Zentrum Ressourceneffizienz

On behalf of:

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection

VDI ZRE Publications: Brief analysis no. 32

# Technologies for digitally recording of resource consumptions


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VDI ZRE Brief analysis no. 32: Technologies for digitally recording of resource consumptions

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This brief analysis was developed on behalf of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection.

The brief analyses of the VDI ZRE provide an overview of current developments in the field of resource efficiency in research and industrial practice. They contain a compilation of relevant research results, new technologies and processes as well as best-practice examples. The brief analyses thus provide an introduction to selected resource efficiency topics for a broad audience with business, research and administration background.

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# Technologies for digitally recording of resource consumptions

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| **AI** | Artificial Intelligence |
| **BUS** | Binary Unit System |
| **$CO_2$** | Carbon dioxide |
| **CRISP-DM** | Cross Industry Data Standard Process for Data Mining |
| **ERP** | Enterprise Resource Planning |
| **GHG** | Greenhouse gas |
| **GSM** | Global System for Mobile Communication |
| **HMI** | Human-Machine Interface |
| **$I^2C$** | Inter-Integrated Circuit |
| **IoT** | Internet of Things |
| **KDD** | Knowledge Discovery in Databases |
| **LIN-Bus** | Local Interconnect Network – Binary Unit System |
| **LON** | Local Operating Network |
| **MSG** | Metal shielding gas |
| **MOST-Bus** | Media Oriented Systems Transport |
| **PLC** | Programmable logic controller |
| **PPS** | Production Planning System |
| **RFID** | Radio Frequency Identification |
| **SEMMA** | Sample, Explore, Modify, Model, and Assess |
| **SENT** | Single Edge Nibble Transmission |

| | |
|---|---|
| **SME** | Small and medium-sized enterprises |
| **SQL** | Structured Query Language |
| **TDSP** | Team Data Science Process |
| **UI** | User Interface |
| **UMTS** | Universal Mobile Telecommunication System |
| **USB** | Universal Serial Bus |
| **VDI** | Association of German Engineers (*Verein Deutscher Ingenieure*) |
| **VDI ZRE** | VDI Centre for Resource Efficiency (*Zentrum Ressourceneffizienz*) |
| **WEKA** | Waikato Environment for Knowledge Analysis |
| **WPAN** | Wireless Personal Area Network |

# 1 INTRODUCTION

Digitalisation and climate action are some of today's megatrends in business.[1] The challenges of recent years have increased awareness and made companies more conscious of using available resources more sparingly. At the same time, however, the importance of being a technological leader in international competition cannot be ignored. It is becoming more and more important for businesses to consider the themes of digitalisation and climate action collectively to generate more synergy between both ends of the scale.[2] By combining both themes, businesses can achieve significant cost savings through the reduction in material and energy consumption. These savings and the increasing customer demand for environmentally friendly and resource-efficient products can also help to improve a business' competitive position.

Knowledge of the material and energy quantities used in the manufacture of products can help businesses to identify saving potential. Only by knowing how much material and energy is consumed can a business identify unplanned losses or unnecessarily high consumption quantities and derive corresponding measures to save resources.

Material and energy quantities used in production are measured using measurement technology. Compared to analog measurement technology, digital technology has the advantage of allowing users to automatically generate high data density with high information content within just a short period of time. There are many different digital technologies available for directly and indirectly recording material and energy quantities. This brief analysis provides an overview of which resources can be recorded and what measuring technology can be used to do so. It also shows the various possibilities for processing and evaluating the ascertained resource data.

Chapter 2 first outlines the fundamental terminology and illustrates the interplay between digital technologies for resource recording and measures for increasing resource efficiency.

1 Cf. Zukunftsinstitut GmbH (2020).

2 Cf. Öko-Institut e. V. (2022).

Chapter 3 looks at the relevant measurement methods and technology needed to digitally record resource consumption. This takes into account the full process, from recording to the integration of the consumption data. This also contains an overview of the relevant resources and the sensor types required to track these resources.

Building on this, chapter 4 then details the process of recording, saving and integrating resource consumption data. Various data mining methods are presented here (e.g. CRISP-DM or TDSP).

Chapter 5 outlines the opportunities and barriers to digitally tracking resource consumption. Using practical examples, this chapter also details how other businesses have implemented digital resource consumption recording and what benefits this has had for the company.

# 2 MEASURING RESOURCE CONSUMPTION IN PRODUCTION

## 2.1 Increasing resource efficiency through knowledge of material and energy flows

Resource efficiency is an important theme and not just in view of the current global challenges. It has become a central component of business and a key aspect of climate action. This is particularly clear to see when we consider the cost structure of manufacturing industries: 41.4% of all costs in manufacturing industries in Germany in 2017 were for materials and approx. 2% for energy (cf. Figure 1).

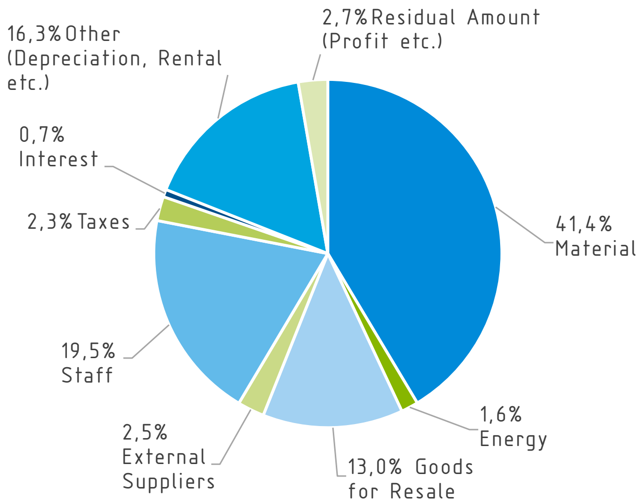


**Figure 1: Cost structure of manufacturing industries in Germany (2017)[3]**

This gives rise to a significant leveraging effect when it comes to potential material and energy savings. Resource efficiency can be used as an indicator here to identify potential areas for material and energy savings. As outlined in VDI 4800 Blatt 1, it is calculated based on the relationship between a

[3] Cf. Statistisches Bundesamt (Federal Statistical Office) (2019).

particular benefit (product, function, functional unit) and the expenditure of natural resources (e.g. amount of energy, raw materials or water used).[4]

According to VDI 4800 Blatt 1, natural resources include any renewable and non-renewable primary raw materials, energy resources, water, air, land and ecosystem services[5], with the three former resources being the most relevant in relation to manufacturing industries. However, the production of goods rarely involves the direct use of primary raw materials and energy resources. Primary raw materials are generally converted into materials relevant for production (e.g. materials, pre-products, consumables, operating supplies, components, assemblies) and final energy (e.g. thermal energy, electrical energy, compressed air) as part of upstream conversion and processing steps.

In order to be able to calculate resource expenditure, system limitations must first be defined. For businesses, this means determining the system boundaries in which resource efficiency should be measured (i.e. at a company, department, system or process level).

Once the system parameters have been set, companies must then define the benefit. For manufacturing companies, this can be defined as the number of manufactured products, for example. The complexity of calculations for determining the extent of natural resource use depends on the system boundaries outlined. Businesses must be able to provide the necessary information on the use of natural resources based on the previously defined system limitations.

To be able to calculate their resource use, businesses first require information on the used quantities of raw materials, energy and water. This already poses an initial challenge for businesses due to[6]

- unknown quantities of used resources,
- non-transparent distribution of resource costs,

[4] Cf. VDI 4800 Blatt 1:2016-02, p. 12.
[5] Cf. VDI 4800 Blatt 1:2016-02, pp. 13 et seq.
[6] Cf. Hirzel, S.; Sontag, B. and Rohde, C. (2011), pp. 7 et seq.

- varying budget responsibilities for funding of investments, and
- lack of clear regulation of staff responsibilities (resource managers).

There are multiple approaches for each of these challenges. These initially enable businesses to track energy and material flows at the company level and then perform a breakdown for the corresponding areas of the business. For this approach it is important to document where the data comes from and how it is broken down for the relevant departments and systems. It is useful to clarify whether system datasheets, specific measured values or even distribution ratios are used for this purpose. This is the only way to ensure transparency in the recording of resource consumption and allow for subsequent adjustments to the basis for calculation, for example as part of system replacements or process adjustments.

It is therefore recommended to define responsibilities as part of this initial resource consumption recording. This will create a solid organisational basis for later resource consumption recording. On a larger scale, measures for overcoming the above challenges can result in a holistically and strategically planned resource management system that is supported with digital resource consumption recording.

Analysing raw material, energy and water consumption in the relevant business areas allows the company to identify high resource consumption and losses. Resource consumption must first be quantified in order to develop measures for preventing loss and using resources more efficiently.

### Energy and material flows in manufacturing companies

Businesses within manufacturing industries use many different forms of energy and pre-products as well as materials, consumables and operating supplies. Knowledge of consumption volumes for individual production stages during production- or process-oriented[7] production processes provides the basis for determining high consumption or losses. Based on this knowledge, businesses can subsequently develop measures for using resources more efficiently and/or reducing the amount of resources used.

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[7] **Material conversion production processes (e.g. chemical processes)**

Businesses within manufacturing industries use large amounts of electrical and thermal energy across a wide range of production- and process-oriented operations. Access to consumption data for both energy forms is therefore very important for increasing resource efficiency.[8]

The materials used in production- and process-oriented product manufacturing processes are extremely diverse and vary in materials (e.g. metal or plastic). They also all have different physical and chemical properties, such as the state of matter (solid, liquid, gas), geometry, density, reactivity, etc. In principle, all material flows arising as part of production can be considered. From an economic standpoint, it is more effective to consider material flows with the highest share of quantity and/or costs in the first step.

### Measures for increasing resource efficiency

Knowledge of resource consumption within the company also helps to identify resource loss and areas of high consumption and subsequently develop measures to reduce resource use. The VDI 4800 Blatt 1[9] and 4801[10] guidelines outline practice-oriented measures for increasing resource efficiency. The resource efficiency measures that offer huge potential for resource savings and which are relevant to the manufacturing industry are presented below.

### Measures to prevent loss

- **Use of waste heat:** Due to the physical or chemical processes taking place, industrial production processes often generate waste heat. Identifying where this heat originates from and the amount of waste heat generated can allow businesses to use this waste heat in other places within or outside of production where thermal energy is required. This avoids thermal energy being lost.

- **Reduction of accepted loss, post-treatment and exclusion/reduction of reject batches and storage loss:** The reasons for material loss in

8 Cf. Umweltbundesamt (German Environment Agency), Bundesministerium für Wirtschaft und Klimaschutz (Federal Ministry for Economic Affairs and Climate Action) (2021), p. 31.

9 Cf. VDI 4800 Blatt 1:2016-02, pp. 38 et seqq.

10 Cf. VDI 4801:2018-03, pp. 17 et seqq.

production and chemical processes are manifold. By recording material flows, businesses can avoid loss, e.g. caused by accepted scrap, reject batches or storage loss. Identifying where and why material is being lost (e.g. through a reject batch) can help the business to rectify the cause.

- **Cascading use and internal reprocessing:** Where material streams arise as part of the production process that are not used as part of product manufacture and which have no purpose at the end of the process, these material streams can be fed back into the production process or reused gradually as part of cascading use. To do so, businesses must quantify the material streams that arise during production and define the relevant materials.

### Measures for resource optimisation

- **Avoidance of energy use:** Knowledge of consumption volumes for any types of energy used in production processes (e.g. electrical energy or thermal energy) is essential for developing measures for a more efficient use of energy (e.g. use of more efficient pumps or loss-free provision of compressed air).[11]

- **Optimisation of production processes:** The quantification of energy and material consumption in production forms the basis for optimising production and procedural processes. This makes it possible to identify processes that use large volumes of resources. In turn, businesses can develop solutions for improving the corresponding process in the aim of reducing the amount of energy and material used.

- **Efficient building infrastructure and envelope:** The possibilities for increasing efficiency in building infrastructures and envelopes are wide-ranging and the associated energy savings can be substantial. Typical measures include, for example, switching to a needs-based system for utilities such as light, heat and air conditioning or the use of an effective building insulation.[12] It is only possible to develop effective measures

[11] Cf. VDI 4800 Blatt 1:2016-02, p. 48.
[12] Cf. VDI 4800 Blatt 1:2016-02, p. 50.

when the building infrastructure's energy consumption is known and information on the amount of heat lost is available.

## 2.2 Efficiency potential through digital resource consumption data recording

The digital recording of resource consumption data makes it possible to identify resource efficiency potential quickly and precisely and thus lays the groundwork for the targeted design and prompt implementation of the measures illustrated in the previous chapter. Another advantage of the digital recording of consumption is the provision of valid data for energy management systems in the desired quality. This allows businesses to plan, manage and monitor energy-related targets with even more precision and structure energy monitoring more efficiently.[13] Digital resource consumption data recording also offers further potential beyond this.

### Increasing evaluable data quantities

Digital recording makes it possible to generate significantly more data in a shorter period within the company, resulting in a larger database. This is especially the case if sensors are used in areas that are inaccessible or hard to reach for people. In such cases, digital recording allows businesses to automatically record temperatures in set time intervals and forward this data without interrupting the actual production process itself. This also allows businesses to perform more complex analyses on internal resource consumption.[14] It is therefore recommended for businesses to identify the areas in which data is still being recorded manually and review how this data could be recorded digitally going forward. This may require certain systems to be retrofitted. The "Ecological and economic evaluation assessment of resource use – Industry 4.0 retrofit measures on tooling machines" (German: *Ökologische und ökonomische Bewertung des Ressourcenauf-wands – Industrie-4.0-Retrofit-Maßnahmen an Werkzeugmaschinen*) study by VDI ZRE explains and analyses the retrofitting of a tooling machine as an example.[15]

[13] Cf. Arns, M.-A. and Heupel, T. (2019), p. 58.
[14] Cf. Arns, M.-A. and Heupel, T. (2019), p. 61.
[15] Cf. VDI Zentrum Ressourceneffizienz GmbH (2022).

### Data variety as efficiency potential

The increased amount of data often also results in a large variety of data as data is frequently collected for various purposes. Where, for example, goods inward/outward for materials and finished products is already recorded, this data can be used to analyse material streams and material consumption. The extent of digital consumption data recording can be reduced by using digital data sources that are already available, and this data can be digitally processed to identify resource efficiency potential, including cross-department potential.[16] Businesses should therefore perform a review to see if and in what departments material and energy flow data is recorded, even where this was not the purpose of the original data collection.

### Networking production systems and resource management systems

Digitally recording consumption data also gives businesses the option to identify further and more complex cause-effect relationships between the systems and resource consumption. This, in turn, makes it possible for production systems to automatically react to changing consumption levels and reduce potential scrap or tool wear, for example.[17] It also means resource needs can be planned as a whole, allowing businesses to generate saving potential (e.g. through the switch to a needs-based provision of compressed air or a consolidation of compressed air systems) by digitally recording compressed air consumption in various areas of the company.[18]

### Pattern recognition

It is possible to analyse the digitally recorded resource consumption data using pattern recognition. Patterns identified using pattern recognition can then be used to develop suitable measures for increasing resource efficiency.[19] In its simplest form, pattern recognition can be achieved using an Excel table that filters or marks the systems with the highest energy use, for example. Patterns can also be recognised using deep learning or other AI

[16] Cf. Arns, M.-A. and Heupel, T. (2019), p. 62.

[17] Cf. Arns, M.-A. and Heupel, T. (2019), pp. 60 et seq.

[18] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021), pp. 132 et seqq.

[19] Cf. Arns, M.-A. and Heupel, T. (2019), p. 63.

algorithms. These methods are recommended for more complex processes or cause-effect relationships.

### AI algorithms

A wider variety of data can also be used to train AI algorithms (e.g. deep learning algorithms) to recognise patterns in datasets that would otherwise be impossible or very difficult for people to see. These algorithms also form the basis for evaluation of resource consumption data in digitalised resource management systems.[20] You can find an overview of the analysis methods used in practice in the VDI ZRE study entitled "Potential of weak artificial intelligence for operational resource efficiency" (German: *Potenziale der schwachen künstlichen Intelligenz für die betriebliche Ressourceneffizienz*).[21]

### Real-time analysis

Digital recording makes it possible to perform analysis in real time for the first time ever, allowing businesses to quickly react to changes to the production sequence or environmental changes[22] (e.g. if a hall door is opened and the wind coming in compromises the shielding gas dome when performing gas-shielded metal-arc welding). With real-time analysis, environmental changes like this are identified and the shielding gas feed can be adjusted accordingly, preventing components from being scrapped due to erroneous weld seams. Real-time analysis thus enables businesses to be more proactive rather than reactive, helping greatly to increase material and energy efficiency.

### Supporting decision-making and making life easier for decision-makers

In general, thanks to its larger quantities of data and better -quality of data, digital recording helps to increase forecasting quality and thus improves the level of production planning. This, in turn, helps decision-makers to react to changes to operating procedures more time-effectively and in a more

[20] Cf. Arns, M.-A. and Heupel, T. (2019), p. 61.
[21] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021), pp. 179 et seq.
[22] Cf. Arns, M.-A. and Heupel, T. (2019), p. 62.

targeted manner, while also preventing businesses from reacting to an extent disproportionate to the change.[23]

Digital recording also allows businesses to perform efficient digital evaluations and visualisations of the collected data, ultimately reducing the effort required for analysis and decision-making on the part of the company's decision-makers.[24]

To efficiently reduce resource use, it is therefore very important that consumption data is recorded promptly, efficiently, correctly, in full and in a way that is cost-effective; digital recording is therefore the perfect solution.

[23] Cf. Arns, M.-A. and Heupel, T. (2019), pp. 63 et seq.
[24] Cf. Arns, M.-A. and Heupel, T. (2019), p. 64.

# 3 MEASURING TECHNOLOGY AND COMMUNICATIONS TECHNOLOGIES

To be able to digitally record resource consumption, businesses should first become familiar with the various options for measuring consumption and available measurement methods, techniques and sensor types (see chapter 3.1) in advance. This puts businesses in the position to consider all options and the related margins of error early on when planning resource recording (e.g. resource consumption and loss, amount of scrap, tool wear). “The role of measuring technology [here] is to objectively and quantitatively record a physical quantity in a way that can be reproduced. More specifically, this implies:

- Objective: independent from human sense organs,
- Reproducible: able to be repeated and monitored
- Quantitative: given a concrete number.”[25]

To process a measured value digitally generated using a measuring device, the value must be communicated to other systems via an interface. There are multiple interface systems that are used within the industry (see chapter 3.2).

## 3.1 How can methods for resource consumption be measured?

The use of resources such as material, energy and water in industrial production within the manufacturing sector can be calculated by measuring the corresponding measured variable. There are over 100 measured variables that can be recorded using the measurement technology available. Bock et al.[26] provides an overview of the measured variables that can currently be recorded. The choice of measured variable subsequently determines the measuring process and instruments (measuring devices and accessories)

[25] Mühl, T. (2022), p. 1.

[26] Cf. Bock, K.; Dittrich, P.-G.; Ettrich, K.; Graf, V.; Großer, V.; Fröhlich, T.; Hänschke, F.; Hartmann, H.-D.; Hoffmann, D.; Hoffmann, K.-P.; Ortlepp, T.; Schmidt, F.; Schütze, A.; Simmons, T.; Sinn, W.; Slatter, R.; Töpfer, H.; Tschulena, G.; Werthschützky, R.; Wilde, J. and Zieger, G. (2018), p. 12.

that can be used. Measuring devices available on the market are predominantly aimed at recording physical and chemical measured variables.

**Measuring measured variables**

“Measuring […] is the carrying out of planned activities for the quantitative comparison of measured variables with a unit of measurement.”[27]

Here, the measured variable is the product of measure and unit of measurement. The measure represents the quantitatively measured value; the unit of measurement represents the relationship to other physical quantities determined via a formula.[28]

The unit of measurement can vary depending on the level at which resource consumption is being examined (company-wide vs. machine level) and the purpose of evaluation. It is therefore important to use one consistent database for resource consumption. Failure to do so results in inaccuracies in the evaluation of resource consumption due to rounding up/down for resource consumption measurement which, in turn, leads to incorrect conclusions being drawn.

Before measuring the consumption of a resource for a specific purpose, businesses should first review the necessity for a measurement. Regardless of the intended purpose of the resource data, datasets may already exist in other company systems, e.g. datasets on goods inward data from the company’s internal ERP system for consideration of resource consumption on a global scale or datasets from manufacturing technology machines. If datasets already exist that fulfil the intended purpose, businesses should avoid going forward with new recording as the process of recording itself uses resources. Unnecessary resource use must be avoided.

### 3.1.1 Measured variables

But what measured variable should a business choose for a specific production-relevant resource whose consumption must be calculated for a specific

[27] Parthier, R. (2020), p. 1.
[28] Cf. Parthier, R. (2020), p. 2.

application? First, it is useful to clarify precisely what is meant by the term resource consumption.

When determining resource consumption, the amount of material, energy and water is recorded at certain intervals and then shown in relation to time. This allows businesses to see the increase or decrease in resources over time and then analyse the cause of this increase/decrease.

The illustration of resource quantity depends on the resource type and aggregation state. The quantity figures for materials and water are stated in figures such as quantity, mass (e.g. kg), substance amount (e.g. mol), volume (e.g. $m^3$), concentration (e.g. $kg/m^3$) or mass/substance/volume flows (e.g. kg/h, mol/min, $m^3/h$). Energy quantities are usually stated using thermal energy amounts (e.g. kJ, kWh) or electrical power (e.g. kW).

There are measured variables that can be used to calculate resource quantities directly. This means that the measured values can be used to draw direct conclusions on resource quantities and thus resource consumption. There are also measured variables that cannot be used to determine resource quantities and consumption directly; these variables must first be converted in one or more steps. The selection of measured variables that can be used to measure the quantities and consumption of production-related resources (directly or indirectly) is listed in Table 1.

**Table 1: Measured variables and corresponding resource type**

| Measured variable | Resource | Determination of resource quantity | |
|---|---|---|---|
| | | Di-rectly | Indi-rectly |
| **Mechanical measured variables for solids** | | | |
| Mass | Material | X | |
| Mass flow | | X | |
| **Mechanical measured variables for liquids and gases** | | | |
| Flow | Material | X | |
| Volumes | | X | |
| Fill level | | | X |
| Density | | | X |
| Pressure | | | X |
| **Thermal measured variables** | | | |
| Temperature | Energy | | X |
| Thermal conduction | | | X |
| **Electrical measured variables** | | | |
| Electricity | Energy | | X |
| Voltage | | | X |
| **Chemical measured variables** | | | |
| Concentration | Material | X | |

## 3.1.2 Measuring technology and sensors

If a suitable measured variable has been identified for recording the “resource quantity” dependent variable, the measuring tasks must be defined. If it has been confirmed which requirements the measurement should meet, a suitable measuring technology can be selected (e.g. sensor, measuring device, measuring method and signal transfer).

More precise details relating to the measured variable and acceptable margin of error are outlined when defining the measuring task. The place of measurement is also precisely defined, taking into account any potential constraints (e.g. temperature gradient, humidity). The measurement conditions and the type of further processing for the measuring signal are also identified.[29] In addition to the choice of measurement principle and sensors, the measurement method and type of signal transfer determine the measuring

[29] Cf. Helbig, W. (2021), pp. 5 et seq.

technology suitable for the measuring task. The approach for carrying out measurement and the type of signal processing is determined based on the measurement method.[30] A distinction is made here between analogue and digital measurement methods. Both methods are characterised by DIN 1319-2.[31] For analogue measurement methods, the measured values are generated by infinitely processing the measuring signal. For digital measurement methods, the measured value output is generated by way of a phased processing of the measuring signal. Here, the measured variable is quantified by the measuring signal in predefined steps. The measuring signal generated in this way can then be used directly for digital further processing.

Businesses must determine whether the measured variable should be recorded in longer intervals (discontinuous) or permanently in short intervals (continuous). The amount of data is significantly smaller for datasets from discontinuous measurements in comparison to continuous measurements. The advantage of using the discontinuous method is that it is sure to result in a better level of data handling and a more straightforward evaluation routine. The disadvantage, however, is that it can lead to a loss of information due to the reduced data density. This is not an issue for the continuous method. However, the evaluation routine for continuously recorded data can be more complex due to the high data density. Factors such as the type of the measured variable, the measuring task, the objective of measurement and the measuring technology used all help to determine which of the two measurement models to use.

### Sensors

Sensors implement the measurement principle and generate the measured values. They are therefore a central component of a measuring device. More and more sensors are now being used due to the increasing digitalisation of industrial processes. Their respective field of application is generally highly specific. Data measured using sensors can be used for various purposes, including the recording of resource quantities, process control and quality assurance.

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[30] Cf. Parthier, R. (2020), p. 45.

[31] Cf. DIN 1319-2:2005-10.

**Function of sensors**

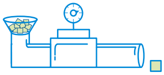
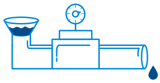
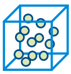
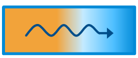
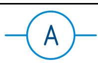
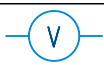
The basic role of sensors is to convert chemical, physical and biological measured variables into electrical signals. In many cases, these generated measured values have a linear correlation with the measuring signals.[32]

In the case of passive sensors, the generated electrical signal is converted into a standardised analogue signal using a transducer and then displayed directly on a measuring device. Sensors are fitted with microcontrollers for generating digital measured values. The electrical measuring signals generated by the sensor element are also converted into analogue signals using a transducer. These signals are then translated into a digital signal format and further processed.[33]

The type of sensors required can differ depending on the type of resource being directly or indirectly recorded. The corresponding sensors for some common measured variables that can be used to calculate resource consumption directly or indirectly (cf. Table 1) are shown in Table 2. The measured variables and measuring sensors listed here are just a small number of the large selection of potential measured variables and sensor types. This overview can serve as an initial orientation to become more familiar with the various themes related to the digital recording of resource consumption.

32 Cf. Tränkler, H.-R. and Reindl, Leonard M. (2014), p. 3.
33 Cf. Parthier, R. (2020), pp. 177 et seq.

**Table 2: Sensor types for selected measured variables for direct or indirect recording of resource consumption[34]**

| Measured variable | Sensor types |
|---|---|
| **Mechanical measured variables for solids** | |
| Mass  | Electric load cells |
| Mass flow  | Image sensor |
| **Mechanical measured variables for liquids and gases** | |
| Flow  | Magnetic-inductive flow sensor, ultrasound flow sensor, differential pressure determination, impeller flow sensor, vortex flow meter, mass flow meter (Coriolis principle), thermal flow meter |
| Fill level  | Float, ultrasound sensor, radar/microwave, optical sensor (e.g. ultrasound), conductivity meter, hydrostatic measurement (hydrostatic head pressure), gravimetric measurement (container weight), capacitive sensor |
| Density  | Oscillating U-tube |
| Pressure  | Inductive pressure transducer, capacitive pressure transducer, piezoelectric pressure transducer, piston pressure scale |
| **Thermal measured variables** | |
| Temperature  | Resistance thermometer, infrared temperature sensors, thermoelement |
| Thermal conduction  | Conductivity sensor, thermal flow sensor |
| **Electrical measured variables** | |
| Electricity  | AC sensors, DC sensors |
| Voltage  | Voltage sensors |
| **Chemical measured variables** | |
| Concentration  | Infrared spectrometer, mass spectrometer, UV/VIS spectrometer |

[34] Cf. Fleischer, J.; Klee, B.; Spohrer, A. and Merz, S. (2018), p. 11.

The sensors required vary depending on the type of resource being recorded. While electrical recordings are largely taken using electricity meters and resistance meters, this differs in the case of material flows depending on the respective aggregation state. For example, flow can be measured for fluid substances while quantities of solid substances can be counted using buttons, camera systems or via weight measurement. An overview of the resource types, corresponding measured variables and suitable sensor types is provided in Table 6 in the Appendix.

To ensure high performance, sensors for use in production- and process-oriented product manufacturing should offer high measuring certainty and long-term stability, and should be able to be used in a wide range of temperatures. They should also boast a low construction volume, low energy requirements and be suitable for process interfacing with standardised process and electrical interfaces (sensor input and output).[35]

## 3.2 Interfaces and communications technologies

When it comes to recording, saving and evaluating data on resource consumption, the choice of suitable sensors is not the only thing to take into account. The sensor interfaces to other systems and system-to-system interfaces, as well as interfaces between people and systems, are also important to consider. This is because these interfaces largely determine whether or not data can be transmitted and determine the format of this transfer. This, in turn, also determines the information content that can be transmitted. Technically speaking, for example, a sensor might be able to record highly complex data and a system might be available to evaluate this data; if there is no suitable interface between the sensor and the evaluating unit, however, digital recording of the resource consumption will fail. It is therefore important to check which interfaces the used sensors and processing units are suitable for.

To better understand how interfaces and communications technologies influence what options are available for data evaluation, businesses need to look

[35] Cf. Bock, K.; Dittrich, P.-G.; Ettrich, K.; Graf, V.; Großer, V.; Fröhlich, T.; Hänschke, F.; Hartmann, H.-D.; Hoffmann, D.; Hoffmann, K.-P.; Ortlepp, T.; Schmidt, F.; Schütze, A.; Simmons, T.; Sinn, W.; Slatter, R.; Töpfer, H.; Tschulena, G.; Werthschützky, R.; Wilde, J. and Zieger, G. (2018), p. 19.

at the basic sequence from measurement to evaluation. This process is shown in Figure 2 using a sensor-based measurement, a bus system and an evaluation unit as an example. The process is explained in more detail below.

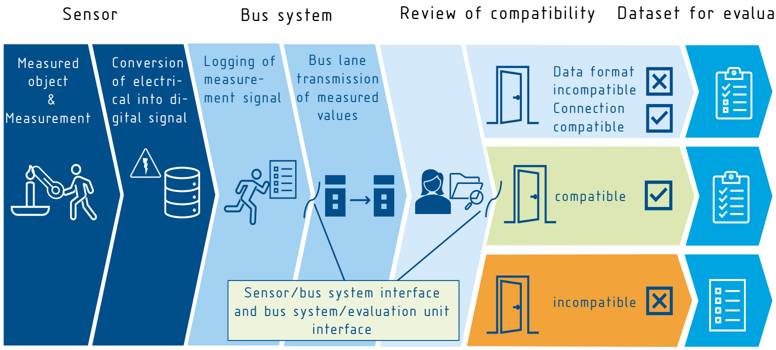



**Figure 2: Schematic view of a measurement system from recording to evaluation**[36]

Sensors record physical quantities in the form of electrical signals and then convert these into digital signals.[37] Bus systems can be used here to transmit these signals and communicate them to a subsequent processing unit. As different sensors use the same lines (referred to as bus lanes), signals must be encoded so that they can be traced. Protocols are used for this purpose. The data must be converted between the various recording, storage and processing units so that it can be transmitted. This conversion at the interfaces can lead to data loss, as shown in Figure 2. To prevent unwanted data loss, it is therefore recommended to first become familiar with the relevant interfaces and transmission formats to create an overview of the possible interface conflicts. This can also serve as the starting point for any potential adjustments to the interfaces. The many forms of interfaces include: [38]

- **Hardware interfaces**
  - Interfaces between two physical components, e.g. USB port and USB stick

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[36] VDI ZRE figure.

[37] Cf. Marxer, M.; Bach, C. and Keferstein, C. P. (2021), p. 307.

[38] Cf. Hottinger Brüel & Kjaer GmbH (n.d.).

- **Software interfaces**
  - Access to system routines
  - Communication between processes
  - Connection between individual components of a program or cross-program interfaces

- **Network interfaces**
  - Allows access to computer network, e.g. Ethernet connection to computer

- **User interfaces**
  - Areas where people interact with machines

Interfaces therefore have a significant impact on the quality and quantity of data. To ensure that the desired data quality and quantity remains consistent, businesses must consider the measuring and recording system as a whole and adjust individual components. Suitable sensors and the transmission technology and evaluation systems used are chosen based on the dataset that the company wants to achieve as this defines the content of the data.

The evaluation system is chosen based on whether it is capable of receiving and evaluating data with this content. The evaluation system, in turn, defines the data format for recording and evaluating the data content. The evaluation system connections then define which bus systems can be used, i.e. how the data is transmitted, e.g. via Ethernet, USB, RFID, UMTS, etc. (cf. Table 7 in Appendix).

The following bus systems have become well established in a wide range of industries so far:[39]

- CAN (vehicle technology, drive technology, machine control)
- INTERBUS (drive technology, machine control, automotive engineering in Europe)
- LON (building automation)
- KNX (building automation)
- PROFIBUS-DP (engineering, production technology)

[39] Cf. Schiessle, E. and Schreier, J. (2018).

- PROFIBUS-PA (chemical and mechanical process technology)

The choice of bus system as a type of data transmission can sometimes heavily impact data processing speed. A differentiation is therefore made between serial and parallel transmission for bus systems. Serial bus systems are the most widely used as these are very cost-effective. Serial bus systems only involve one transmission line shared by the connected sensors. This can negatively impact transmission speed – it is comparable to a building with multiple people accessing the same WiFi. This reduces the speed for each individual person.

In contrast, for parallel bus systems, each sensor has its own transmission line. However, this type of bus system is expensive. Businesses must therefore decide between a data transmission model that is fast but expensive or one that is cost-effective but slower.

In addition to cable-based bus systems, WPANs (Wireless Personal Area Network) can also be used to transmit data. WPANs are used for wireless data transmission. They often only have a limited reach (up to 10 m) and are used in particular in the area of IoT applications. The most well-known WPAN system is Bluetooth.[40] WPAN can therefore be a suitable alternative to cable-based bus systems where businesses require wireless transmission or where this is more effective based on the infrastructure and broadband set-up.

Once the transmitting system has been defined, businesses can look for a suitable sensor for the measuring task and the corresponding connections. The selection of sensors, evaluation systems and transmission systems often means there are multiple suitable options and thus the process can also be iterative – especially when the systems and sensors are also intended for other evaluations and measurements, e.g. for controlling production. Businesses should also note whether the data is saved as part of a stationary storage system or stored in a cloud, as this influences the choice of systems used.

[40] **Cf. Grasreiner, S. (4 February 2022).**

Overall, it is worth considering the levels of industrial communication (cf. Figure 3) when choosing systems. These are indicated by the application functions and information models, communication services and information models, transport-oriented protocols as well as data quantities and transmission speeds. Here, the quantity of data to be transported and the transmission speed determine the choice of transport-oriented protocols.

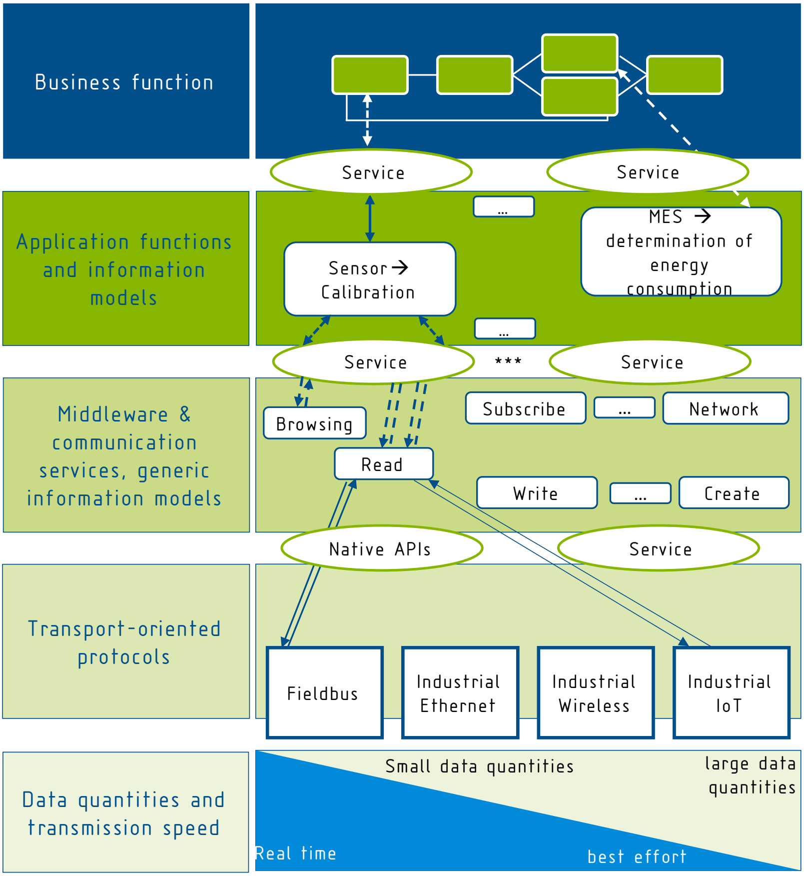


**Figure 3: Diagram of levels in industrial communication**[41]

[41] Based on Wollschlaeger, M.; Debes, T.; Halhoff, J.; Wickinger, J.; Dietz, H.; Feldmeier, G.; Michels, J.; Scholing, H. and Billmann, M. (2018), p. 20.

# 4 RECORDING DATA AND INTEGRATING IT INTO PRODUCTION

Businesses are using more and more sensors[42]. These, in turn, are generating an increasing amount of data. However, this does not necessarily mean that this data can be used. To ensure that a business gains value from the data and avoid the sole goal being the collection of data in and of itself, the data must be used. However, this data is often available to businesses in varying levels of quality and in various quantities, and this makes its processing significantly more difficult or prevents processing altogether. On the one hand, this is due to the software and hardware landscape within businesses that has grown throughout time. On the other hand, this is also due to the fact that data collection was originally often carried out for a special case, which explains the differences with regard to the data sources.

To ensure that the collection of data runs as smoothly as possible, businesses should first consider whether the data can be used for further analyses for other business areas and how it should be collected to ensure that it can be subsequently recorded by other systems. This prevents businesses from creating data lakes[43] that cannot be reused. A systematic approach to recording, processing and integrating data can also help here to transform data lakes within the business into valuable information resources. Suitable data mining methods help to systematically develop a consistent database.

The fundamental steps to any data mining method are listed and explained in Figure 4. This involves defining the objective, developing the data structure and determining the necessary data quality. The process of data preparation is then determined and the type of modelling is chosen. Defining the data evaluation and implementing the model are the next steps. The process

[42] Cf. Deutscher Industrie- und Handelskammertag e. V. (2021), pp. 3.

[43] A data lake is a data repository containing data from different sources in structured and unstructured forms.

is rounded off with the collection of user feedback. An overview of the most common data mining methods are shown in Table 8 in the Appendix.

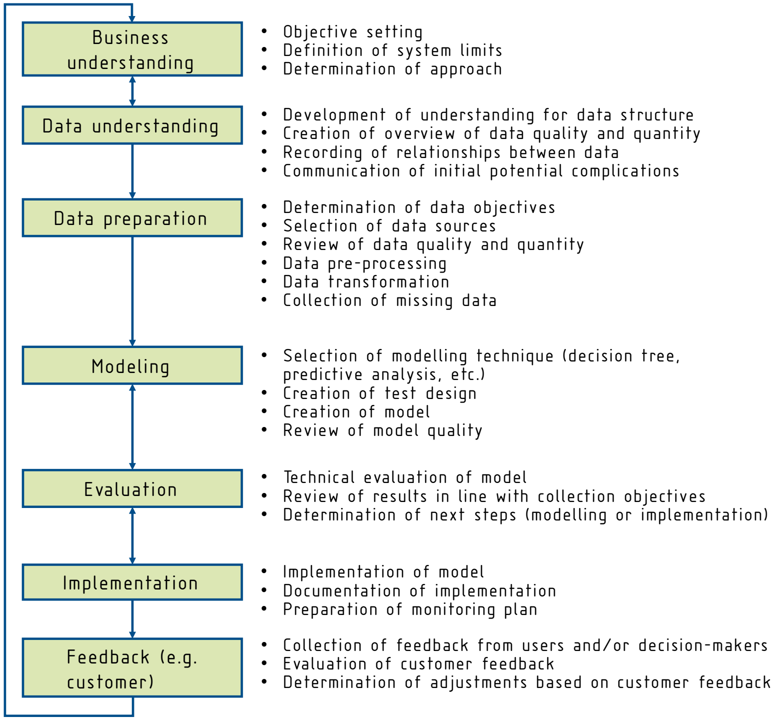


**Figure 4: Methods for the systematic recording, processing and integration of data**[44]

The length of the individual steps may vary in their application. In general, 20% to 30% of the time is needed for the selection of the relevant databases. The largest section of time is used for data processing (50% to 70%). 10% to 20% of time is used for modelling, and the subsequent integration of the data and data models takes up another 5% to 10% of the overall time.[45] Time needed for modelling may not apply where the business is not developing its own system for the digital recording of resource consumption or where the system will be trained using machine learning. This is the case where the

[44] Based on MarkTab Consulting et al. (2022).
[45] Cf. Wuttke, L. (2022).

collected data will be integrated into existing software or into software specifically procured for this purpose.

To make implementing data mining methods easier, this chapter is structured based on the essential data mining steps and serves as a guideline for the systematic collection, processing and integration of data.

## 4.1 Defining the objective of the resulting data

Before a business can start to get to grips with the recording, processing and integration of data, it must first consider the objective of collecting the data. This helps businesses to avoid wasting capacity on recording data that will ultimately not be used. Setting a specific objective allows businesses to collect as little or as much data as needed. Limiting the objective scope also allows the business to break down targets into individual tasks which can then be implemented to achieve the overarching objective.

It is helpful to consider the essential properties of data to narrow the range of objectives. In basic terms, data can be defined using three specifics:

- Volume (i.e. the amount of data per unit): this has a huge impact on the amount of effort required for the recording and processing of the relevant data.

- Data speed (i.e. how quickly new data can be generated, processed and evaluated): for example, if data is collected on a daily basis, there is only one dataset per day, hourly collection results in 24 datasets per day, collection every minute generates 1,440 datasets and collection every second equates to 86,400 datasets.

- Variety: this means the number of structures and formats that a dataset can be provided in.[46]

Additional properties should be considered for large data quantities, such as the variability of the data stream. This means the quantity of datasets that will be processed simultaneously. It determines the amount of computing

[46] **Cf. Katal, A.; Wazid, M. and Goudar, R. H. (2013), p. 404.**

power required to store and process the data. The complexity of the data stream also indicates the level of work involved to adjust the datasets and the value of the data (i.e. what conclusions can be drawn from the data, e.g. with regard to resource saving potential).[47]

Businesses do not need to be completely clear on the objective of data collection at the start of the process. Instead, they should derive concrete data objectives from the ongoing project. An example project might be as follows: 'Reduction of material and energy consumption for production machine 2 in hall 1.' This results in the following objectives:

- Identification and implementation of measures to increase material efficiency of production machine 2
- Identification and implementation of measures to increase energy efficiency of production machine 2

To realise these objectives, the business must first collect the corresponding data, which is then the goal of data collection. The goals of data recording could therefore be as follows:

- Recording of energy consumption of production machine 2
- Recording of material consumption of production machine 2
- Recording of operating and stand-by times of production machine 2
- Recording of orders processed on production machine 2
- Recording of maintenance and repair times

Whether or not these data collection goals are enough to achieve the previously defined objectives depends largely on whether the necessary data is collected from production machine 2. If this is not the case, sub-goals can be developed which, once prepared, contribute to the actual data collection goal. The approach for systematically recording, processing and integrating data

[47] **Cf. Katal, A.; Wazid, M. and Goudar, R. H. (2013), pp. 404 et seq.**

outlined in the following chapters could therefore be applied as an iterative model.

For example, if the “Recording of energy consumption of production machine 2” goal cannot be measured in this form, the following sub-goals can be derived:

- Recording of energy consumption of production hall
- Recording of energy distribution/quantity in production hall

Sub-goals are always one aggregation state more general than the primary goals. Businesses should continue to define goals, sub-goals, sub-sub-goals, etc. until data collection objectives have been determined that are at least possible in theory.

## 4.2 Selecting and developing a database

Once the objectives of data collection have been set, businesses can start to select or develop a suitable database to gradually meet the objectives.

### 4.2.1 Quality criteria for developing a data basis

To ensure a qualified selection of data sources, it is important to determine the quality criteria that the data must meet in order to achieve the previously defined objectives. The requirements are geared towards the subsequent users of the data, generally systems that access this data for further processing. Requirements relating to the actuality, completeness and accuracy of the datasets may vary depending on use. For example, for a company-wide consideration of resource consumption, the completeness of the data might be a high priority, whereby the company is able to consider a longer period of recording in terms of actuality than would be the case for the control of production systems. In addition to the content-related requirements of users, there are also further influential factors that are necessary when it comes to the quality and structure of a suitable data basis. These include: [48]

[48] **Cf. Hildebrand, K.; Gebauer, M. and Mielke, M. (2021), p. 73.**

- External legal requirements
- External reference information
- Internal company standards
- Technical requirements (system, application, database)

It is therefore important for businesses to consider these needs and requirements when compiling the stakeholder quality requirements. The relevant quality requirements can have various dimensions, as shown in Figure 5.

When drafting the quality requirements, it is not necessary to consider all dimensions in the same way. Businesses must instead decide which dimensions are relevant for completing the tasks and in which form. Here, businesses should also take into account the quality requirements for other measuring projects to take advantage of any synergy effects when developing the database.

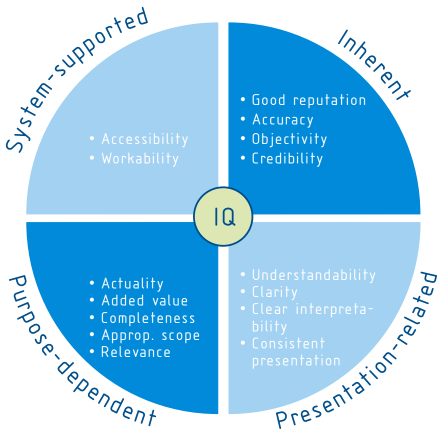


**Figure 5: Overview of the information quality dimensions**[49]

[49] Based on Hildebrand, K.; Gebauer, M. and Mielke, M. (2021), p. 77.

The set quality requirements serve as the basis for choosing suitable data sources and developing new ones.

**Table 3: Structuring of data quality using three main features (based on Larry English)**

| Quality of data definition |
|---|
| Data specification |
| Business rules |
| Integrity conditions |
| **Content-related data quality** |
| Completeness of data |
| Clarity/singularity of datasets |
| Compliance with business rules |
| Precision and accuracy of collected data |
| **Quality of data presentation** |
| Time of data provision |
| Format type |
| Format structure |

shows a practice-oriented and easy-to-implement classification of data quality features for industry users. This classification divides data quality into three mean features and a total of ten sub-features.

### 4.2.2 Choosing from existing datasets

Businesses should first check to see whether databases already exist which meet the quality criteria and are suitable for the data objectives. This ensures that data is not collected, saved and processed twice and in doing so also reduces the effort required for data collection. Businesses can use various internal and external data sources to develop a database. Typical internal and external data sources are listed in Table 4.

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**Table 4: Internal and external data sources**[51]

| External sources | Internal sources | |
|---|---|---|
| | Business level | System level |
| Parts lists, orders | Product/component database | Sensor data |
| Supplier catalogues | Supplier database | PLC, FC |
| Raw materials, consumables and operating supplies development | Inventory database | MES |
| Availability data/history | Query/order database | Manual data |
| Demand history | Customer database incl. order history | Static data |
| - | - | DBS, data warehouse, data lake |

To start with, it does not matter which format the data is in – it is more important to check whether the data meets the defined quality criteria. It is often more straightforward to adapt the data format than it is to increase the quality of the data as this generally requires the data to be re-recorded.

### 4.2.3 Generating new datasets

Similar to when selecting from existing datasets, the generating of new datasets is also geared towards the previously defined quality criteria. These criteria may need to be adjusted depending on the type of generation.

Before new datasets can be generated, businesses should check to see if the data can be generated with the available hardware and software and if the data generated this way will meet the previously defined quality criteria. Generating data using existing hardware/software keeps costs as low as possible and has the smallest environmental impact. If the existing systems are not suitable for generating the required data or meeting the quality requirements, businesses should review their systems to see if they can be

[51] VDI Zentrum Ressourceneffizienz GmbH (2019), p. 109.

retrofitted to bring them up to the required standard. Only where this is not possible should the business develop a new system for generating data.

Developing a new measurement system involves a lot of planning and comes with high costs both economically and ecologically speaking, and so businesses should check to see if it is possible to obtain the missing data from existing data, or use existing data as a substitute. If this is not possible, it must be ensured that the value gained from generating and evaluating the new data exceeds the associated effort and expense. When considering the value of the data, businesses should not view the generating of datasets exclusively from a resource efficiency perspective. Businesses should instead consider whether the data can be otherwise evaluated and generate additional value. This holistic approach to planning prevents data from being repeatedly collected.

## 4.3 Recording and processing datasets

Once the necessary data has been selected or generated, it must then be recorded and processed for subsequent integration and evaluation.

As shown in chapter 4.2.2, there are multiple data sources within a business. As a result, the data used to digitally record resource consumption often comes from a variety of sources and repositories. The dataset recording and processing stage is therefore all about building a coherent data pool from the large number of data sources. To do so, the data must undergo various adjustments.

On the one hand, preselecting data sources may result in the same data being available in various formats and in multiple locations (data lakes). It is therefore important to process the data so as to ensure a coherent data pool.[52] This requires the selected datasets to be cleansed to remove any duplicate entries. That way computational costs for collecting the data in the case of repeated analyses are reduced. Businesses must also decide here where this data cleansing should take place. It should also be clarified whether the data is corrected in the original recording system or whether the data required for

[52] **Cf. Chapman, P.; Clinton, J.; Kerber, R.; Khabaza, T.; Reinartz, T.; Shearer, C. and Wirth, R. (2000), p. 25.**

evaluation is copied and then corrected and expanded in a new database and cleared of duplicate entries.[53]

Once all duplicate entries have been removed, the next stage can begin. The second stage involves deriving the data that is required but which cannot be measured directly. This process itself can involve multiple steps with new datasets being derived from already derived data. For example, energy consumption data at the machine level can give rise to consumption data at the department or, with additional users, the company level.[54]

This process should result in a dataset containing only data that is required for digitally recording resource consumption. The next step is to standardise the data format. Here, the format used is based on the requirements of the subsequent evaluation system. To ensure that the datasets can be used for later evaluation, they must be translated into a suitable format for transmitting and evaluating the data. Format harmonisation can be done in the form of a semantic or syntactic adjustment to the information.[55]

In the case of a semantic adjustment, the datasets are adapted so that they can also be correctly recorded during the subsequent evaluation. Failure to consider semantics can lead to data being incorrectly identified and thus evaluated. This may be the case, for example, where numbers are recorded without units or in inconsistent format (kg, g, kilogram, etc.).[56]

A similar situation arises for syntactic adjustment. More specifically, syntactic adjustment involves recording various information elements of data in the correct sequence. Recording data in the incorrect sequence can lead to errors as part of the subsequent evaluation.[57] This may be the case, for example, where units are sometimes recorded before the measured numbers and other times after.

Finally, businesses should check to see if the data has its own data format for transmission and evaluation. For example, the data will be of no use if it

[53] **Cf. Bleiholder, J. and Schmid, J. (2020), p. 124.**
[54] **Cf. Bleiholder, J. and Schmid, J. (2020), pp. 288 et seq.**
[55] **Cf. Bleiholder, J. and Schmid, J. (2020), p. 124.**
[56] **Cf. Bleiholder, J. and Schmid, J. (2020), p. 124.**
[57] **Cf. Bleiholder, J. and Schmid, J. (2020), p. 12.**

is documented e.g. in images and the corresponding evaluating unit can only evaluate data from databases. Businesses must be aware that the data format may need to be changed prior to adapting the data and vice versa.

Where data exists that is missing information required for subsequent evaluation, this must be added. In such cases, businesses should also review why this information is missing in order to develop successive measures that ensure all information is recorded for any subsequent data collection projects.

## 4.4 Reviewing and adjusting datasets

To ensure that the dataset leads to a reliable result, the data must be reviewed and then adjusted.

### 4.4.1 Reviewing datasets

In traditional data mining methods, a data evaluation model is usually developed and reviewed during the modelling and simulation stages. This should also be done where no system is yet in place for subsequently evaluating the resource data. In such cases, businesses should use methods that evaluate the previously developed data pool and aggregate it into useable key figures. These key figures can vary depending on the project. A selection of key figures is listed in Table 5.

**Table 5: Overview of potential energy efficiency key figures**[58]

| Key figure | Description |
|---|---|
| Thermodynamic energy efficiency | Energy used in the process per used energy |
| Energy consumption intensity | Energy consumption per product |
| Total energy consumption | Absolute value of required energy |
| Energy productivity | Sample space per energy used |
| Specific energy requirement | Energy requirement per produced quantity |
| Specific energy demand | Energy demand for production |
| Energy efficiency factor | Process energy requirement per total energy requirement |

Businesses should use a test dataset (e.g. with already known results from previous projects) to review the data pool and the selected methods. This

[58] Labbus, I. (2021), p. 51.

allows the business to review both the data pool quality and the validity of the chosen evaluation methods.

If there is already an evaluation system in place, e.g. in the form of software for an energy management system, the evaluation methods are defined by the software and businesses must choose from these methods. In any case, it is always important to validate and verify the previously created data pool. A test dataset should be used as a reference here too. Depending on the type of software used for subsequent data evaluation, the data can be reviewed in a test environment. If that is not possible, the data must be integrated into the real system and tested there. Businesses should be cautious here. If the evaluation system is connected to other systems that automatically react in the presence of certain parameters, these must be separated from the rest of the system during testing.

### 4.4.2 Adjusting datasets

Once the evaluation system has been reviewed using test data, businesses should check how suitable the system is for recording resource consumption. This may result in certain changes being made to the evaluation system depending on how many objectives are met. In turn, these changes may require businesses to adjust or replace the chosen evaluation methods and the data pool used. The process of simulating the evaluation system and making any necessary changes is repeated as many times as needed until a suitable level of objective achievement is reached. The data pool is then reviewed to ensure that it is suitable for the adapted evaluation system. The data may need to be recollected, selected, processed and reviewed as a result of this review. The sections outlined in chapter 4 should therefore be understood as a cycle that creates an evaluation system and/or data pool(s) that is/are suitable for digitally recording resource consumption as part of an iterative process.

Missing data can be artificially generated using algorithms. This data will then be available in the form of synthetic data. This form of dataset is not determined by way of measurement – it is generated based on already collected data. Establishing synthetic data can help to adapt older datasets in particular that were collected under other quality standards to bring them in line with the latest standards, without having to remeasure the values (where possible). Doing so leads to a larger data pool for evaluation.

## 4.5 Integrating datasets

Once a suitable data pool has been created and reviewed, businesses can start to integrate the datasets into the evaluation system or integrate the evaluation system itself. Here, it is important to distinguish whether the data will be integrated into existing systems or whether new systems will be created based on the existing data pool.

### 4.5.1 Data integration of new and existing datasets

When choosing a suitable process for data integration, businesses should first consider whether there is already an evaluation system fit for the objective of analysis or whether a new system needs to be created. This step largely determines what restrictions will be involved with the integration of data.

Integrating data into an existing evaluation system is often relatively easy from a technical standpoint due to familiarity with and complete integration of the system, its interfaces, etc. Existing systems may also come with technical restrictions that limit how effectively the evaluation of resource consumption achieves the relevant objectives. In extreme cases, this may result in changes being made to the evaluation system. Interfaces must still be defined, data must be mapped, the frequency of data extraction must be determined and other additional requirements (e.g. security requirements) must be taken into account for an existing evaluation system.

The same applies when acquiring a new evaluation system. A selection can be made as part of this acquisition based on the data pool and analysis objective to ensure a high level of objective achievement for the evaluation of resource consumption. This also makes it easier to integrate the data from a technical standpoint. However, this does lead to increased training efforts for the operation of the evaluation system, as well as additional procurement costs and implementation time.

### 4.5.2 Aspects of data integration

Independent from this segmentation, data integration involves a multitude of challenges. One source of these challenges is the fact that data is often not recorded, managed and stored at one individual location – it is frequently collected and saved in various systems at different locations in consideration of a wide range of different technical and legal guidelines.[59] The purpose of data integration is therefore to extract and bundle datasets identified and processed from the previously defined data sources and provide these datasets to the relevant evaluation system. However, there are some aspects to consider here.

**Integration direction:** Integration direction is about whether the data will be pooled on the same level or across different data levels.[60] The digital recording of resource consumption generally involves the vertical integration of data, meaning integration between differing data levels. Sometimes a combination of horizontal and vertical data integration is used to reduce integration complexity. For example, data may first be bundled on the shop-floor level as this level often already involves similar data formats. This, in turn, reduces the amount of effort and expense required to bundle the data. Only once it has been bundled is the data transferred to a higher data level, e.g. for evaluation.

**Level of automation:** The level of automation indicates whether the data will be integrated automatically or using human input.[61] As far as possible, businesses should always strive for automated integration. Integration using human input leads to disproportionately high costs/effort due to the number of analyses involved.

**Integration time:** The integration time indicates when data will be integrated.[62] The time of integration depends largely on the objective of analysis pursued and the dependencies between the systems involved. If the business is planning real-time analysis, there will be multiple different integration times with relatively little data. This allows for fast transmission. However, this approach generates a wide range of datasets due to the frequent recording of data.

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[59] Cf. Bleiholder, J. and Schmid, J. (2020), p. 123.
[60] Cf. Kusturica, W. (2018).
[61] Cf. Kusturica, W. (2018).
[62] Cf. Kusturica, W. (2018).

For interval integration, a point in time is defined until which data should be collected. The collected data is then integrated as a bundle. This method requires significantly fewer datasets, but it is not possible to react to the data results immediately. Businesses should therefore carefully consider in which cases real-time recording is economically and ecologically feasible and in which areas an interval-based integration is sufficient. For example, if a business is looking to improve a system's energy consumption during production, resource consumption must be recorded in close to real time as a minimum. If a business is looking to analyse the fundamental energy consumption of individual departments, recording to the day is sufficient.

**Integration reach:** The integration reach determines the business areas from which the relevant data will be bundled and integrated.[63] This is particularly significant when the data sources are saved in various locations. For example, if the business has locations abroad, the transmission of data could entail additional legal conditions that in turn influence data integration. This also applies where the business is active in value networks and would like to aggregate and integrate data between companies.

[63] Cf. Kusturica, W. (2018).

# 5 DIGITALLY RECORDING MATERIAL AND ENERGY FLOWS

Once it is clear which sensors are suitable for which kind of energy or material, the real recording of material and energy flows can begin. The sections below outline in more detail the areas in which it makes sense to digitally record material and energy flows and explain the challenges involved with recording. There are also examples of how other companies have overcome these challenges.

## 5.1 Evaluation options for material and energy flows

Previous sections have looked predominantly at the digital recording of resource consumption. A certain objective was defined prior to recording. It is now up to the business to choose a suitable evaluation system for the data objective where such a system does not already exist within the company. Several standards are outlined below as an initial overview. To ensure real value can be obtained from the recording of resource consumption, this data must be analysed and used to derive saving measures. There are various options for managing and depicting this data for the purposes of evaluating internal resource consumption: [64]

### Energy management system in accordance with DIN EN ISO 50001

An energy management system is the "entirety of all elements that relate to and interact with one another for the implementation of an energy policy and strategic energy goals, [sic!] as well as the processes and procedures for achieving these strategic goals"[65].

Such a system involves planning energy use as a whole, and putting measures in place to control and evaluate this use. The ISO 50001 standard is concerned exclusively with achieving as efficient a use of energy as possible, but the fundamental approach can also be adapted for increasing material efficiency (see Figure 6).

[64] Cf. Scherf, C.-S. et al. (2021), pp. 66 et seqq.
[65] ISO 50001:2018-12, p. 8.

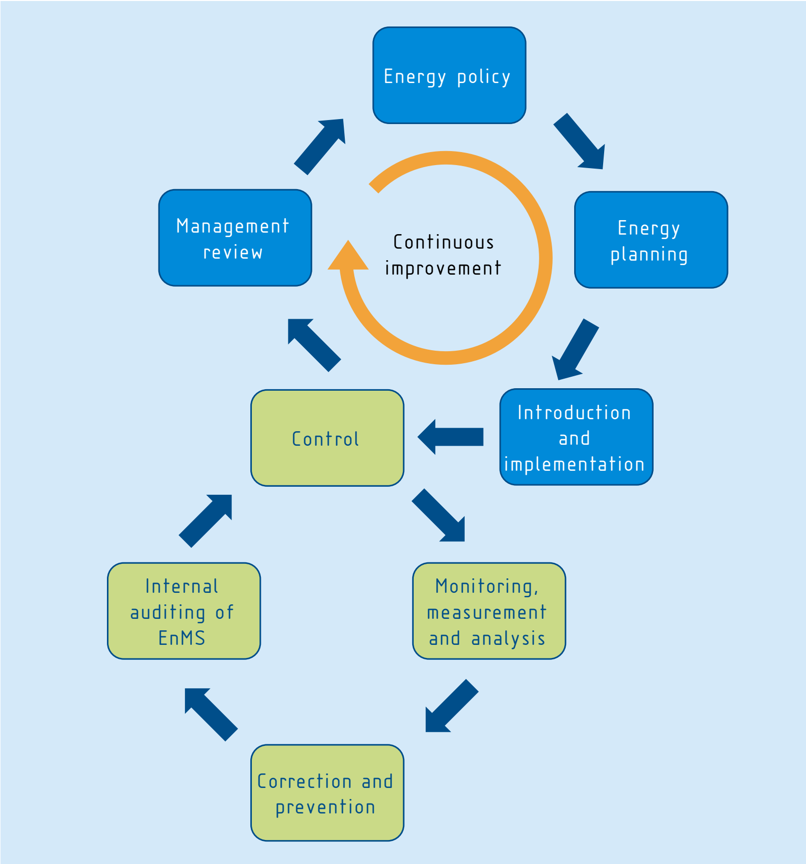


**Figure 6: Energy management system model**[66]

### Eco-Management in accordance with DIN EN ISO 14001:2015-11

The eco-management system as set out in DIN EN ISO 14001:2015-11 is a holistic system for determining, monitoring and improving resource efficiency and reducing any negative impacts on the environment caused by the activities of the business.[67] It can be used to evaluate and interpret digitally recorded resource consumption. The results can either be used to devise

[66] Based on ISO 50001:2018-12, p. 6.
[67] Cf. Scherf, C.-S. et al. (2021), p. 66.

suitable measures directly or for the purposes of drafting mandatory environmental targets.

### Eco-Management and Audit Scheme (EMAS)

The EMAS system can be considered a stricter version of the eco-management system above as it takes into account both direct and indirect environmental influences. The implementation of environmental targets is also reviewed by external environmental experts and entered into the EMAS register.[68] These significant extensions seen within the EMAS system are highlighted in blue in

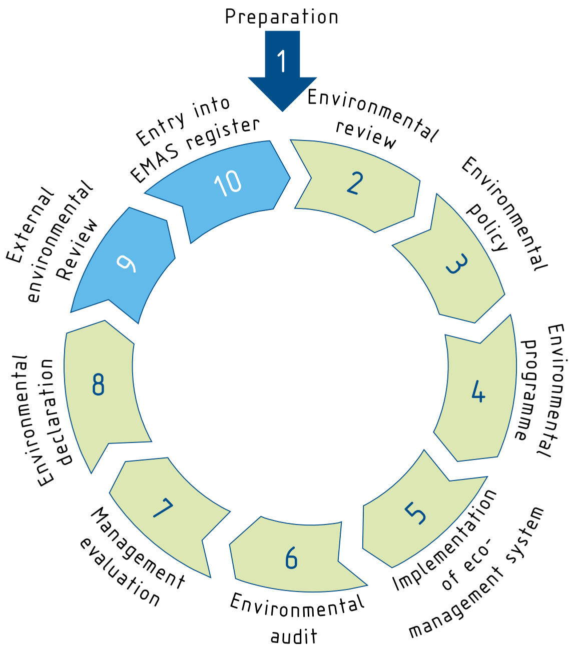


**Figure 7: EMAS cycle for implementing an eco-management system**[69]

[68] Cf. Scherf, C.-S. et al. (2021), p. 68.
[69] Based on Scheuch-Schmid, K. (2018), p. 21.

### Lifecycle assessment/analysis in accordance with DIN EN ISO 14040 and 14044

In addition to devising measures for increasing resource efficiency, digitally recorded resource consumption can also be used as a data pool for performing a lifecycle assessment and/or analysis. This is particularly relevant for businesses that must provide information on the environmental impact of their products and services to their customers.[70]

### ETSI standard TS 103 199 Environmental Engineering and Life Cycle Assessment of ICT equipment, networks and services

The way in which lifecycle assessments are carried out often varies greatly. The ETSI standard sets out a framework for standardising lifecycle assessments for the telecommunications and ICT sector. Its basic structure is based on the standard ISO 14040 Environmental management – Life cycle assessment – Principles and framework. The standard provides a guideline for determining system limits, functional units and allocation rules, and evaluating the general data quality.[71]

### Greenhouse Gas (GHG) Protocol

The Greenhouse Gas Protocol is a standard for voluntarily reporting on greenhouse gas emissions (GHG emissions). Emissions recording includes all greenhouse gases outlined under the Kyoto Protocol. The GHG Protocol differentiates between the "Corporate Standard" and "Corporate Value Chain" guidelines. The former involves performing a lifecycle assessment of GHG emissions in accordance with scopes 1 and 2, while the latter also includes emissions in accordance with scope 3. This is significant because more and more businesses are now obligated to provide information on their own GHG emissions to their customers.[72]

## 5.2 Measures for increasing material and energy efficiency

Depending on the evaluation system used and the nature of the data recording objective, possible areas of saving potential can be identified. However,

[70] Cf. Scherf, C.-S. et al. (2021), p. 70.
[71] Cf. Scherf, C.-S. et al. (2021), pp. 71 et seq.
[72] Cf. Scherf, C.-S. et al. (2021), p. 74.

these do not necessarily have to involve adapting the forms of material and energy used. Instead, material and energy savings are achieved by adapting products and processes, or even the business model itself. It is therefore important to identify the factors that influence material and energy use and optimise these areas to ensure resources are used as efficiently as possible. The corresponding measures can take many different forms.

### 5.2.1 Opportunities and challenges

The digital recording of resource consumption generally involves few direct risks. Instead, opportunities and challenges arise from the collection and evaluation of digitally recorded resource consumption and the resulting changes.

#### 5.2.1.1 Opportunities and motivation factors

In its first stage, the digital recording of resource consumption creates transparency. This makes it possible to analyse consumption and the subsequent adjustments made for products, processes, systems used and infrastructure. It forms the basis for all further measures and thus largely determines the quality of any subsequent analysis.

The digital recording of resource consumption also comes with a high potential for scaling, as the data can not only be used to analyse consumption but also to draw conclusions on the performance of certain systems and processes. This, in turn, has an impact on cost and resource efficiency.

Digitally recorded consumption data can also be used as the basis for environmental reports and communication with external stakeholders to help ensure the business is run more sustainably.[73]

In its core form, the digital recording of resource consumption provides a basis that can be used to reduce consumption both directly and indirectly (e.g. via system and process adjustments) and, in turn, improve a business' edge among its competitors. This also allows the business to communicate

[73] **Cf. Scherf, C.-S. et al. (2021), p. 33.**

an improved, more sustainable position to stakeholders to tap into potential new markets and target groups.[74]

#### 5.2.1.2 Internal and external challenges of the digital recording of resource consumption

As appealing as the benefits of digitally recording resource consumption may be, businesses should understand that this process also involves many challenges. However, these challenges can be taken into account early on when planning, allowing businesses to overcome them with suitable measures.

##### Internal challenges

Challenges often arise before any recording takes place, as part of the project planning phase. Business must first perform a review to see whether the existing company culture is conducive to such a change. How do employees feel about change, what are the concerns among staff with regard to the topics of digitalisation? It is recommended that businesses involve employees in the project early on and inform them about the process. Businesses should also highlight how the measures will ensure the future of the company and thus their jobs.[75]

Another aspect to consider is the available knowledge and skills that a business requires to digitally record resource consumption. Successful data collection requires skills in the areas of electrical engineering and IT, as well as knowledge of resource efficiency. To gain an overview of the relevant skills, businesses are recommended to create corresponding skills profiles relating to the various tasks involved as part of data collection and compare these profiles with employee qualifications. This will highlight any potential need for training measures. Training courses and advanced training should not be considered purely with a view to completing the project. Training can instead be used to help alleviate employee concerns and worries while creating a foundation for further digitalisation measures within the company.[76]

[74] Cf. Scherf, C.-S. et al. (2021), pp. 31 et seqq.
[75] Cf. Scherf, C.-S. et al. (2021), p. 33.
[76] Cf. Scherf, C.-S. et al. (2021), pp. 33 et seq.

The collection of data, the required sensors and IT, as well as the necessary employee training, however, all come at a cost and require businesses to dedicate a section of its staff. Businesses should be conservative in their estimations for data collection in particular as this generally involves the most expenditure in the case of the digital recording of resource consumption. To reduce implementation expenditure, at least with regard to financial resources, businesses are recommended to break down the whole project into sub-projects and take advantage of suitable funding programmes for these.[77]

The biggest challenge for businesses likely lies in correctly gauging the required data quantity and quality. A wide range of data is often already collected within the business. However, this does not mean that this data can also be used for recording resource consumption. It is therefore useful to seek the input of data mining experts early on in the process. Consultancy firms, research institutes, universities and other higher education facilities can be contacted for support.[78]

### External challenges

Not all challenges arise within the business itself. For the digital recording of resource consumption in particular it is important to be aware of any potential external barriers and consider these as part of the planning process.

The business' internal IT infrastructure is paramount for digital recording. It is therefore important for businesses to review which IT infrastructure is available. For example, if the business is located in an area with a weak internet connection, it is recommended to use cable connections for data transport to take as much strain off the IT infrastructure as possible.[79]

Further to technical equipment within the business, it is also important to consider any regulatory barriers, e.g. in the form of data protection and data security. For example, businesses should consider whether any conclusions can be drawn about the employees working with the material. With regard to data security, it is also worth noting which and how many interfaces arise

[77] Cf. Scherf, C.-S. et al. (2021), pp. 34 et seq.
[78] Cf. Scherf, C.-S. et al. (2021), p. 36.
[79] Cf. Scherf, C.-S. et al. (2021), p. 36.

within the company as a result of the digitalisation project. Businesses should examine whether and how these interfaces can be used by unauthorised parties (externally) to acquire company data.[80] This aspect becomes even more relevant where data is shared with other value-added partners.

### 5.2.2 Real life examples

As discussed, digitally recorded resource consumption can be used for a wide range of objectives. However, recording should not be an end in itself. Data collection and the resulting measures should also be economically worthwhile for the business. To this end, the sections below outline several implementation examples from businesses that digitally record their resource consumption and have been able to use this data to derive measures that are both economically and ecologically beneficial.

#### 5.2.2.1 Identifying tool wear using solid-borne sound sensors

The Bavaria-based family company Hufschmied Zerspanungssysteme GmbH develops and manufactures process-optimising machining tools. Using a combination of sound sensors, artificial intelligence (AI) and a digital evaluation model, the company was able to create a new system for quality control during the process.[81]

Machining tool wear is inevitable. However, recognising the sound that suggests the tool has begun to wear is not easy and requires the ear of an experienced operator. Such experienced operators are rarely at the machine around the clock, however. Growing automation within machining processes also makes detecting tool wear early increasingly difficult. This often leads to tools being replaced after a specified period of use or once a certain degree of wear has been identified. Companies generally do not carry out a data-based review of the tool's remaining runtime. The defined wear time, however, is influenced by many different factors and is often set with a relatively high safety margin (often 20%).[82]

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[80] Cf. Scherf, C.-S. et al. (2021), pp. 36 et seq.
[81] Cf. VDI Verlag GmbH (2022).
[82] Cf. VDI Verlag GmbH (2022).

To be able to automatically detect any beginning tool wear, the system developed by the company uses solid-borne sound sensors and a teachable AI. The AI recognises anomalies in the production processes, identifies inhomogeneities in the material (e.g. cavities in cast products) and “hears” the beginnings of tool wear and blade breakage. To make this possible, the sound emitted by the tool is recorded during the machining process, compared with a target value and then saved to a database. Using AI, the system can then detect the level of tool wear based on the deviation from the target value. The machine operator can see the wear via an HMI (human-machine interface), allowing them to respond to any corresponding deviation and replace the tool.[83]

By allowing operators to monitor the remaining runtime during the manufacture of components, this automated system saves time during production and can prevent any unwanted downtimes due to tool breakage. The available tool runtime is also increased thanks to a more efficient use of the tool’s service life. According to the company, these measures have allowed them to increase tool service lives by around 40%.[84]

It also became clear during this process that the acoustic monitoring of tools allowed the company to get an idea of the condition of the machine, enabling them to carry out predictive maintenance.[85] [86]

#### 5.2.2.2 Energy reduction of compressed air systems through data analysis

The Coburg-based company Kaeser manufactures compressed air systems and also offers services for these systems. The air compressors produced by the company come in various sizes and at different price points. Most compressors are traditionally purchased by customers and remain in use for many years. The product price and quality are the most important factors in the decision to purchase these products – the most suitable and most energy-

[83] Cf. VDI Verlag GmbH (2022).
[84] Cf. VDI Verlag GmbH (2022).
[85] Cf. Hufschmied, R. (2021).
[86] Cf. VDI Verlag GmbH (2022).

efficient product is often disregarded. This is a relevant factor, however, as compressed air accounts for approximately 11% of industrial energy use.[87]

To allow more room for flexibility with regard to using a suitable compressor for the current compressed air consumption and create energy saving potential through new products, Kaeser opted for the new “SIGMA AIR UTILITY” operator model. Kaeser operates a performance-based contracting model. This means that customers no longer purchase systems directly and instead only pay for the system’s output. In the case of Kaeser, companies only purchase compressed air directly at a cubic metre rate. The systems are provided and maintained by Kaeser. Generated data is used in particular to ensure that the systems can be inspected decentrally and the “compressed air as a service” model can be provided as cost-effectively as possible. To do so, the data generated by the compressed air system and the sensors within the system is transmitted to a master control unit and then sent to Kaeser.[88]

The data collected is analysed in real time and the results are used to optimise compressor control and thus increase energy efficiency. Compressor control becomes more efficient the more customers use the compressors as the collected data is taken to train the algorithms using machine learning. This step, in turn, facilitates more precise pattern recognition that then allows businesses to gain information on system control and use. This is beneficial for both Kaeser, which wants to operate the systems for as long as possible and is able to reduce maintenance effort this way, and the customer who is able to save compressed air. The sensors used by Kaeser not only monitor compressed air consumption but are installed as critical components to prevent machine downtime. In total, by digitally monitoring compressed air systems, Kaeser was able to save approx. 30% of operating costs.[89] [90] [91]

#### 5.2.2.3 Energy data management in the chocolate industry

Based in Glonn near Munich, Hans Brunner GmbH manufactures chocolate moulds (e.g. for chocolate Easter bunnies). The company works actively in

87 Cf. Schmid C. et al. (2003), p. 6.
88 Cf. Oswald G. and Krcmar H. (2018), pp. 99 et seqq.
89 Cf. KAESER KOMPRESSOREN SE (2022).
90 Cf. Oswald G. and Krcmar H. (2018), pp. 99 et seqq.
91 Cf. Schmid C. et al. (2003).

many different areas of resource efficiency. It reprocesses its products, reuses components and recycles materials. In doing so, the company was able to repurpose around 270,000 magnets from used moulds in 2018. It also recycled around 11,000 kg of plastics. Through its energy efficiency measures, the company is able to save 30,000 l fuel oil and 100,000 kWh of energy annually. The use of process waste heat in particular and the diverting of any excess heat into the district heating grid ensure an even energy balance. The company also makes use of its own solar power system for its energy supply.[92] [93] [94]

The company would like to continue to drive forward these developments and achieve a higher level of energy efficiency. Recording consumption on all systems manually, however, is very time-consuming and difficult to manage, particularly for SMEs. The company therefore developed a way to digitally record consumption together with a service provider.[95] [96] [97]

The company developed its system based on open standards and worked on an open-source solution together with the Competence Centre eStandards (German: *Kompetenzzentrum eStandards*). This allows the company to transmit load profile data for the COSEM standard, for example. The energy data recorded in the cloud can then be analysed, allowing the manufacturing company to make corrections and develop improvement measures. With quick access to real-time data on energy consumption relevant for billing, the company is able to use energy-intensive loads at the optimal time. The company's own energy traffic-light system helps to visualise this step.[98] [99] [100]

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[92] Cf. Wolff, T. (2018).
[93] Cf. Mittelstand 4.0-Kompetenzzentrum (2019a).
[94] Cf. Mittelstand 4.0-Kompetenzzentrum (2019b).
[95] Cf. Wolff, T. (2018).
[96] Cf. Mittelstand 4.0-Kompetenzzentrum (2019a).
[97] Cf. Mittelstand 4.0-Kompetenzzentrum (2019b).
[98] Cf. Wolff, T. (2018).
[99] Cf. Mittelstand 4.0-Kompetenzzentrum (2019a).
[100] Cf. Mittelstand 4.0-Kompetenzzentrum (2019b).

### 5.2.2.4 Holistic production management model for material and energy saving

Reutlingen-based Rieber GmbH & Co. KG is a manufacturer of kitchen technology and primarily produces gastronorm containers, large kitchen components and aircraft water and wastewater tanks. The focus of the company's value chain lies in the deep-drawing, smouldering and welding production steps. Making up 50% of overall costs, material costs are the largest cost drivers within the company. However, despite this, 35% of materials used by Rieber were previously lost to waste or scrap.[101]

Energy losses also play an essential role. The ability to obtain energy consumption data for specific products and processes is very important for the company, especially in the context of identifying energy efficiency potential. To reduce material use, the company seeks to uncover unused saving potential. To do so, it first visualises material streams and information flows. The company also implemented measured variables and control parameters to quantify potential. This step is important as the wide range of products and large differences in product quantities at Rieber can often result in conflicting objectives which, in turn, negatively impact optimisation measures. In certain circumstances, this can mean that savings in one process result in losses in another. The aim is therefore to improve the value chain as a whole.[102]

Using an automated data recording system, the company was able to record various material and energy flows in one material flow model to achieve its objectives. The Excel-based material flow model uses production data and is generated with data from the SAP system. The e!sankey software was then used to visualise the flows. The choice of software also makes it possible to illustrate complex cause-effect relationships between individual business areas. Using the system, Rieber can now identify the real causes of waste and develop targeted measures to prevent it from happening. For example, Rieber was able to reduce the amount of waste in the stamping process by 10% by re-nesting the components. This measure led to an absolute material saving of around 33 t of stainless steel per year. The company was also able

[101] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), p. 146.
[102] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 146 et seqq.

to save 600 MWh of energy a year due to the active use of waste heat potential that was made possible through the digital recording of resource consumption.[103]

#### 5.2.2.5 Automatic process shutdown

Baden-Württemberg-based Scheuermann + Heilig offers products and services in the area of forming and assembly technology and manufactures plastic components.[104]

As one of its primary objectives, the reduction in energy use secures the company's competitive edge and brings with it some ecological advantages. To achieve this, the company has introduced an energy management system certified in accordance with ISO 50001 which digitally records energy flows. The recording of these flows showed that the energy use of systems is a suitable indicator for identifying potential areas of improvement. The company had already started to instruct employees to shut down systems that were not in use. However, this was not implemented across the board, resulting in an unnecessarily high energy demand while the systems were on standby.[105]

To solve this problem, the company implemented an automated shutdown mechanism. 45 presses were fitted with time and logic relays in just eight weeks. The machines could be fitted with the devices in just a few hours using additionally purchased standard components.[106]

Switching to this needs-based energy model allowed Scheuermann + Heilig to save approx. 300,000 kWh of energy per year, equating to approx. 180,000 kg of $CO_2$ emissions. In terms of costs, the avoided excess energy consumption saved the company over 50,000 euros a year. This equates to a payback period of around three months.[107]

[103] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 146 et seqq.
[104] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 158 et seqq.
[105] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 158 et seqq.
[106] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 158 et seqq.
[107] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 158 et seqq.

### 5.2.2.6 Efficient control of rinsing bath cascades

John Deere is a corporation that is active across the globe. At its six German locations, the company produces agricultural technology such as tractors, combine harvesters and forage harvesters. The driver's cabins for these vehicles are manufactured in Bruchsal.

The production process for manufacturing the driver's cabins was systematically analysed to find areas of the process that used a high amount of resources. As part of this analysis, it became clear that the painting process used lots of water.

Several pre-treatment steps are required prior to the actual painting itself, such as degreasing, pickling and zinc phosphating. The treated parts must be cleaned in a water rinsing bath in between each of the pre-treatment steps to ensure that they are clean for the next stage. To ensure that the rinsing bath continues to clean effectively, the concentration of dirt in the bath must be reduced. To do so, fresh water must be added to the rinsing bath. However, the concentration of dirt in the rinsing baths is not recorded using measurement technology. This means that fresh water is added arbitrarily at regular intervals. The rate at which fresh water should be added was calculated based on the maximum system capacity, meaning water use was much higher than would have been needed to run the system efficiently.

To significantly reduce the amount of water used in the painting process' multi-step pre-treatment stage, the company decided to install measuring technology in the rinsing bath to determine the level of contamination using conductivity probes. Once the limit concentration of dirt particles is reached, the corresponding optimum amount of fresh water is added in real time for a more targeted approach. This measurement/regulation system was designed by an interdisciplinary project team consisting of engineers from the areas of coating, chemical and control technology. After many different attempts, it was possible to infer the level of contamination using a measured value for conductivity. In addition to the measurement/regulation system, the company also installed a suitable filter at the end of each pre-treatment stage, allowing it to further reduce water use by preventing as many dirt particles from entering the rinsing bath.

This needs-based dosing of fresh water using measurement/regulation technology allowed John Deere to reduce its water use by 30% in total. This, in turn, reduced the amount of wastewater generated by approx. 30%, allowing the company to significantly lower its energy expenditure and the associated costs for wastewater processing (vacuum distillation system). The investment costs were recovered in cost savings within the first year of operation.[108]

#### 5.2.2.7 Increasing efficiency through the use of Industry 4.0 instruments

Blechwarenfabrik Limburg GmbH is a packaging manufacturer for chemical-technical filling materials. The company processes over 25,000 t of tin plate for millions of tubs, bottles, canisters and cans per year.[109]

When it moved its production site, the company was also forced to digitally optimise its production and logistics systems. This optimisation was focused primarily on automating process management. The aim was to combine the instruments of a digital factory into a new system to help preserve resources.

To achieve this, the machines from the previous production site were fitted with modern sensors and video technology. The company also implemented a digital production planning system (PPS). The PPS controls the needs-based material flow in the factory hall using a driverless transport system.

This allows all necessary materials and operating supplies to be transported from the warehouse to the production floor as needed. Here, the software-based PPS uses a digitally recorded model of the production process that is supplied with data from the warehouse and production floor in real time. The PPS is also linked to an ERP system. This allows the company to plan production processes and demand using the ERP system. The system is also connected to an energy management system that digitally monitors and controls the production site's energy flows (gas, electricity and compressed air) in real time.

[108] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 218–221.
[109] Cf. Menn, P. (2021).

According to the company's own assessment, digitally networking all processes has led to a significant increase in the efficiency of the production systems which has, in turn, improved overall material and energy efficiency.

By digitally interconnecting its processes, the company was able to use its systems more energy-efficiently and improve its overall material and energy efficiency. For example, by automating its internal material transport system, the company was able to reduce transport damage and thus avoid the loss of up to 100 t of tin plate annually. More efficient digital system control and capacity planning using the ERP and PPS systems also allowed the company to increase the capacity of its production machines to achieve even more energy efficiency. The digital energy management system further makes it possible to identify and rectify any inefficiencies or leaks. The company is set to save approx. 2,600 t GHG ($CO_2$ equivalents) per year.[110] [111]

#### 5.2.2.8 Data mining for SMEs

GEFASOFT Automatisierung und Software GmbH develops, produces and sells automation systems for industry. As part of the SIDAP research project funded by the *Bundesministerium für Wirtschaft und Energie* (English: Federal Ministry for Economic Affairs and Energy), the company undertook to investigate and prepare the transfer of smart data concepts into production technology.

The project aimed at expanding GEFASOFT's existing "Legato Sapient" product (a manufacturing execution system) with several functions. These functions include, for example, operational and machine data recording and the calculation of key performance indicators. Using the software, it will be easier and more cost-effective for SMEs to access data mining methods.

The system developed by the company makes it possible to record, evaluate, process and visualise process data, and then subsequently analyse the results. Access to a database using SQL queries as an interface makes the exchange for data mining easier. It is even possible for SMEs to integrate complex calculation algorithms cost-effectively thanks to the use of open-source

[110] Cf. Scherf, C.-S. et al. (2021).
[111] Cf. Menn, P. (2021).

programming languages such as R and WEKA. All results can be displayed easily on a web-based interface. The designated dashboard can also be customised to offer the perfect overview.

This project has resulted in the creation of a software that allows SMEs to mine data easily and display the results with minimal effort and costs. In general, the system does not involve any licencing costs, as it is based on an open-source environment.[112]

[112] Cf. Schütz, D. (2018).

# 6 CONCLUSION

The digital recording of resource consumption provides businesses with countless opportunities to control and reduce their resource use in the long term. Here, it is important for businesses to analyse the entire process, from measurement to evaluation, in order to consider any challenges and, if necessary, iron out any potential issues e.g. data quality and transmission options) as part of the initial planning. The digital recording of resource consumption can therefore be a useful starting point for making improvements within the business itself or across the value chain and can go a long way in helping a business to save resources, protect the climate and improve its own competitive position.

The value of data for measuring resource saving potential in particular is not always clear for businesses. The evaluation and use of purposefully generated or existing datasets with a view to deriving resource efficiency measures will therefore be a central field of development in the coming years, especially for small and medium-sized enterprises. Businesses should create an overview of and utilise existing resource data, adapting and expanding the data pool where necessary. There are already methods for doing this (e.g. data mining) which help businesses to systematically record, process and store data relating to resource use. These methods can also be used to identify any shortfalls in the previous data recording system which can be resolved using appropriate sensors and measurements.

However, to be able to tap into any identified resource saving potential, businesses must create an environment that allows them to implement these plans. This includes setting up and ensuring access to broadband internet and 5G. Legislation must also ensure legal compliance in the area of data processing and use. The digital (further) training of potential employees will also be another important and shared field of development for both the government and businesses going forward.

In this way, a resource-oriented digitalisation approach can not only help industry to achieve its climate targets, it can also help to strengthen a business' competitive edge and, in turn, improve Germany's position as a destination for business and industry.

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# APPENDIX

Table 6 provides an overview of relevant measuring sensors for directly and indirectly recording production-related resources.

**Table 6: Measuring devices and sensors for direct and indirect resource recording**[113]

| Measured variable | Sensor type | Resource | Example |
|---|---|---|---|
| **Mechanical measured variables for solids** | | | |
| Mass | Electric load cells | Materials (solid, liquid) | Determination of mass of objects or liquids |
| Mass flow | Image sensor, barcode/QR code scanner, RFID/NFC | Materials (solid) | Determination of mass of objects per unit of time; prerequisite: knowledge of object mass |
| **Mechanical measured variables for liquids and gases** | | | |
| Flow | Magnetic-inductive flow sensor | Materials (liquid) | Measurement of liquid flow quantities |
| Flow | Ultrasound flow sensor, differential pressure determination, impeller flow sensor, vortex flow meter, mass flow meter (Coriolis principle), thermal flow meter | Materials (liquid, gas) | Measurement of flow quantities of liquids and gases |
| Flow | Magnetic-inductive flow sensor | Materials (gas) | Measurement of gas flow quantities |
| Density | Oscillating U-tube | Materials (liquid) | Density measurement of liquids; mass of liquid can be determined using density with knowledge of liquid volume |
| Pressure | Resistance pressure transducer, inductive pressure transducer, capacitive pressure transducer, piezoelectric pressure transducer | Materials (gas) | Measurement of gas pressure for determining gas quantity and/or gas concentration |

[113] Cf. Fleischer, J.; Klee, B.; Spohrer, A. and Merz, S. (2018), p. 11.

| Measured variable | Sensor type | Resource | Example |
|---|---|---|---|
| Pressure | Capacitive pressure transducer | Materials (liquid) | Measurement of liquid pressure for determining liquid quantity and/or concentration |
| Fill level | Float, ultrasound sensor, radar/microwave, optical sensor (e.g. ultrasound), conductivity meter, hydrostatic measurement (hydrostatic head pressure), gravimetric measurement (container weight), capacitive sensor | Materials (liquid) | Measurement of liquid fill levels in a container (for determining liquid volume) |
| Fill level | Ultrasound sensor, radar/microwave, laser and/or optical sensor, radiometric method | Materials (solid) | Fill level measurement of bulk goods in a container (for determining bulk goods volume) |
| **Thermal measured variables** | | | |
| Temperature | Resistance thermometer, infrared temperature sensors, thermoelement | Energy | Temperature measurement in solids, liquids and gases for directly determining the stored, absorbed or released thermal energy quantities (e.g. thermal loss) |
| Thermal conduction | Conductivity sensor, thermal flow sensor | Energy | Determination of thermal conductivity of solids, liquids and gases for calculating stored thermal energy quantity |
| **Electrical measured variables** | | | |
| Electricity | Electricity sensors | Energy | Electricity measurement for determining electrical power and thus electrical energy quantity |
| Voltage | Voltage sensors | Energy | Voltage measurement for determining electrical power and thus electrical energy quantity |
| **Chemical measured variables** | | | |
| Concentration | Infrared spectrometer, mass spectrometer, UV/VIS spectrometer | Materials (solid, liquid, gas) | Measurement of material quantity/mass of solids, liquids or gases |

Table 7 lists relevant bus systems from the real world

**Table 7: Practice-oriented bus systems[114]**

| Bus systems | Name |
|---|---|
| I²C | Inter-Integrated Circuit |
| SENT | Single Edge Nibble Transmission |
| LIN bus | Local Interconnect Network – Binary Unit System |
| Ethernet | Ethernet |
| USB | Universal Serial Bus |
| FireWire | FireWire |
| MOST bus | Media Oriented Systems Transport |
| RFID | Radio Frequency Identification |
| Bluetooth | Bluetooth |
| WPAN | Wireless Personal Area Network |
| GSM | Global System for Mobile Communication |
| UMTS | Universal Mobile Telecommunication System |

Table 8 provides an overview of the common data mining methods.

**Table 8: Methods for the systematic recording, processing and integration of data**

<table>
<tr><th>Process step</th><th>KDD[115]</th><th>Crisp-DM[116]</th><th>SEMMA[117]</th><th>TDSP[118]</th></tr>
<tr><td>1</td><td>Data</td><td>Business understanding</td><td>-</td><td>Business understanding</td></tr>
<tr><td>2</td><td>Selection</td><td rowspan="2">Data understanding</td><td>Sample</td><td rowspan="3">Data acquisition and understanding</td></tr>
<tr><td>3</td><td>Processing</td><td>Explore</td></tr>
<tr><td>4</td><td>Transformation</td><td>Data preparation</td><td>Modify</td></tr>
<tr><td>5</td><td>Data mining</td><td>Modelling</td><td>Model</td><td rowspan="2">Modelling</td></tr>
<tr><td>6</td><td>Interpretation/evaluation</td><td>Evaluation</td><td>Assessment</td></tr>
<tr><td>7</td><td>Knowledge</td><td>Deployment</td><td>-</td><td>Deployment and customer acceptance</td></tr>
</table>

[114] Cf. Schiessle, E. and Schreier, J. (2018).

[115] Cf. Fayyad, U.; Piatetsky-Shapiro, G. and Smyth, P. (1996), p. 41.

[116] Cf. Chapman, P.; Clinton, J.; Kerber, R.; Khabaza, T.; Reinartz, T.; Shearer, C. and Wirth, R. (2000), p. 13.

[117] Cf. Shafique, U. and Qaiser, H. (2014), pp. 220 et seq.

[118] Cf. Haakman, M.; Cruz, L.; Huijgens, H. and van Deursen, A. (2021), p. 13.

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