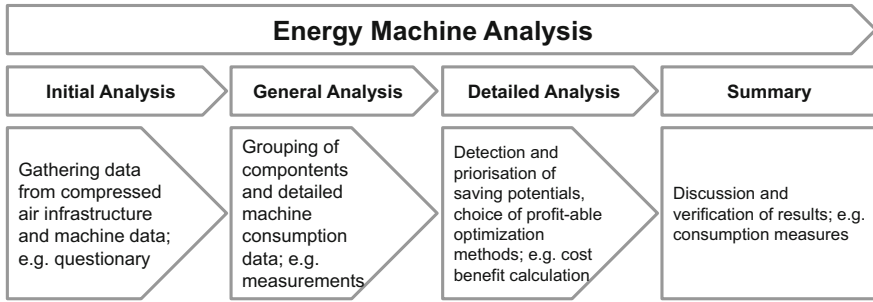


Fig. 9.4 Main phases of the machine optimization concept

identify compressed air savings. The detailed analysis as the second phase determines the actual demand and the impact of the specified measures to optimize the demand of the components. This can be the basis for the economic evaluation of optimization measures and further recommendations. Finally, the optimization has to be performed either by service experts or by trained employees. Within the summary phase, the verification of implemented optimization methods has to be done by evaluating measurements.

The optimization of existing machinery aims at the reduction of energy and compressed air demand as well as the shortening of cycle times, simplified installation, simplified maintenance and improved process reliability.

9.5.5 Engineering of New Machinery

Instead of optimizing an existing machine, the correct dimensioning and engineering of a new machine offers far more saving potentials also in case of drive systems. The choice of pneumatic cylinders with or without rod as well as the choice of cylinder diameter and damping technology influences the dynamics of the system as well as the energy demand. The combination of “technology choice”, “operational strategy” and “dimensioning” leads to the implementation of a modern and energy-efficient actuation system. Most manufacturers for drive components offer engineering tools supporting the customers during the process of machine engineering. Axle-type drive components represent a small number of components since they can vary in diameter, stroke and guide. The process of component choice is challenging and requires expert knowledge.

The main steps during this process are as follows: the initial step is the definition of the application and specification of requirements such as moving/gripping and installation position. Relevant limitations such as existing infrastructure required safety classes and environmental conditions are to be defined as well. With the help of simulation software, a pre-assessment of components can be made respecting defined technical criteria such as geometry aspects, accuracy limitations, dynam-

ics and mechanical limitations such as guides. A set of possible solutions is the results of the pre-assessment and needs further design criteria for the final choice of components. Final selection criteria are stock availability of components at the customers, effort for maintenance, life cycle costing (LCC) calculations as well as existing technology know-how at customer.

9.6 Verification and Sustaining

9.6.1 Verification

Following the implementation, the improvement measures have to be verified. After the improvement measures have been implemented, a further measurement can determine the success of the actions taken. This can be done easily by performing the same measurements as defined for the identification process. Finally, a sustaining process has to be established in order to guarantee that losses are avoided in advance and errors during design and operation of machinery are not to be repeated.

9.6.2 Sustaining

Section 9.5.2 described three different levels of leakage management. A professional elimination of leaks, i.e. the repair or replacement of leaking or faulty pneumatic components, has to be performed in order to stop wasting energy. This often provides the earliest return on investment. Looking at long-term benefits, the mentioned activities must be taken regularly to maintain the optimized condition of the machines and the compressed air infrastructure.

The benefits from using external expert services are proven. With the help of external maintenance services (ideally compressed air or pneumatics specialists), the systems can be brought to the latest energy-saving standards. Typical preventive and corrective maintenance services include:

- Inspection: Checking for damage, component inspection, checking of air preparation and filtration.
- Preventive maintenance: Air filter replacement, silencer replacement, lubrication/re-lubrication of guides, etc., tightening of loose fittings, screws and belts.
- Corrective maintenance: Elimination of leaks, component replacement, component repair.

In a second step, employees' awareness of energy efficiency should be raised and barriers must be reduced. This is essential to ensure that the measures implemented are successful in the long term. This newly raised awareness should also be com-

municated to suppliers (e.g. in performance specifications) and customers (e.g. via marketing).

The approach was evaluated at partner facilities of the automotive and rail industry sector focusing on their specific needs (Chap. 4). The involved partners covered a broad range of competences and interests such as technology provider, system integrator, service provider and manufacturer. These different perspectives and contributions are relevant to identify and implement the most promising optimization potentials.

9.7 Application

The analysis at the partner's facilities increased the level of transparency and clearly indicated the hot spots in terms of areas with high compressed air demand levels. Audits with mobile inspection and measurement equipment such as ultrasound detection devices provided an overview of occurring leakages in relevant application areas, e.g. on machine level between valve and the clamping devices.

In the following chapters, chosen solutions for specific applications are described.

9.7.1 *Supporting Technology Decision in Engineering of Actuation Systems in Automotive Industries*

Same as in every other industry, production processes in the automotive industry are based on a number of various actuation tasks. Figure 9.5 shows a selection such as gripping of car assembly parts, positioning of cutters and applying high forces for pressing processes. Which technology to choose is first of all a question of fulfilling technical specifications such as cycle time, forces and loads. Especially in automation, one actuation task might be realizable with different technologies (e.g. electrical, pneumatic and hydraulic) and nowadays with many components in different sizes and power ratings. That degree of freedom offers the chance for an energy-optimized design of actuation systems during the machine planning process, namely the use of an assessment tool.

Within the shown case, a simple but every effective set-up for an assessment tool for energy efficiency improvements within the application scenarios is identified, while quantifying the potential energy savings as well as payback time for investments and maintenance costs at the same time. This way, decision-makers have the possibility to carry out energy diagnosis focusing on most relevant alternatives and getting reliable data during the planning process at comparatively low costs.

The principle set-up for the assessment is highlighted in Fig. 9.6 and depicted as follows:

- Separation of process in single actuation tasks S

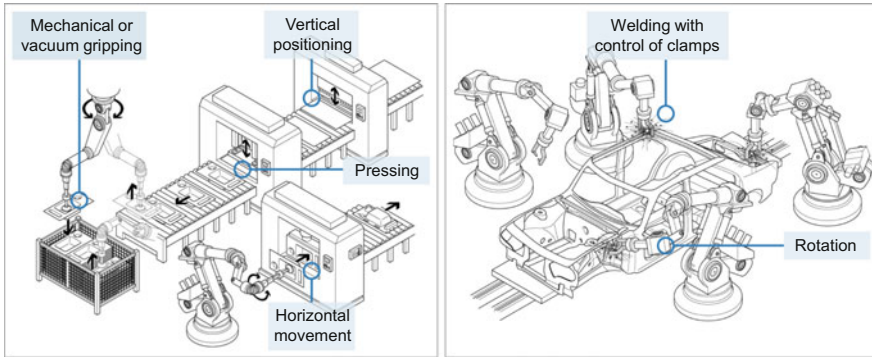


Fig. 9.5 Manufacturing processes in the automotive industry require various automation tasks such as horizontal or vertical movements and positioning, pressing, gripping or high-speed rotations

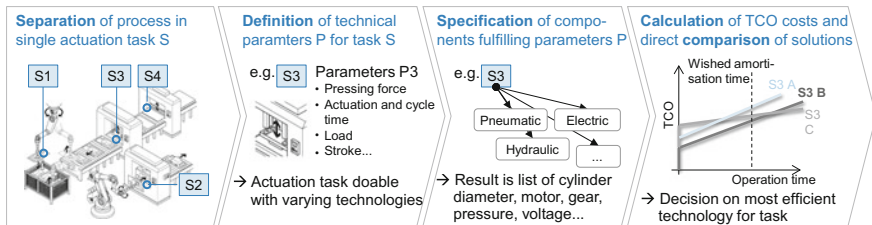


Fig. 9.6 Step-by-step process for supported technology decision for actuation systems in automotive industry

The separation should be done on component level. Several tasks could be later aggregated on a cell or machine level to represent different application scenarios.

- Definition of technical parameters P for each task S
With a pre-done mapping of major tasks in automotive industry (e.g. gripping, welding, positioning), the main parameters are easily added to each task. Typical values are the load, the stroke length, cycle time and standby time, relevant forces.
- Specification of components fulfilling parameters P
To be evaluated, components are either given or can be gathered by an additional design tool with dynamic simulation support. The result is a list of component sizes and power ratings fulfilling the technical parameters P as well as investment costs for each configuration. Sometimes, the dynamics simulation support already calculates the energy demand for one cycle which can be used for the next step.
- Calculation of total costs of ownership (TCO).

For complex functions that cannot be described by formulas or empirically, it can be helpful to use simulations, e.g. to determine the energy requirements of electric drive systems in a control loop with different positioning profiles. The graphical and numerical analysis can be performed with a simple break-even point determination. At the end of the assessment, a mapping of the whole hierarchical system structure

(e.g. whole production line) with an aggregation of the results on the individual actuation tasks is possible.

On the basis of the derived data, a decision-maker can decide what type of, e.g. clamping device is favourable in the long-term economic sense or at a specific amortization time for the machinery. Analogous, calculations can be done for other components such as welding guns. The more detailed the back-end calculations for energy costs are, the more precise the TCO forecast will be.

The shown way of technology assessment with demand data and break-even point (compare Fig. 9.6) should be used nowadays when discussing of energy-optimized production processes. They give a clear indication about the share of energy costs in each production line and support approaches for energy-transparent machinery. The decision-maker is now able to decide to what extent this information is relevant and may support to switch to other actuation technologies.

9.7.2 Creating Energy Transparency on Machine Level

Energy data is important for a strategic energy management—especially, the identification of potentials as well as the verification of implemented measures depends on the availability of this data. As Müller et al. state a typical challenge in production is this availability of energy data from a top factory level down to the machine level (Müller et al. 2009). Furthermore, bare energy data without additional data or reference values makes a profound evaluation hard or even impossible. Additional data can be machine data (e.g. machine states) or production data (e.g. information about the processed order, the number of produced parts or the currently produced part).

A possible solution to this problem is a continuous energy monitoring system with distributed sensors on machine level, which is able to complete monitoring solutions on building level (Posselt 2015). The following approach focuses on a solution that monitors electrical energy and compressed air demand as well as the machine states of the corresponding machine.

For a first practical implementation, a machine group with an estimated high energy-saving potential was chosen and equipped with suitable sensors for electrical energy and compressed air flows. The machines are part of a job-shop production as it can be found for the production of automation components (e.g. valves and valve terminals). To ensure the retrofit ability, clamp-on current transformers for electrical energy measurement were selected. The compressed air demand is measured using a pressure and a flow sensor.

An additional PLC captures the sensor values and obtains machine states via a data connection to the main PLC of the machine. Both PLCs are placed within the electrical cabinet of the machine. The additional PLC is able to pre-process the energy and machine data and provides a basic visualization. The number of produced parts is not provided by the main control of the machine group. To calculate KPIs like “required energy per part”, the produced parts are estimated with a counter for the

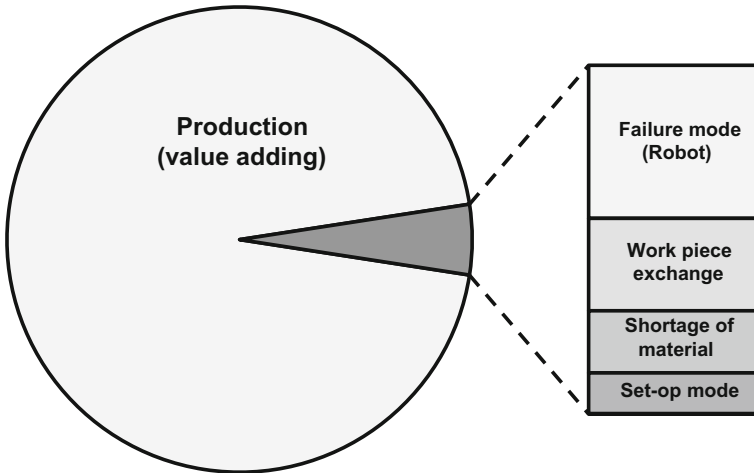


Fig. 9.7 Production state and non-value-adding states of a machine

machine state “changing workpiece”. The pre-processed data is made available to supervising systems via OPC UA. Supervising systems can be SCADA, MES, ERP or energy management software systems. Those systems are capable of automatically evaluating the data from the machine. Further functionality could be intelligent alerting, the generation of reports or the visualization of the data for different users.

With the additional equipment, a continuous monitoring of the energy flows on the machine level could be achieved. Energy flows can be separated into value-adding energy, if the machine is in “production state”, and non-value-adding energy, in case the machine is in states that are not productive like “standby” or “parts shortages”. The base for new benchmarks and KPIs like “used energy per produced (good) part”, “energy per processed order” or “percentage of power consumed in value-adding machine states” (see Fig. 9.7) is now given. These benchmarks and KPIs can be used for many purposes like:

- Supporting maintenance work (to identify issues or for predictive maintenance).
- Identifying optimization potentials.
- Tracing actions for increased energy efficiency with respect to their effectiveness, adherence or the achieved savings.
- Allocation of energy costs to different organizational units.
- Raising awareness for energy usage.

In further steps, the developed solution will be transferred to more machines that exceed a threshold in energy demand which makes them relevant for a continuous monitoring. For machines with an energy demand below the threshold or old machines with a low estimated remaining operating time, temporary measurement can support the overall energy transparency. Equipping existing machines with hardware to obtain energy transparency is just a first step towards an energy-transparent

factory. The energy-transparent machines together with energy metres from the facility build the basis for an energy transparency system. The energy transparency system has the following main features:

- Providing visualization of all relevant energy flows of a factory.
 - Seamless integration of energy data from facility and production.
 - Adapted visualizations for different user roles and their preformed tasks.
- Support of continuous improvement processes.
 - Identification of improvement possibilities.
 - Verification of improvement measures.
- Supervision of energy flows.
 - Detecting leakages or pressure drops in compressed air networks.
 - Detecting load peaks.
 - Detecting unusual behaviour of machines as a precursor of machine fails.

9.7.3 Intelligent Machine Monitoring in Rail Industry

9.7.3.1 Problem Statement

The guidelines above provide various approaches to optimize compressed air installations and applications in new and existing factory environments, whereas assessing saving potentials of compressed air distribution and utilization systems is a perpetual issue in production environments. Especially, industries with a high degree of manual manufacturing operations profit from stepwise improvement in production, following the well-known lean principles. As an example, the manufacturing of metro cars requires relatively a high share of manually performed operations, focussing on the area of roof and undercarriage assembly. The dominating manual production operations are weld seam preparation (bevelling) and weld seam finishing (trimming). The manual chip-cutting operations are performed with compressed air-driven power tools (angle grinders, vertical grinders, die grinders, drills, tappers and riveting hammers), as exemplarily depicted in Fig. 9.8.

Compressed air-driven tools are favoured over electric tools in the given production site because of the presence of very rough working environments (high dust and noise emissions), comparably lighter tools and very robust mechanics of such. The disadvantage of the utilization of compressed air-driven tools in rough working environments is the fact of seemingly rising leakages due to ageing and contaminated joint and gaskets. Gaskets, couplings and pneumatic hoses are subject to frequent connection and disconnection of power tools, which is accelerating and conveying the contamination and ageing processes. These effects are even hard to reduce by frequent maintenance intervals. Therefore, the degree of leakages in the present working environment is fairly high in comparison with higher automated production facilities.

Fig. 9.8 Pneumatic power tool (grinder) used in manual post-processing of welding seams



Due to the high noise emissions in the working environments, obvious leakages of broken gaskets or joints are hardly perceptible. Hence, leakages are difficult to be removed and are therefore omnipresent.

The operation of an optimized compressed air infrastructure can be further supported by decentralized, automated devices, which shut down the energy supply (compressed air) of supply net branches during non-demand times. This approach is described in the case at hand. To verify and assess the potential of an automated compressed air supply management in production, a functional prototype was tested at Siemens production site in Vienna. The goal was to counter the problem of wear-out effects in train manufacturing. Therefore, a compressed air-saving module was developed, which was placed in the branch lines of the compressed air distribution infrastructure. The branches are leading to manual workstations. After laboratory testing of the module, the smart distribution network was implemented in the pilot demonstrator. The prototype of the air supply unit was placed in the body in white production for train coaches. Manual manufacturing steps, such as milling and deburring after joining processes, are performed by various hand-held compressed air power tools.

The module, depicted in Fig. 9.9, contains a smart control unit which is capable of automatically recognizing demand and standby times of connected power tools. During demand times, the smart distribution network supplies the power tools with compressed air at grid pressure level. During standby times, the grid pressure is auto-



Fig. 9.9 Mobile functional prototype of the smart air-saving unit

matically cut off and leakages in the downstream periphery are therewith reduced to a minimum. When demand occurs again after an automated pressure cut-off, the unit is capable of automatically recognizing the demand and seamlessly resupplying the power tools with full grid pressure. This behaviour can be seen in Fig. 9.10. Additionally, the smart unit is capable of logging productive compressed air demands and the saved amount of pneumatic energy on a continuous basis. For the demonstration case, an additional visualization unit allows to present these performance indicators to the observer on a human-machine interface (HMI screen), as depicted in Fig. 9.12. The testing period was set to 4 weeks of operation. The gained data was evaluated according to the potentials, and qualitative interviews were conducted along the working personnel to estimate the practical influence of the automated shutdown functionality.

9.7.3.2 Functional Prototype

To reveal and assess saving potentials, a modified air supply unit with prototypical functions, as described in Table 9.2, was installed at a compressed air supply hose in a manual manufacturing workstation. The hardware of the module includes sensors to monitor the volume flow and the pressure level, as well as valves for safe switching of the compressed air supply.

The installation was placed in a pipe of the compressed air infrastructure near a manual working station, as shown in Fig. 9.11. The volume in the hose between the module and the coupling was used for implementing the described functions

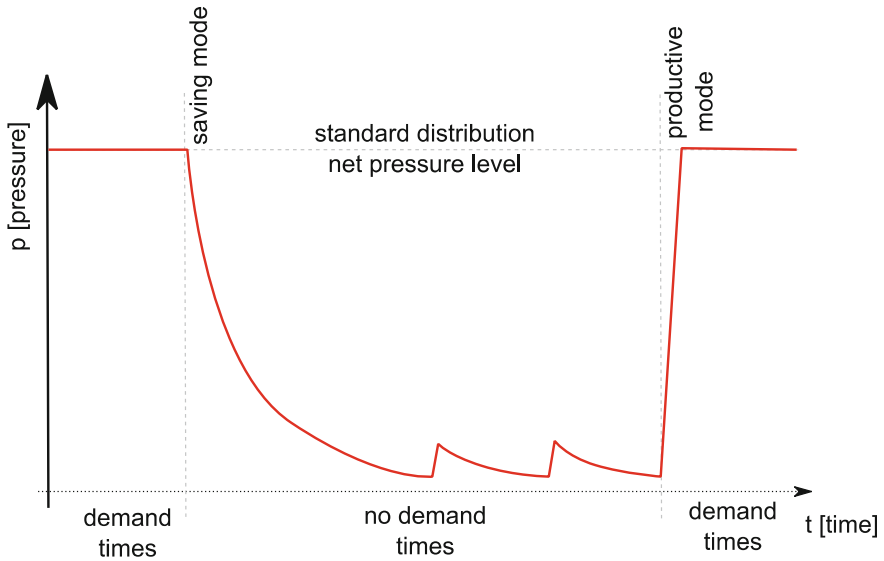


Fig. 9.10 Ideal pressure demand profile of the manual working station

Table 9.2 Additional functions of the compressed air supply unit

Function	Description
Automated shutdown	The module shuts down the energy supply if there is no active use of compressed air
Automated switch-on	The module smoothly switches on the compressed air supply with a short delay if a demanding consumer is detected
Savings monitoring	Based on pressure gradients in the closed supply branch, the leakage rate of the downstream branch is calculated
Estimation of potentials	The potentials are estimated based on the leakages and certain site-specific factors

(compare Table 9.2). For a period of 4 weeks, data was acquired and saving potentials were monitored.

Besides the leakage monitoring, the module is capable of performing network condition monitoring (pressure level, pressure drops, maximum and average demands, etc.). Leakage-level alarms can be triggered visually and as a digital output signal for external alarms processing.

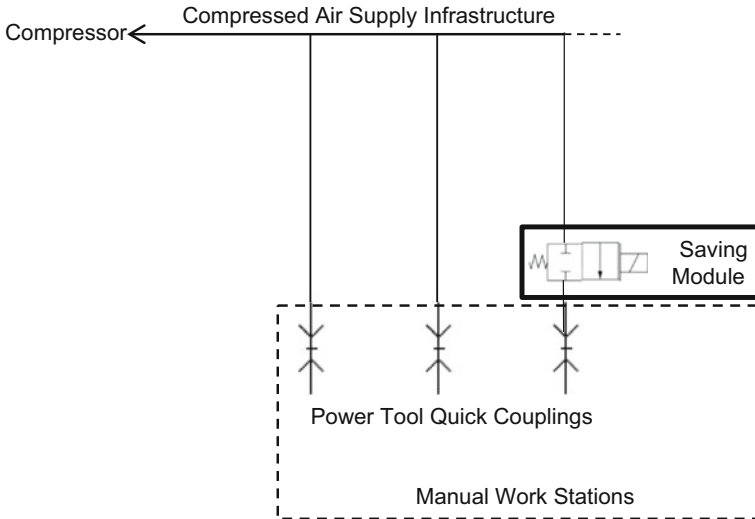


Fig. 9.11 Application environment of the compressed air-saving unit prototype

9.7.3.3 Results

The environmental and economic benefits are potentially high, as leakages during standby times are reduced to a technically possible minimum. During demand times, when power tools are in use, the leakages cannot be reduced automatically, but due to a continuous condition monitoring, alarms can guide energy-saving services by providing an instant return of investment (human workforce and maintenance material) calculation, as depicted in Fig. 9.12, in the screenshot from the detachable HMI screen. The smart distribution network is installed for long-term testing at the demo site to evaluate specific savings and suitable parameter values to improve the control algorithms to be adaptable for varying application conditions.

The assumed high savings were validated by the conducted measurements. The assessment during the testing period leads to high savings and hence quick amortization times below 1 year. A challenge for a broad implementation of such a decentralized solution is the unforeseen malfunctioning of the control unit, as the module is designed to seemingly integrate in the workflows of daily operations. The huge advantage of the developed solution is that shop floor personnel do not need to change their behaviour during operation of the hand-held tools, which favours a high degree of acceptance. Conclusively, retrofitting existing compressed air supply infrastructure to a *Smart Distribution Network* is recommendable for certain industries branches with a high share of utilized manual power tools, as the Siemens case above proves. Furthermore, continuous monitoring of compressed air networks featured by those decentralized devices provides the basis for the initiation of demand-oriented energy-saving services and reactive maintenance approaches in production. Combined with

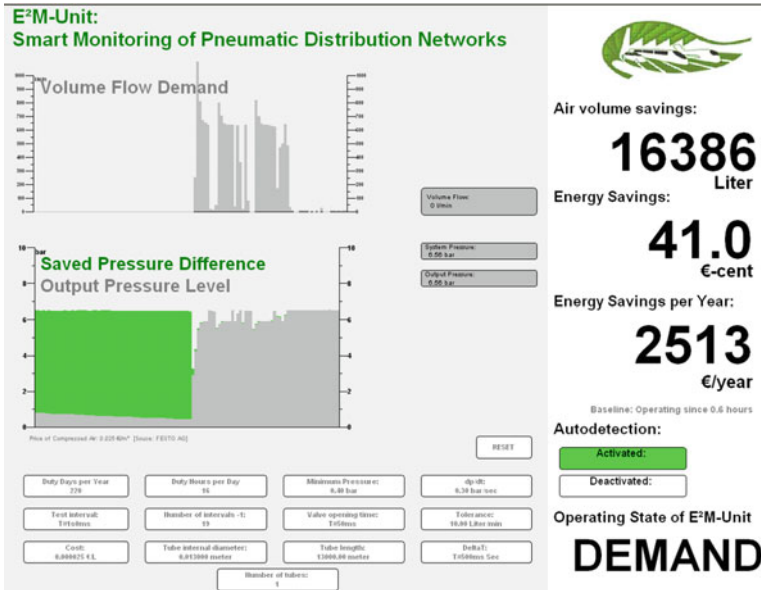


Fig. 9.12 User interface for quick evaluation of the functional prototype in the demonstration environment

advanced control and online analytics, even concepts approaching predictive maintenance become accessible.

9.7.4 Supported Technology Decision for Actuation Systems in Automotive Industry

Same as in every other industry, production processes in the automotive industry are based on a number of various actuation tasks. Figure 9.5 shows a selection, such as gripping of car assembly parts, positioning of cutters and applying high forces for pressing processes. Which technology to choose is first of all a question of fulfilling technical specifications such as cycle time, forces and loads. Besides that, and especially in automation, one actuation task might be realizable with different technologies (e.g. electrical, pneumatic and hydraulic) and nowadays with many components in different sizes and power ratings. That degree of freedom offers the chance for an energy-optimized design of actuation systems during the machine planning process, namely the use of an assessment tool.

Within the EMC2-Factory project, a simple but very effective assessment tool for energy efficiency improvements within was developed, able to quantify the potential energy savings as well as payback time for investments and maintenance costs at the same time. This way, decision-makers have the possibility to carry out, with low

cost, a thorough energy diagnosis focusing on most relevant alternatives and getting reliable data during the planning process.

The principle set-up for the assessment is highlighted in Fig. 9.6 and depicted as follows:

- **Separation** of process in single actuation tasks S
The separation should be done on the component level. Several tasks could be later aggregated on a cell or machine level to represent different application scenarios.
- **Definition** of technical parameters P for each task S
With a pre-done mapping of major tasks in automotive industry (e.g. gripping, welding, positioning), the main parameters are easily added to each task. Typical values are the load, the stroke length, the cycle and standby time and relevant forces.
- **Specification** of components fulfilling parameters P
To be evaluated, components are either given or can be gathered by an additional design tool with dynamic simulation support. The result is a list of component sizes and power ratings fulfilling the technical parameters P as well as investment costs for each configuration. Sometimes, the dynamics simulation support already calculates the energy demand for one cycle which can be used for the next step.
- **Calculation** of TCO costs (investment and energy costs)
A connection to backend simulation for those complex functions which cannot be described through formulas or empirically might be helpful, e.g. energy demand of electric drive systems in a feedback control-loop with different positioning profiles. The graphical and numerical analysis can be performed with a simple break-even point determination. At the end of the assessment, a mapping of the whole hierarchical system structure (e.g. whole production line) with an aggregation of the results on the individual actuation tasks is possible.

On the basis of the derived data, a decision-maker can decide what type of, e.g. clamping device is favourable in the long-term economic sense or at a specific amortization time for the machinery. Analogous calculations can be done for other components such as welding guns. The more detailed the back-end calculations for energy costs are, the more precise the TCO forecast will be.

The shown way of technology assessment with demand data and break-even point figures (compare Fig. 9.6) should be used nowadays when discussing energy-optimized production processes. They give a clear indication about the share of energy costs in each production line and support approaches for energy-transparent machinery. The decision-maker is now able to decide to what extent this information is relevant and may support to switch to other actuation technologies.

9.8 Results and Outlook

The described approaches provide a guideline for operational energy saving in the area of compressed air. It has been developed together with the involved partners

and evaluated at partner's production sites as a part of the European research project EMC2-Factory.

The implementation of the developed solutions as described in Sect. 9.4 has shown that this has to be done under consideration of the specific needs, based on an iterative analysis and covering a wide section of the live cycle. It begins with the consideration of energy efficiency during the design and engineering, covers the operation phase with new approaches for the energy monitoring during the operational phase and ends with closing the control loop by automatically switching of parts of the compressed air distribution in unproductive times to make use of identified energy-saving potentials.

The described measures and solutions are rather to be understood as possible blueprints and patterns than precise requirements. Each industry application has its specific boundary conditions and calls for more or less tailored solutions which should be developed together with partners.

The research work in the field of using compressed air more efficiently is ongoing, and more innovative solutions are on the way. It is foreseeable that drive components have to become smarter, e.g. to monitor or control the energy demand more effectively and in correlation to the real demand of the desired application in terms of technical parameters (such as force or velocity).

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