Assessment of product-service systems for increasing the energy efficiency of compressed air systems

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Abstract: Energy-optimised system operations should be a cornerstone for cleaner production in industry. However, the high energy consumption of compressed air systems (CASs) is often ignored. Product-service systems (PSSs) represent a method to improve energy efficiency, but can only be successful if they offer a win-win situation for both parties, namely the supplier and the customer. When selecting the most appropriate PSS, different quantitative or qualitative criteria have to be taken into account. Asymmetric information and differing objectives between the supplier and the user of a technology, characterise this decision problem. Like the two sides of a coin, investment in an energy-efficient production technology is judged differently by the manufacturer than by the customer. This paper presents a new approach offering multi-criteria group decision support based on the PROMETHEE method, which clearly depicts conflicting targets of decision-makers, and thus supports articulating criteria, preferences and weights of various stakeholders. This method was applied in a case study evaluating different concepts of leakage management, which were compared to the traditional business concept – acquisition and use of the compressed air system by the end-user. Within the context of the decision problem of choosing a best CAS, some further methodological developments are proposed. [Received 8 November 2014; Revised 31 August 2015; Accepted 29 December 2015]

Keywords: product-service systems; PSSs; compressed air; energy efficiency; multi-criteria decision making; MCDM; conflicting objectives.

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1 Introduction

Energy-efficient production technologies and products play a major role in achieving cleaner production. For instance, industry accounted for roughly 43% of total electricity consumption in Germany in 2010, which could be reduced significantly by energy-optimised system operations (Hirzel et al., 2012). The right choice of technology (effectiveness) and correct operation (efficiency) determine how much primary or end-use energy is required to provide energy services required in production processes.

Innovative equipment manufacturers have developed intelligent mechatronic systems and components, employing low-power technologies and optimal system design. However, these innovations still need to be accepted by customers, many of them in small and medium-sized enterprises (SMEs). Asymmetric information and differing objectives between the supplier and the user of a technology, characterise the decision problem. Like the two sides of a coin, the investment in an energy-efficient production technology is judged differently by the manufacturer than by the customer. This decision problem becomes obvious for suppliers and customers of product-service systems (PSSs) for increasing the energy efficiency of compressed air systems (CASs). Information asymmetry is subject of research in contract theory and economics, especially with regard to its implications for market behaviour and the market institutions that are created to mitigate the adverse effects implied by the theory. In this paper, however, various stakeholders (i.e., the supplier and the customer) evaluate a new PSS taking multiple criteria into account, while having different and inhomogeneous information.

As compressed air is rarely discussed from an environmental perspective, it even surprises many (environmental) managers that it accounts for 10–15% of the total electricity use of a company (Baas, 1998; Taylor, 2006; Hirzel et al., 2012). An energy savings potential ranging from 20–40% has been reported (Baas, 1998) through the following activities:

1 lowering pressure, preventing leaks, and re-designing the existing pipeline system in companies

2 implementing a central supply via a ring pipeline system in industrial ecosystems.

Baas and Boons (2004) find that compressed air is perceived as a production mean for which the maintenance manager is responsible. Often, the energy and environmental aspects of using compressed air are unknown, perhaps because the company's core competencies are in other areas. Therefore, some compressed air suppliers established

PSSs for increasing the energy efficiency of CASs (Hirzel et al., 2012). Critical factors for success include building trust for the exchange of knowledge between participating firms, and reducing the scale of the investment needed for the installation. For such a PSS, the supplier invests in the installation and the pipelines, runs the process, maintains the system, and is responsible for a continuous supply (Baas and Boons, 2004). The new business model of PSS represents a competitive opportunity for many companies, which seek to reduce resource consumption by modifying the way their products and services are designed, marketed and used (Park et al., 2012; Beuren et al., 2013), and thus contributing to cleaner production through improved energy efficiency.

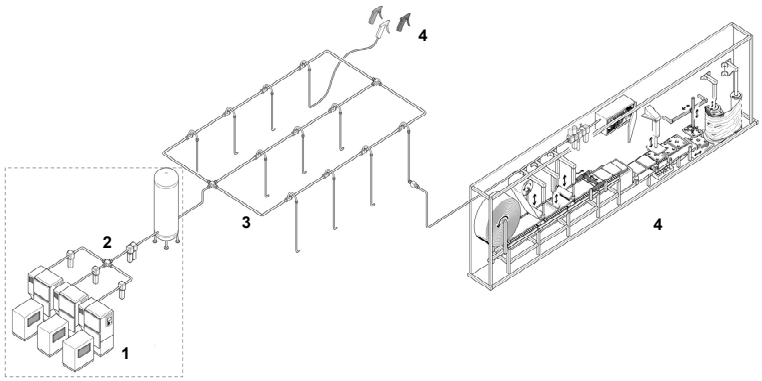
In the next section, CASs and their potential as PSSs are described. The main focus of this paper is on the analysis of the multi-criteria decision problem, where the weighting of the various criteria might deviate significantly between the provider and the customer of the PSS. The outranking approach PROMETHEE is being further developed for taking their different attitudes into account. Finally, a case study is presented, which has been conducted in cooperation with a supplier for CASs and its customers to increase the energy efficiency of CASs by implementing leakage management as different alternatives of PSSs. The relevant evaluation criteria are analysed and several scenarios are tested using the proposed approach.

2 PSSs for CASs

CASs are a cross-cutting technology used in almost every sector of the manufacturing industry. They can be divided into four main parts: compressed air generation, treatment, distribution and end-use (US Department of Energy, 2003; Seslija et al., 2009). The compressed air is used in different processes. It is applied, e.g., for the propulsion of cylinders in highly automated processes, for the direct use in processes as drying processes or as transportation medium of bulk goods (Hirzel et al., 2012). However, CASs are very energy-intensive compared to other media such as hydraulic or electrically-powered motor systems and account for 10% of the total industrial electricity consumption in Europe (Radgen and Blaustein, 2001). Their efficiency lies between 5 and 19%, depending on the compressed air application (Gloor, 2000). The energy costs for generating compressed air have a very high share of 70% in the total life cycle costs of a compressor station (Radgen and Blaustein, 2001). This is why energy efficiency improvements are so important for compressed air generation and use.

Radgen and Blaustein (2001) propose various measures to reduce the energy consumption of CASs which could realise cost-effective savings of more than 30% in total. Despite the high energy costs involved, saving measures are often not implemented. General barriers related to energy efficiency measures (Sorrell, 2007; Weber, 1997) as well as specific barriers related to CASs hinder the implementation of such measures (Radgen and Blaustein, 2001). For instance, a lack of monitoring and separate accounting of compressed air usage or management's limited time and attention (Radgen and Blaustein, 2001) prevent the operators of CAS from realising these savings. These barriers seem to exist because operating CAS is not part of the company's core competence (Halme et al., 2007; Lay et al., 2007).

Figure 1 Exemplary scheme of a CAS



Notes: 1: compressed air generation, 2: compressed air treatment,
3: compressed air distribution, 4: compressed air end-use.
Source: Hirzel et al. (2012)

One solution to overcome these challenges might be to outsource efficiency measures to an expert, e.g., the compressor manufacturer or supplier of pneumatic components. This would cause a shift from a product to a service supplier by vertically integrating upstream processes in the supply chain (Wise and Baumgartner, 1999). Recently, much more attention is being paid to this concept of so-called PSSs. These systems are characterised by a transfer of responsibilities and risks from the customer to the provider (Baines et al., 2009a; Lay et al., 2009; Tukker and Tischner, 2006). This is caused by a different value proposition in PSSs compared to the traditional business concept. A widely used segmentation for PSSs distinguishes three groups – product-oriented, use-oriented and result-oriented – with a service content and product content which increases or decreases according to the given value proposition (Tukker and Tischner, 2006; Williams, 2007). In the context of mechanical engineering, a product-oriented PSS could be a repair service, whereas a use-oriented PSS might be the certain availability of a machine. Examples for result-oriented PSSs could be achieved output or savings.

PSSs are often mentioned in connection with positive environmental impacts (Halme et al., 2007; Baines et al., 2007; Goedkoop et al., 1999; Mont, 2002; Mont and Tukker, 2006; Manzini and Vezzoli, 2003; Roy, 2000), by prolonging the life span of a product (e.g., all components of a CAS) (Manzini and Vezzoli, 2003; Roy, 2000), recycling products (Goedkoop et al., 1999; Mont, 2002; Manzini and Vezzoli, 2003) or using them more efficiently during the operation phase (Reiskin et al., 2000; Stoughton and Votta, 2003).

PSSs result in organisational changes, which also contribute to implementing technical measures. However, there are different configurations for reducing the energy consumption of CASs. There is no single best solution for suppliers, but they can provide a modular offer. Selecting the ideal configuration for a specific customer remains a complex task, as each customer has different requirements. Additionally, besides profitability and energy consumption, the configurations also influence the market and the emerging risks in different ways. Hence, this is a multi-criteria decision problem which should also involve all the relevant decision-makers. To support selecting a

suitable configuration, this paper presents a decision support approach, which takes different perspectives and potentially conflicting goals into account.

PSSs further contribute to sustainable development, because the potentials to increase energy efficiency are frequently not exploited by traditional business concepts (Reiskin et al., 2000; Baines et al., 2007; Geldermann et al., 2009; BiPRO, 2010). This can be achieved by shifting inducements (buying incentives or motivation). In traditional business concepts, there are conflicting inducements between customers and suppliers, because the customer wants to decrease the volume of used material, while the supplier wants to increase material sales. These inducements can be aligned in PSSs, as both parties want to increase the value of the service. The principles of material efficiency services can be transferred to energy efficiency services with certain restrictions. Hence, both types of services are discussed in the following.

Increasing efficiency implies decoupling the amount of material or energy input to the process from the output (Reiskin et al., 2000; Ligon and Votta, 2001). Particularly for use- and result-oriented PSSs, this decoupling promises positive results, as the service provider is paid for fulfilling the customers' needs (Tukker, 2004). Some PSSs even include the obligation to reduce the consumption of resources in their value proposition, so that savings are directly linked to payment (Halme et al., 2007; Hockerts, 1999). In this case, the responsibilities, but also any financial risks arising from energy-saving measures are transferred to the service providers, so that they then have a vested interest in overcoming the lack of monitoring and properly accounting for consumption. Furthermore, potential efficiency measures are considered under life cycle aspects rather than focusing only on the investment costs. One way for the provider to increase his profits is by saving energy or materials while keeping the same output. If these savings are shared between the provider and the customer, this can also lead to changes in production planning (Reiskin et al., 2000; Stoughton and Votta, 2003; Bierma and Waterstraat, 1999).

Results of a survey confirm that customers can observe the effects of aligned incentives due to a reduction in energy or material consumption when employing use- or result-oriented PSSs (Schröter et al., 2010). The share depends on the specific category of PSSs. For use-oriented PSSs, about one third recognised reduced energy or material consumption; in the case of result-oriented PSSs, between one third and up to more than half of the customers stated that energy consumption could be decreased.

Additionally, result-oriented PSSs are a good way to promote the market penetration of resource-efficient technologies, because the customer assumes no financial risks for the investment (Bertoldi et al., 2006). If the customer had to foot the bill for the investment costs, energy-efficient technologies would spread less rapidly in the market, as efficient technologies usually have higher investment costs than standard technologies. If life cycle costs are considered instead, efficient technologies are generally less expensive (Woodward, 1997). Especially when small and medium-sized companies are the customers, energy services can help to improve their financial situation (liquidity), as they do not have to bear the investment costs themselves (Gruber and Brand, 1991). On the other hand, large companies tend to be less reluctant to introduce new business models, because they have sufficient resources to fund such projects (Schröter et al., 2010).

Despite their benefits, only a few eco-efficient PSSs exist in the market (Tukker, 2004). These few, which include energy contracting, are not very widespread yet and are also not feasible for the overall economy (Sorrell, 2007). One reason is that the business perspective has not been properly analysed because the main focus has been on technical innovations. However, institutional innovations are indispensable for supporting the shift of business strategies from production-based to service-based values. Another difficulty in establishing eco-efficient PSSs is the insufficient consideration of economic viability by the provider, as the PSS requires the creation of an added value to be successful (Tukker, 2004; Mont et al., 2006).

This poses the question of how a PSS should be configured to create added value, save energy and fulfil both the provider's and the customer's needs. A suitable method is needed to take all the decision-relevant aspects into account, which will be described in the following section.

3 Multi-criteria decision-making to support a strategic choice of PSSs

The choice of a suitable PSS can be characterised as a multi-criteria decision problem. Besides meeting the customer's needs, a PSS should be competitive and – in the special context of sustainability – environmentally-friendly (Baines et al., 2009b). Part of the decision-making process is to reveal preferences related to economic and technical objectives, as well as risks and market effects.

Methods of multi-attribute decision making (MADM) can be used for comparing and ranking alternatives such as cleaner production technologies (Miettinen and Hämäläinen, 1997; Spengler et al., 1998). MADM belongs to the more general area of multi-criteria decision making (MCDM) and allows for assessing a set of previously known discrete alternatives, while simultaneously considering various criteria measured in different metric units, in some cases including qualitative criteria (Belton and Stewart, 2003; Figueira et al., 2005).

MADM methods were developed to derive a transparent decision-making process and allow for compromise based on the different decision criteria in the absence of a dominant alternative (Brans and Mareschal, 2005; Huang et al., 2011; Geldermann and Rentz, 2005).

In recent decades, several multi-criteria decision aid (MCDA) methods have been proposed to assist the selection process of the best compromise alternatives. Reviews on MCDM and MADM used in sustainable energy planning can be found in Wang et al. (2009), while Zhou et al. (2006) provide an overview of decision aid in energy and environmental modelling. The preference ranking organisation method for enrichment evaluations (PROMETHEE) (Brans et al., 1986) family of outranking methods and their applications has attracted much attention from academics and practitioners (Behzadian et al., 2010). It can also be used for group decision support (Macharis et al., 1998). Positive aspects of other methods have been integrated into the newly developed group decision approach of PROMETHEE (Macharis et al., 2004; Turcksin et al., 2011), as the consideration of criteria in a hierarchy like in the analytical hierarchy process (AHP) (Saaty, 1990) and veto-effects from Elimination Et Choix Traduisant la REalité (ELECTRE) (Roy, 1991). Thus, the decision process can be better structured and clearly presented using the hierarchy (Macharis et al., 2004), and the veto-effects help to find a compromise solution which is acceptable to all the decision-makers (Leyva-Lopez and

Fernandez-Gonzalez, 2003). Within the context of the decision problem of choosing a best PSS configuration, some further methodological developments are proposed in order to identify and analyse the influence of conflicting targets between the decision-makers (Weißfloch, 2013). Therefore, a new problem structuring and weighting process similar to the approach of Macharis et al. (1998) is developed, which takes into account the heterogeneous motivations of the supplier and customer of PSSs, which are the decision makers according to the notation of PROMETHEE. First of all, the r decision-makers and their share of the vote v^r have to be determined. The set of possible alternatives $A = \{a_1,\ldots,a_i,\ldots,a_m\}$ can already be fixed or defined by the group of decision-makers. Afterwards, the set of criteria $C = \{c_1,\ldots,c_j,\ldots,c_n\}$ is specified by each decision-maker. All of these criteria are taken into account in the decision process after a consolidation process has taken place, which discusses the handling of similar or dependent criteria. In this case, the final criteria have to be defined within the group. Depending on the number and whether they are assignable to main categories, the criteria can then be structured in a hierarchy. In the end, each decision-maker r weights the criteria i individually w_i^r and states whether they have to be maximised or minimised. A three-step approach is then applied to determine the weights for the group decision based on the individual weightings:

1 The individual contribution t of each decision-maker r for criterion i $(w_{t,i}^r)$ to the group weighting is determined for every criterion by multiplying the individual weighting w_i^r (of each decision maker r on criterion i) by the share of the vote v^r of the decision maker r and the factor '+1' or '–1', as the best characteristic of a criterion can be the maximum ('+1') or the minimum ('–1'). This optimisation direction can vary between the decision-makers (for example for the investment, which is completely differently judged by the supplier and the customer), so that this factor is important for the next step.

$$w_{t,i}^r = \pm 1 \cdot w_i^r \cdot v^r \tag{1}$$

2 The weighting of the group g $w_{t,i}^g$ results from the addition of all the individual contributions t on a criterion i. The algebraic sign of this sum indicates whether a maximisation or a minimisation of this criterion should be considered for the group decision.

$$w_{t,i}^g = \sum_r w_{t,i}^r \tag{2}$$

3 In the end, the group weighting is normalised to 1 $(\sum_i w_{n,i} = 1)$ to be able to compare the individual weightings with the normalised group weighting ($w_{n,i}$).

$$w_{n,i} = \frac{\left|w_{t,i}^g\right|}{\sum_i i \left|w_{t,i}^g\right|} \tag{3}$$

In the case of conflicting targets, a veto-function is integrated. Each decision-maker can define a minimum value – in the case of the maximisation of the criterion – or a maximum value – for the minimisation of this criterion – which has to be fulfilled by this criterion. This should lead to a target range, i.e., the maximum value should lie above the minimum value; otherwise it is not possible to reach a consensus using this mathematical aggregation method. If the criterion is outside this corridor, this alternative is no longer considered in the decision process.

The PROMETHEE method is then applied to the outcome. PROMETHEE is based on pair-wise comparisons of the alternatives concerning the different criteria (e.g., Brans and Mareschal, 2005; Spengler et al., 1998). Thus, as the next step, the outranking relation π can be calculated, to determine the degree of dominance of alternative a_{i*} over a_i with regard to all criteria. Hereby, the respective preference functions p of each criterion i under consideration of the determined group weighting are added:

$$\pi^g\left(a_{i*}, a_i\right) = \sum_{j=1}^{n} w_{nj}^g \cdot p_j\left(a_{i*}, a_i\right) \tag{4}$$

For PROMETHEE I leaving and entering flows are calculated, which represent the mean of all pair wise comparisons of one alternative. The leaving flows Φ^+ indicate the strengths of the alternative:

$$\Phi^{+,g}\left(a_{i*}\right) = \sum_{i=1}^{m} \pi^g\left(a_{i*}, a_i\right), \tag{5}$$

while the entering flows Φ^- show the weaknesses:

$$\Phi^{-,g}\left(a_{i*}\right) = \sum_{i=1}^{m} \pi^g\left(a_i, a_{i*}\right) \tag{6}$$

The partial preorder according to PROMETHEE I can be defined based on the intersection of the two preorders from the positive and the negative outranking flows. A complete preorder avoiding incomparability can be defined according to PROMETHEE II based on the net flow $\phi(a_{i*}) = \phi^+(a_{i*}) - \phi^-(a_{i*})$:

a a_{i*} is preferred to a_i if $\phi(a_{i*}) > \phi(a_i)$

b a_{i*} and a_i are indifferent if $\phi(a_{i*}) = \phi(a_i)$.

In PROMETHEE II, the difference between the leaving and entering flows is generated, which leads to a total preorder. There is no incomparability. Brans and Mareschal (2005) point out that the calculation of the net outranking flow in PROMETHEE II goes along with a loss of information compared to PROMETHEE I, because positive and negative criteria values can compensate each other, similar to utility functions in multi-attribute utility theory (MAUT) (see also Belton and Stewart, 2003; Geldermann and Rentz, 2005). Thus, it is recommended to always use both options, because the complete ranking based on PROMETHEE II can only be fully understood if the partial ranking based on PROMETHEE I is also known. The calculation of the rankings can be made for the group as well as for each decision-maker individually.

4 Case study on the assessment of PSSs for increasing energy efficiency by CAS

The newly developed method is applied to the case study, which aims to increase the energy efficiency of CAS using a PSS (Hirzel et al., 2012). The investigated company produces automation technology and operates all over the world. It already supports its customers with services along its products' life cycle, from dimensioning to maintenance and repair. Energy efficiency is already a relevant topic for the service portfolio. The firm also tries to raise awareness about life cycle cost calculations so that its customers understand that savings are possible in the longer term by using a more efficient technology which may require a higher investment at the outset.

The company is thinking about enlarging its service portfolio by offering energy-efficient PSSs. Reducing energy consumption helps to enhance the competitiveness of compressed air technology even though energy prices are increasing. Accordingly, the firm developed a set of PSS configurations which matches this strategy. These are presented in the next section. The aim of this case study was to support the company in selecting the most suitable PSS for their different customers.

4.1 Alternatives

The case study company identified different measures to reduce the high energy consumption of its customers. These were an appropriate dimensioning of the whole CAS with only very low safety margins, a modernisation of an old CAS with more efficient drives, valves and cylinders and a reduction of leakages. The case study company choses the reduction of leakages for a first approach as it is the one with the highest potential. Reducing leaks can be applied in 80% of all companies and has an average energy saving potential of 20% (Radgen and Blaustein, 2001). But even for this one measure, there are still many options when designing the PSS.

First, it has to be decided in which part of the CAS the leakage management takes place. This can be either in the distribution network, or in the connected machines which use the compressed air, or in both.

Another aspect is the technology used to detect the leakages. One possibility is to go through the production area with an ultrasonic detector and a special test instrument which help to identify and locate leakages; this approach is called the 'offline variant' in the following. A second possibility is to integrate a condition-monitoring system. Here, a sensor has to be installed in front of every machine and every pipe. The corresponding data is recorded in a management system. Leakages can be recognised by comparing the sensors' results over time. The precise location then has to be detected using an ultrasonic detector. This approach is referred to as the 'online variant'.

Additionally, the organisational responsibilities for the leakage management are either assigned to the provider or the customer. Depending on the chosen technology, these are:

- implementation of sensors and management system
- monitoring sensor data
- maintenance and calibration of detection devices

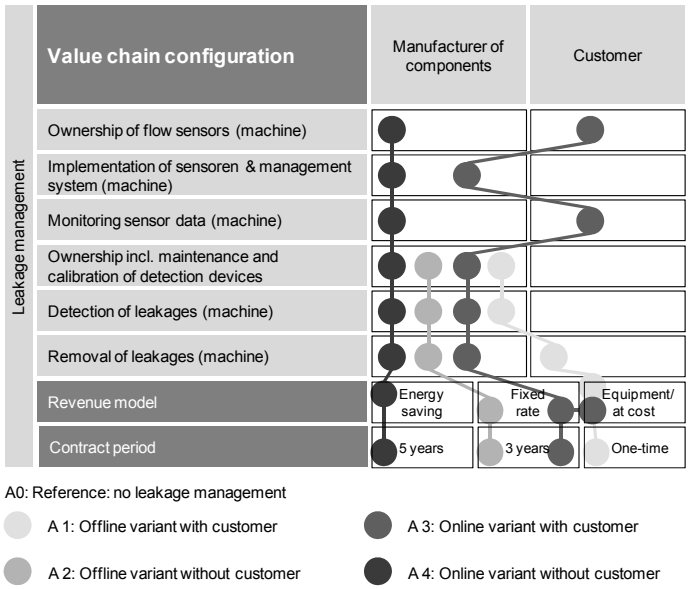
- detection of leakages
- removal of leakages.

The revenue model can also vary depending on the category of PSSs (Lay et al., 2009). All these aspects imply differences in the contract duration.

The employees of the investigated company who were responsible for the development of PSSs considered the company's core competences to be at the machine level, so in the short run they wanted to offer only this level to avoid having to cover the whole system. In the end they opted for four configurations of PSSs for leakage management, which are compared to the traditional business model, which is defined as the reference case with no leakage management at all (A0). In this case there are no payments between both the parties.

In the first PSS (A1), the provider offers only leakage detection with the offline variant; fixing the leaks has to be done by the customer. The invoicing is based on actual expenses. The contract covers a one-time execution (Figure 2).

Figure 2 Options of PSS configurations



Source: Own diagram

In contrast, PSS A2, which is also offline, includes the repair of leakages. This service is repeated on a yearly basis for three years and is billed at a fixed rate (Figure 2).

The other two PSS configurations (A3 and A4) are online variants (Figure 2). For A3, the customer purchases the sensors and monitors the recorded data. Installing the sensors and the management system is done by the provider as is the detection and removal of leakages. The service is billed according to a fixed rate, which has to be paid yearly. The contract runs for a period of three years.

In A4, the provider is responsible for everything and also owns the sensors. To refinance these expenses, the contract period is five years. The accounting is based on energy savings, so this PSS is result-oriented.

It is assumed that, for the online-variants, the detection of the leakages in the whole system takes place on average only half as often as for the offline variant and the removal of leakages happens earlier, so that savings are higher. For these reasons, the investment in the sensors could be profitable after a few years depending on the system's condition. Another assumption is that the customer has less know-how about stopping leakages, so that energy consumption is not reduced by as much if the customer does this himself. The aim is, that in all cases the PSS generates win-win situations, so the realised energy savings should be higher than the costs for the measure.

Two scenarios are considered for the evaluation process. In the first scenario (scenario 1), it is assumed that all PSS contracts are renewed over the whole observation period of five years. Scenario 2 observes the same period, but only considers the measures to be applied during their respective contract period. For the remaining time, it is assumed that the leakage rate of the system is the same as before the measure as the leakage rate is increasing again after the measure.

4.2 Customer company

The company in which one of these PSSs should be offered is a mechanical engineering company. It has three different production areas, where compressed air is supplied by an integrated network. In total, the network has a length of 4.6 km and 70 machines are connected. The compressed air is provided by eight compressors. The machinery consists of equipment for manufacturing, assembling and transport.

Based on the example of this customer company, the objective was to work out which of the PSS configurations best meets its needs, but simultaneously benefits the providing company.

5 Decision process

The decision process to find the most suitable solution was supported in a two-part workshop. In the first part, the PROMETHEE method was introduced to the participants from different departments of the case study company. Afterwards, the decision-makers and the criteria were defined. The second part served to collect data. The criteria, the preference functions and the weighting of each decision-maker had to be specified before the results could be calculated.

5.1 Decision-makers

As described above, the decision for a certain PSS configuration should be made at least from the provider's and the customer's perspectives. The case study company stated that both the *service department* and the *sales department* are involved in the decision. As the service department only preselects offers which are financially viable, the financial department does not have to be included.

As the case study was still in the design phase, it would have been complicated to include the *customer company* in the decision process (and in a real-life business environment, it is perhaps not always desirable to let the customer know all the alternatives). Therefore, the perspective of the customer company was represented by

employees of the provider company who are in contact with the customer and know their problems and preferences. For this reason, no division into different departments was considered for the customer company.

When the decision-makers have made up their minds, the question arises whether the decision process is a democratic one, or whether each decision-maker has a different share of the vote. In the case study, the latter is the case. The service department and the customer company each have a 40% share of the vote and the remaining 20% is assigned to the sales department.

5.2 Criteria

The alternatives were already described above. This section determines how to assess the configurations, i.e., based on which criteria.

The main reason for the introduction of PSSs is to increase profitability. Four criteria were considered in this category. The first is the *additional value* which can be generated through more efficient work flows or savings, such as the reduction of energy consumption, over the whole life cycle. The second criterion is the *stabilisation of revenues*. This is enabled by a service-based offer which is carried out on a more regular basis than is possible with product-based offers. For both criteria, 'the higher the better' is valid for all decision-makers. The third criterion is the *takeover of financing by the provider*. This can encourage the customer to invest in energy saving technology, but reduce the provider's liquidity. So this is one of the criteria with conflicting goals. The fourth criterion regarding profitability is the *effort for coordination*. This criterion is part of the transaction costs (Williamson, 2000). So a large effort here will reduce the additional value, but it is difficult to quantify this criterion.

For the question investigated here, the main focus is on the improvement of energy efficiency. Besides an economic influence, this is primarily a technical aspect. The criterion measured in this context was the *energy consumption*. Another technical issue is the *innovation feedback*. Access to the CAS can help the provider detect problems with the application of its products and therefore improve them. But for the customer this also means that competing companies might profit from the customer's information. So this criterion is another one with conflicting goals.

The PSS not only influences technical and economic aspects, but also impacts the market situation. For instance, *customer loyalty* can be positively affected if the provider operates a PSS for several years with direct contact to the customer. Yet a long contract period can also be perceived by the customer as a high degree of dependency on the provider. It therefore follows that this is another criterion with conflicting goals. The *emergence of competitive situations* is also part of this market category. Especially in the compressed air supply chain, it could be that former customers also become competitors. The last criterion of this category is the *protection against competition*. It is not easy to stand out from competitors based only on the products offered (Gebauer and Fleisch 2007), but a sophisticated service offer can help companies to gain the competitive edge over their rivals. The last two criteria are relevant only for the provider.

The changing risks also play an important role in the transition from the traditional business model to PSSs (Baines et al., 2009b; Lay et al., 2009). The *traceability of the value proposition* is a key aspect for customer satisfaction and it is also the basis to

calculate the level of payments for some revenue models. For the traditional business model, there is no value proposition about energy savings but only the delivery of products, which leads to a 100% traceability. There is a higher *conflict potential* from changing the business model. Conflicts are possible between the customer and the provider, but also between different departments within one company, e.g., about who gets the credit. Because, in order to fix leakages, the CAS or at least individual machines have to be switched off, another important risk is that of the *non-feasibility of the measures* at the planned time. This is especially important for result-oriented PSSs. To guarantee the success of a PSS, it is necessary to be able to predict the payments for the service and the energy cost savings. Such a *possibility for pre-calculation* should be given *for the provider and the customer*. For the customer only their own pre-calculations are important; for the provider, on the other hand, both are important, as the customer's possibility to pre-calculate supports their acceptance of the PSS.

The qualitative criteria were determined by the workshop participants assigning them a value between 0 and 10. The emergence of competitive situations only had to be answered with 'yes' or 'no' for each configuration; for the traceability of the value proposition, the participants tried to give a percentage of how precisely the value proposition can be measured. A special techno-economic tool was used (Neugebauer et al., 2010) to calculate the characteristics of the quantitative criteria 'additional value' and 'energy consumption'. The input data were gathered through interviews with the case study company, an inspection of the customer company and reviewing different product catalogues and websites of providers of compressed air technology. The economic evaluation is based on the annuity method. For the takeover of financing by the provider, only data from the interviews was used. The criteria values are listed in Table 1. It should be noted, that the additional value (P1) and the energy consumption (T1) are given as annual values in scenario 1 (which assumes annual contracts) and as total values in scenario 2 (which considers the whole remaining period).

5.3 Preference function

For each criterion, the decision-makers agreed on one preference function, which normalises the differences between the criteria in the pairwise comparisons to an interval from 0 to 1. As it is not possible for each decision-maker to decide about the preference function himself, it was agreed that one preference function should be chosen for the qualitative criteria and one for the quantitative criteria. For the qualitative criteria including the 'takeover of financing by the provider', the linear preference function was chosen (type III). The preference threshold was determined as 10 for the qualitative criteria and 10% of the total project volume for the financing criterion. The only exception is the 'emergence of competitive situations', which can only be answered with 'yes' or 'no'. Therefore, the usual criterion (type I) was selected which has the value 0 if there is no difference between the criteria and 1 if there is a difference. The criterion with linear preference and indifference area is considered appropriate for the quantitative data from the techno-economic model. The indifference threshold was defined as 5% of the total volume of the respective criterion; the preference threshold had the limit of 10%. All values are shown in Table 1.

Table 1 Decision matrix

Criterion		Scale	Preference function				A0 Reference: case	A1 Offline with customer	A2 Offline without customer	A3 Online with customer	A4 Online without customer
			Type[1]	*q*[2]	*p*[3]	*σ*[4]					
P1	Additional value (scenario 1)	Euro/a	V	1,605	3,210		0	15,391	18,991	16,448	16,448
P1	Additional value (scenario 2)	Euro	V	6,706	13,412		0	14,292	50,175	34,451	68,724
P2	Stabilisation of revenues	Low/high	III		10		0	1	7	7	10
P3	Takeover of financing by the provider	Euro	III		15,872		0	400	400	175	62,670
P4	Effort for coordination	Low/high	III		10		0	1	5	9	10
T1	Energy consumption (scenario 1)	kWh/a	V	80,930	161,860		1,618,599	1,397,454	1,352,539	1,267,016	1,267,016
T1	Energy consumption (scenario 2)	kWh	V	404,650	809,300		8,092,995	7,871,850	7,294,815	7,038,246	6,335,080
T2	Innovation feedback	Low/high	III		10		0	5	6	7	8
M1	Customer loyalty	Low/high	III		10		1	2	6	6	9
M2	Emergence of competitive situation	No/yes	I				0	0	0	1	1
M3	Protection against competition	Low/high	III		10		0	1	4	5	8
R1	Traceability of the value proposition	Percent	III		100		100	25	50	70	75
R2	Conflict potential	Low/high	III		10		0	1	2	5	10
R3	Non-feasibility of the measures	Low/high	III		10		0	1	4	4	10
R4	Possibility for pre-calculation for the customer	Difficult/easy	III		10		6	7	8	8	9
R5	Possibility for pre-calculation for the provider	Difficult/easy	III		10		10	10	5	5	2

Notes: [1]Type I: ordinary criterion, type II: quasi criterion, type III: criterion with linear preference, type IV: step criterion, type V: criterion with linear preferences and indifference area, type VI: Gaussian criterion (Brans et al., 1986)
[2]q: indifference threshold
[3]p: preference threshold
[4]σ: turning point of the Gaussian distribution

Source: Workshop results and own calculations

Table 2 Weightings of the decision-makers and the group

		Decision maker	*Share of vote*	*Decision maker*	*Share of vote*	*Decision maker*	*Share of vote*	*Group*	
		Service	*40%*	*Sales*	*20%*	*Customer*	*40%*		
		Weighting ($w^r_{r,i}$)	*Min/max*	*Weighting* ($w^r_{r,i}$)	*Min/max*	*Weighting* ($w^r_{r,i}$)	*Min/max*	*Weighting* ($w_{n,i}$)	*Min/max*
P1	Additional value	30.0%	Max	6.0%	Max	25.0%	Max	27.10%	Max
P2	Stabilisation of revenues	12.5%	Max	12.0%	Max	0.0%	Max	8.64%	Max
P3	Takeover financing by the provider	5.0%	Min	3.0%	Min	15.0%	Max	3.97%	*Max*
P4	Effort for coordination	2.5%	Min	9.0%	Min	10.0%	Min	7.94%	Min
T1	Energy consumption	0.0%	Min	7.0%	Min	8.0%	Min	5.37%	Min
T2	Innovation feedback	0.0%	Max	3.0%	Max	2.0%	Min	0.23%	*Min*
M1	Customer loyalty	15.0%	Max	25.0%	Max	10.0%	Min	8.18%	*Max*
M2	Emergence of competitive situation	7.5%	Min	5.0%	Min	0.0%	Min	4.67%	Min
M3	Protection against competition	7.5%	Max	20.0%	Max	0.0%	Max	8.18%	Max
R1	Traceability of the value proposition	6.0%	Max	3.0%	Max	9.0%	Max	7.71%	Max
R2	Conflict potential	1.0%	Min	2.0%	Min	6.0%	Min	3.74%	Min
R3	Non-feasibility of the measures	2.0%	Min	2.0%	Min	3.0%	Min	2.80%	Min
R4	Possibility for pre-calculation for the customer	1.0%	Max	1.0%	Max	12.0%	Max	6.31%	Max
R5	Possibility of pre-calculation for the provider	10.0%	Max	2.0%	Max	0.0%	Max	5.14%	Max

Notes: The grey lines are criteria with conflicting targets. The italic script shows the result of the direction of optimisation.

Source: Workshop results

5.4 Weighting

Subsequently, the weighting for each decision-maker was made. This was based on direct weighting. The decision-makers could first assign a weight to the categories and then the criteria in each category were weighted according to personal importance. Per category the sum should add up to 100%.

The most important category for both the service department and the customer is profitability and its most important criterion is the additional value. The sales department assigns more importance to a good market situation, especially customer loyalty and protection against competition. The technical criteria are of less or even no importance. The main risks for the service department and the customer are if they cannot make a pre-calculation or trace the value proposition. The sales department considers almost all risks to be equally important. The exact values for all criteria and all decision-makers including the group can be seen in Table 2.

This weighting confirms the results of Lay et al. (2007), who show that PSSs can be a decisive advantage for the energy-efficient usage of compressed air, although the main driver for the providers is economic in nature, e.g., the expectation of higher profits resulting from the offer of these PSSs.

6 Results of the case study

The paper focuses on the provision of compressed air – a highly energy sensitive factor of production – and models it as a product-service facility between the producer (and eventual maintainer) and user of this facility. In the following, the results of the case study are reported and commented.

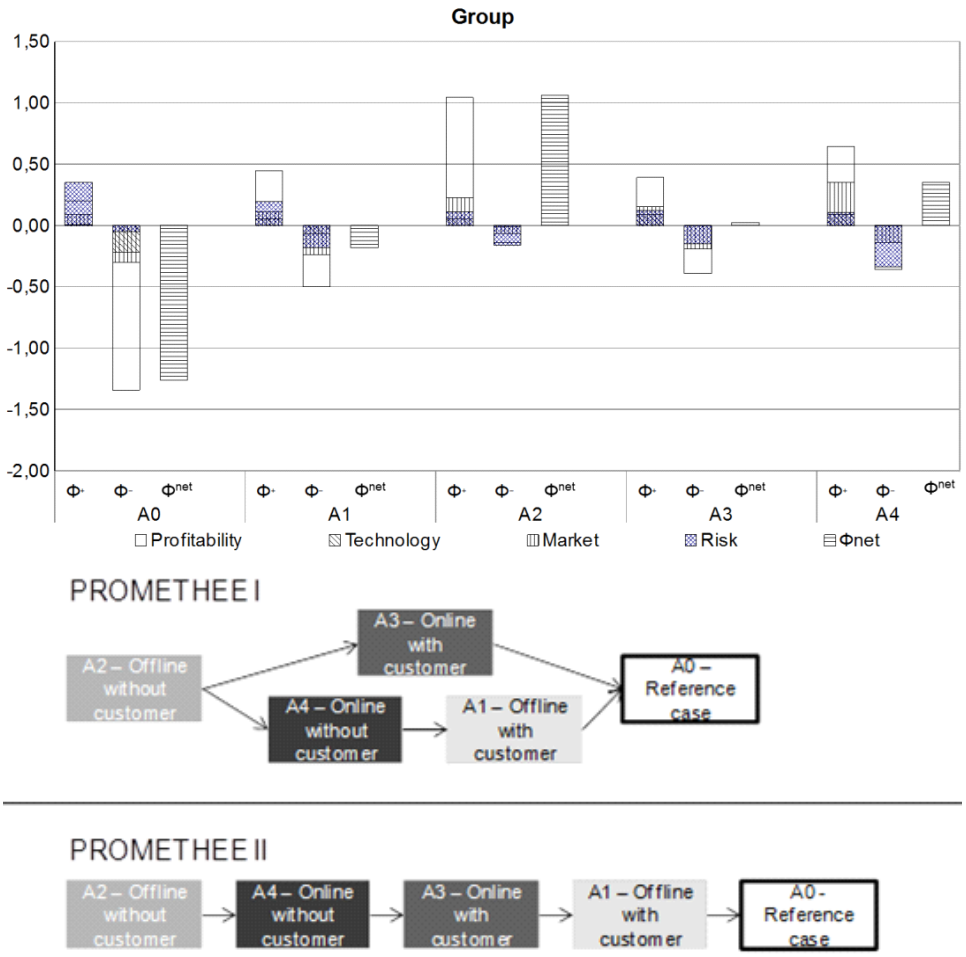
6.1 Ranking of the investigated alternatives

The PROMETHEE method was applied to this problem structuring process. Figure 3 shows the leaving (Φ^+) and entering flows (Φ^-) of the different PSS configurations for the group, as well as the net flow $\Phi^{net} = \Phi^+ - \Phi^-$ within scenario 1. It is dominated by A2 'offline without customer'. For PROMETHEE I, this is followed by the alternatives A4 and A1, which are incomparable to A3, which implies that the strengths but also the weaknesses of A3 are lower than for the other two alternatives. The least preferred alternative is the reference case. If PROMETHEE II is applied, A3 is in-between A4 and A1. Looking at the results in detail, it is apparent that the major advantage of A2 compared to the others is profitability.

Comparing the alternatives for different contract periods (scenario 2) yields different results (Figure 4). Here, there are no incomparabilities so the ranking of PROMETHEE I is identical to that received by PROMETHEE II. For this scenario, A4 is the best solution followed by A2. The other alternatives have the same order as for scenario 1. Again,

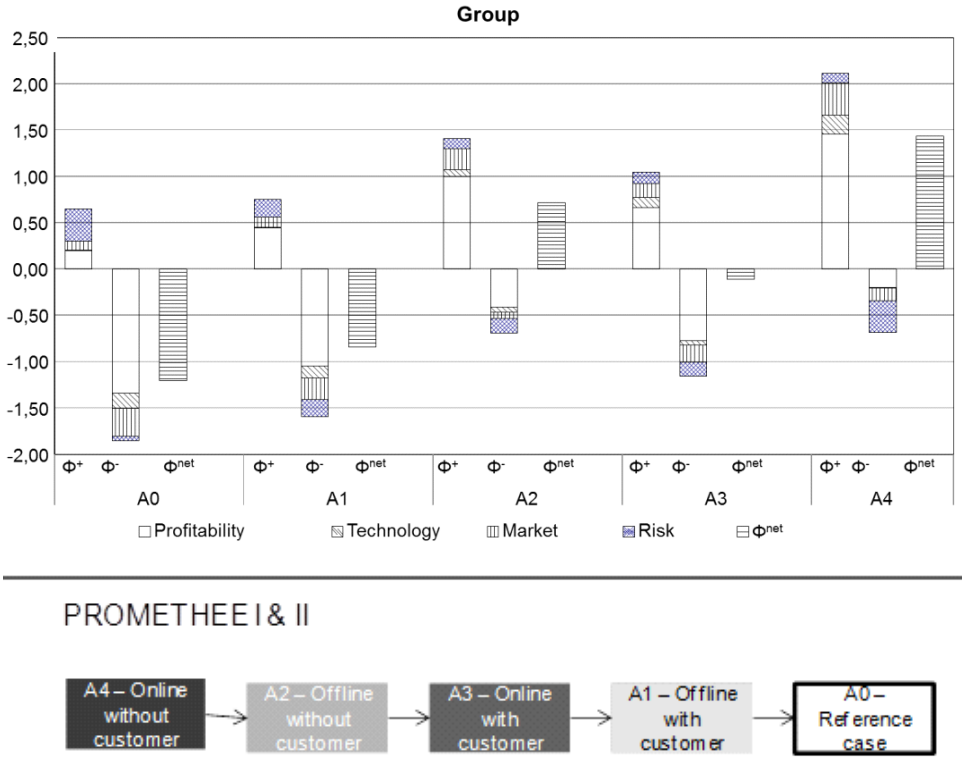
profitability has a major impact on the strengths of the best solution. This is because the energy consumption and therefore also the costs are reduced for all five years and not only for three of the five years. In relative terms, this aspect also results in a big difference in the technological strengths. And it also means a much higher value of the weaknesses in A1, which is carried out only once. Therefore, the difference between the reference case and the offline version with customer contribution is significantly reduced.

Figure 3 Preference flows and ranking of continuous leakage management (scenario 1) according to PROMETHEE I and II (see online version for colours)



Source: Own calculations based on workshop results

Figure 4 Preference flows and ranking of leakage management within one contract period (scenario 2) according to PROMETHEE I and II (see online version for colours)

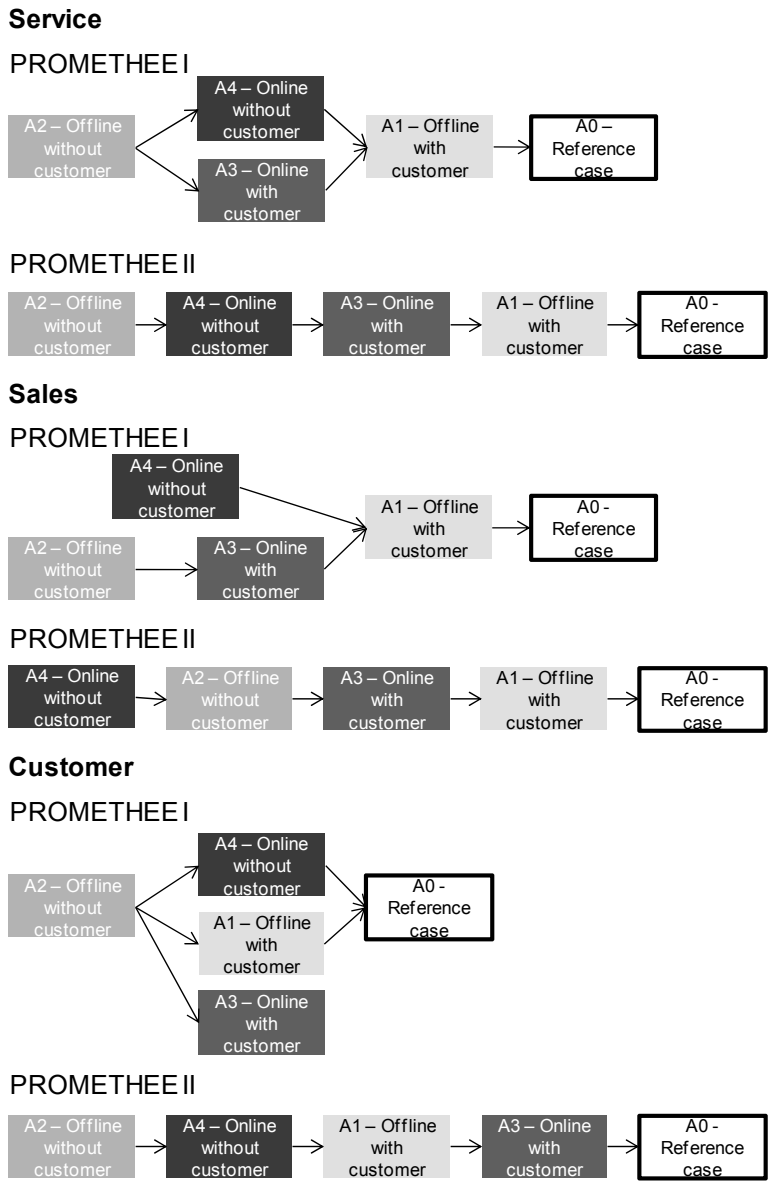


Source: Own calculations based on workshop results

It can thus be concluded that the most important aspect is a regular removal of leakages. Hence, leakage management is a task which should not be done only once or for a limited period, but continually. For the framework conditions of the discussed case study, it is not that important to have the most expensive equipment to be able to react immediately in order to offer a good PSS which matches the preferences of the decision-makers.

The group results are dependent on the weighting which aggregates the values of each decision-maker. Thus, the rankings of the decision-makers were also calculated. As depicted in Figure 5, each ranking is slightly different for scenario 1. The overall ranking of the service department is the same as for the group, but the results of PROMETHEE I show that A1 is outranked by A3 as well for the partial preorder. The most relevant difference is in the ranking of the sales department. Here, A4 is incomparable not only to A3, but also to A2. This leads to A2 and A4 switching places, so that A4 even becomes the best solution when considering the net flows. For the customer, A2 can again be identified as the best solution. Second place is shared by A4, A1 and A3, of which A3 is also incomparable to the reference case. In comparison to the group ranking made with PROMETHEE II, only A1 and A3 change places in the customer ranking. All in all, it can be concluded that A2 seems to be a good compromise as this is (one of) the best solution(s) for all decision-makers according to PROMETHEE I and it is in second place for the sales department with PROMETHEE II, so it is still a good solution.

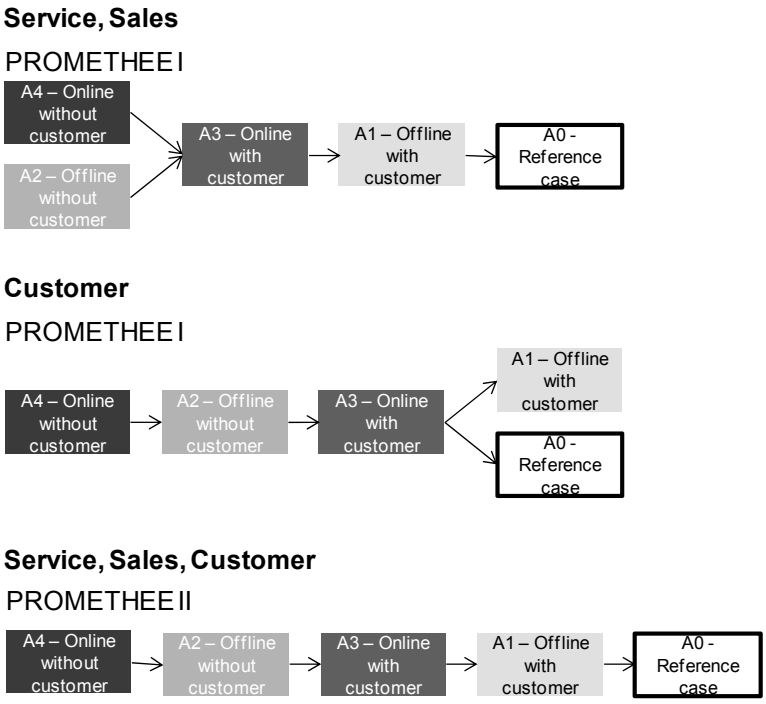
Figure 5 Rankings for single decision-makers for scenario 1



Source: Own calculations based on workshop results

Scenario 2 yields a different result. Here, the group result and all decision-makers have an identical ranking within PROMETHEE II. According to the results of PROMETHEE I, the service and the sales departments cannot order A2 and A4 and A0 and A1 are incomparable for the customer (Figure 6). With these individual results it is easy to justify the group result.

Figure 6 Rankings for single decision-makers for scenario 2

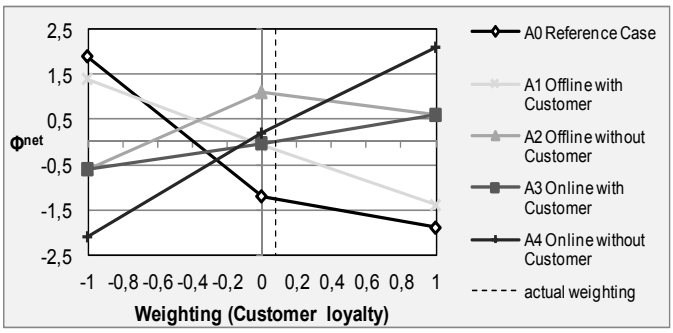


Source: Own calculations based on workshop results

6.2 Sensitivity analysis

The above discussed results are only valid for the given weighting. Sometimes, only slight deviations in the weights can already impact the ranking. Therefore, a common method of sensitivity analysis has been applied where the weight of one criterion is varied between 0 and 100% while the relative weights of the other criteria remain constant (Geldermann and Rentz, 2005). Thus, weight stability intervals can be ascertained, within which the alteration of weights has no influence on the ranking order. For the group decision approach involved here, there is one exception for criteria with conflicting goals. As the direction of optimisation depends on the weights assigned by decision-makers with different opinions, it is also possible that the stability interval reaches beyond '0' in the other direction. Hence, for criteria with conflicting goals, the weights have been varied for maximisation and minimisation. Additionally, it is possible to calculate an inflection point for each decision-maker, at which point the optimisation direction of the group would change. Figure 7 shows the graphical implementation of this sensitivity analysis for an example criterion with conflicting targets.

Figure 7 Sensitivity analysis using the example of customer loyalty



Source: Own calculations based on workshop results

As the group weighting consists of all the decision-makers' weights and shares of the vote, even a small variation of the group weighting implies a significant variation of a single decision-maker. For example, a variation of four percentage points in the group weighting of a criterion means a variation of about ten percentage points for the service department or the customer, and even 20 percentage points for the sales department depending on the share of the vote and the weightings for criteria with conflicting targets (these are not taken into account additively for the group weighting). Therefore, only distances of less than four percentage points from the actual weighting to the interval limit were considered as sensitive. Based on this and the fact that rankings do not change if the lower limit is '0' or the upper limit '100', there is only one sensitive criterion for scenario 1 – the emergence of competitive situations – and no sensitive criterion at all for scenario 2.

6.3 Further considerations

In this case study, a small number of reasonable options for PSSs are discussed. The application of the modified multi-criteria method PROMETHEE helps articulating criteria, preferences and weights of various stakeholders with heterogeneous motivations. Manufacturing companies – both in the role of supplier and consumer – make increasing efforts to derive their decisions and actions from their complex and heterogeneous value systems, taking economic, technical, social and environmental criteria into account.

The presented method and its application in the particular case study should allow for a transfer to other similar problem domains, such as chemical leasing (Reiskin et al., 2000; Geldermann et al., 2009) or pay-on-production schemes as other forms of PSS. An open question concerns the facilitating of the decision making process. In the presented case study, the multi-criteria evaluation was performed within a joint research project, by taking into consideration the viewpoints of the different parties to the contract. As CASs are the core competence of the suppliers (but seldom of the customers, often small and medium-sized enterprises, it can be assumed the supplier compiles and evaluates the various offers, by anticipating the viewpoints of all concerned stakeholders. On the contrary, the customers (or their trade association) may also design different service options and ask for quotations.

The case study revealed asymmetric information and distinct objectives of the supplier and the user of the technology. Contract theory and economics investigate the generic problem of information asymmetry and try to alleviate adverse effects on market behaviour by providing suitable incentives that facilitate the disclosure of some of the private information possessed by the parties. This paper, however, focused on the analysis of the possible conflicts of interest as a basis for a systematic handling of heterogeneous objectives and the design of PSSs, which are fair and suitable for all contract partners. Further research could employ approaches from principal agent theory or negotiation theory to shed light on the actual behaviour of the different business partners.

7 Conclusions

One of the main trends in production is the integrated provision of products and services. The new business model of PSSs represents a competitive opportunity for many companies, which seek to reduce resource consumption by modifying the way their products and services are designed, marketed and used, and thus contributing to cleaner production through improved energy efficiency. Its general concept implies that value is created collaboratively by the producer (and eventual maintainer) and user of such a facility. The systematic handling of heterogeneous value systems and the design of PSSs, however, call for novel approaches, models and methods. In this paper a method for multi-criteria group decision-making with possibly conflicting goals was developed and its applicability was tested on the example of PSSs to increase the energy efficiency of CAS, a highly energy sensitive factor of production.

The results show that using PSSs to reduce leakage is advisable for the case study company as they are more profitable and more energy efficient than the traditional business model. Additionally, they improve the market situation of the provider. However, online variants may especially increase the corresponding risks. These results are dependent on the CAS of the customer company, indicating that the results can only be applied to similar companies in terms of size and leakage rate of the CAS. According to the results, there is limited general advice for a specific configuration, because this is dependent on the contract period and the different characteristics of the criteria. In general, it seems that complete service offers by the provider are more attractive than offers requiring the customer to provide input of some kind. This is due to the assumption made at the beginning that the customer has less know-how in handling the CAS, so that more energy is required if customers try to fix the leakages themselves. In addition, the weighting of customer loyalty (understood as dependency from the customer's perspective) by the customer is quite low; otherwise, the alternatives with less dependence would likely score better. Other customers may have a different focus which would lead to different results. In addition, the weighting of the provider could also change if the offer for another – more or less important – customer is evaluated. Also other PSS configurations could be designed, such as by a service provider who offers leakage management for various CASs in cooperation between several companies and who can gain better know-how of the distribution network.

The newly developed group decision approach based on the multi-criteria method PROMETHEE makes it possible to evaluate decision problems from different perspectives. How criteria with decision-makers' conflicting targets influence the group

result can also be analysed. The proposed approach presents a novel method that can be applied easily in real industrial cases in short decision making workshops. An important part of the results is the sensitivity analysis that shows how the solution depends on different weightings that are chosen arbitrarily or only after short reflection.

Limitations to the proposed method may arise because decision-makers have to agree on criteria characteristics and preference functions. Therefore, further research is necessary to understand whether an aggregation method could also be applied to these characteristics and functions which do not level out the different weightings. Existing extensions to the PROMETHEE method could also be integrated to further develop the group decision process, whose applicability has been proven here. These concern, for example, fuzzy logic (Geldermann et al., 2000) or the two-tuple representation model (Herrera and Martinez, 2000). Furthermore, a weighting process other than direct rating could be included.

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References

Baas, L. (1998) 'Cleaner production and industrial ecosystems, a Dutch experience', *Journal of Cleaner Production*, Vol. 6, No. 3, pp.189–197.

Baas, L. and Boons, F. (2004) 'An industrial ecology project in practice: exploring the boundaries of decision-making levels in regional industrial systems', *Journal of Cleaner Production*, Vol. 12, Nos. 8–10, pp.1073–1085.

Baines, T., Lightfoot, H., Peppard, J., Johnson, M., Tiwari, A., Shehab, E. and Swink, M. (2009a) 'Towards an operations strategy for product-centric servitization', *International Journal of Operations & Production Management*, Vol. 29, No. 5, pp.494–519.

Baines, T.S., Lightfoot, H.W., Benedettini, O. and Kay, J.M. (2009b) 'The servitization of manufacturing: a review of literature and reflection on future challenges', *Journal of Manufacturing Technology Management*, Vol. 20, No. 5, pp.547–567.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Basti, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Micheli, P., Tranfield, D., Walton, I.M. and Wilson, H. (2007) 'State-of-the-art in product-service systems', in *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 221, No. 10, pp.1543–1552.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A. and Aghdasi, M. (2010) 'PROMETHEE: a comprehensive literature review on methodologies and applications', *European Journal of Operational Research*, Vol. 200, No. 1, pp.198–215.

Belton, V. and Stewart, J.T. (2003) *Multiple Criteria Decision Analysis – An Integrated Approach*, 2nd ed., Kluwer Academic Publishers Group, Dordrecht, the Netherlands.

Bertoldi, P., Rezessy, S. and Vine, E. (2006) 'Energy service companies in European countries: current status and a strategy to foster their development', *Energy Policy*, Vol. 34, No. 14, pp.1818–1832.

Beuren, F.H., Ferreira, G., Gitirana, M. and Cauchick, M.P.A. (2013) 'Product-service systems: a literature review on integrated products and services', *Journal of Cleaner Production*, Vol. 47, pp.222–231.

Bierma, T.J. and Waterstraat, F.L. (1999) 'Cleaner production from chemical suppliers: understanding shared savings contracts', *Journal of Cleaner Production,* Vol. 7, No. 2, pp.145–158.

BiPRO (2010) *Chemikalienleasing als Modell zur nachhaltigen Entwicklung mit Prüfprozeduren und Qualitätskriterien anhand von Pilotprojekten in Deutschland*, Umweltbundesamt, Dessau-Roßlau.

Brans, J.P., Vincke, P. and Mareschal, B. (1986) 'How to select and how to rank projects: the PROMETHEE method', *European Journal of Operational Research*, Vol. 24, No. 2, pp.228–238.

Brans, J-P. and Mareschal, B. (2005) 'PROMETHEE methods', in Figueira, J.R., Greco, S. and Ehrgott, M. (Eds.): *Multiple Criteria Decision Analysis – State of the Art – Surveys (No 78)*, pp.163–195, Springer, New York.

Figueira, J.R., Greco, S. and Ehrgott, M. (2005) (Eds.): *Multiple Criteria Decision Analysis – State of the Art – Surveys (No 78)*, Springer, New York.

Gebauer, H. and Fleisch, E. (2007) 'Managing sustainable service improvements in manufacturing companies', *Kybernetes*, Vol. 36, Nos. 5/6, pp.583–595.

Geldermann, J. and Rentz, O. (2005) 'Multicriteria analysis for technique assessment: case study from industrial coating', *Journal of Industrial Ecology*, Vol. 9, No. 3, pp.127–142.

Geldermann, J., Daub, A. and Hesse, M. (2009) *Chemical Leasing as a Model for Sustainable Development*, Georg-August-Universität Göttingen, Göttingen.

Geldermann, J., Spengler, T. and Rentz, O. (2000) 'Fuzzy outranking for environmental assessment. Case study: iron and steel making industry', *Fuzzy Sets and Systems*, Vol. 115, No. 1, pp.45–65.

Gloor, R. (2000) *Energy Savings in Compressed Air Systems in Switzerland*, Swiss Federal Office of Energy, Bern.

Goedkoop, M., van Halen, C., te Riele, H. and Rommens, P. (1999) *Product Service systems, Ecological and Economic Basics*, Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands.

Gruber, E. and Brand, M. (1991) 'Promoting energy conservation in small and medium-sized companies', *Energy Policy*, Vol. 19, No. 3, pp.279–287.

Halme, M., Anttonen, M., Kuisma, M., Kontoniemi, N. and Heino, E. (2007) 'Business models for material efficiency services: conceptualization and application', *Ecological Economics*, Vol. 63, No. 1, pp.126–137.

Herrera, F. and Martinez, L. (2000) 'An approach for combining linguistic and numerical information based on 2-tuple fuzzy representation model in decision making', *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, Vol. 8, No. 5, pp.539–562.

Hirzel, S., Köpschall, M., Hülsmann, S., Neumann, R., Ohmer, M., Hobusch, G., Hobusch, G., Ruppelt, E., Doll, M., Krichel, S., Sawodny, O., Elsland, R., Schröter, M., Weißfloch, U., Blank, F., Ngyuen, Q.K. and Roth-Stielow, J. (2012) *EnEffAH: Energy Efficiency in Production in the Drive and Handling Technology Field – Basic Principles and Measures*, Fraunhofer ISI, Karlsruhe.

Hockerts, K. (1999) 'Innovation of eco-efficient services: increasing the efficiency of products and services', in Charter, M. and Polonsky, J. (Hg.): *Greener Marketing: A Global Perspective on Greening Marketing Practice*, pp.95–108, Greenleaf Publishing, Sheffield.

Huang, I.B., Keisler, J. and Linkov, I. (2011) 'Multi-criteria decision analysis in environmental sciences: ten years of applications and trends', *Science of The Total Environment*, Vol. 409, No. 19, pp.3578–3594.

Lay, G., Kinkel, S., Ostertag, K., Radgen, P., Reinhard, M., Schneider, R. et al. (2007) *Betreibermodelle für Investitionsgüter: Verbreitung, Chancen und Risiken, Erfolgsfaktoren*, Fraunhofer IRB Verlag, Stuttgart.

Lay, G., Schröter, M. and Biege, S. (2009) 'Service-based business concepts: a typology for business-to-business markets', *European Management Journal*, Vol. 27, No. 6, pp.442–455.

Leyva-Lopez, J.C. and Fernandez-Gonzalez, E. (2003) 'A new method for group decision support based on ELECTRE III methodology', *European Journal of Operational Research*, Vol. 148, No. 1, pp.14–27.

Ligon, P. and Votta, T. (2001) 'Strategic contracting increases waste prevention and materials recycling', *Resource Recycling*, Vol. 20, No. 3, pp.38–44.

Macharis, C., Brans, J-P. and Mareschal, B. (1998) 'The GDSS PROMETHEE procedure', *Journal of Decision Systems*, Vol. 7, No. 1, pp.283–307.

Macharis, C., Springael, J., Brucker, K. and de Verbeke, A. (2004) 'PROMETHEE and AHP: the design of operational synergies in multicriteria analysis: strengthening PROMETHEE with ideas of AHP', *European Journal of Operational Research*, Vol. 153, No. 2, pp.307–317.

Manzini, E. and Vezzoli, C. (2003) 'A strategic design approach to develop sustainable product service systems: examples taken from the 'environmentally friendly innovation' Italian prize', *Journal of Cleaner Production*, Vol. 11, No. 8, pp.851–857.

Miettinen, P. and Hämäläinen, R.P. (1997) 'How to benefit from decision analysis in environmental life cycle assessment (LCA)', *European Journal of Operational Research*, Vol. 102, No. 2, pp.279–294.

Mont, O. (2002) 'Clarifying the concept of product-service system', *Journal of Cleaner Production*, Vol. 10, No. 3, pp.237–245.

Mont, O. and Tukker, A. (2006) 'Product-service systems: reviewing achievements and refining the research agenda', *Journal of Cleaner Production*, Vol. 14, No. 17, pp.1451–1454.

Mont, O., Singhal, P. and Fadeeva, Z. (2006) 'Chemical management services in Sweden and Europe', *Journal of Industrial Ecology*, Vol. 10, Nos. 1–2, pp.279–292.

Neugebauer, R., Hirzel, S., Elsland, R., Weissfloch, U., Schroeter, M. and Barth, J.P. (Eds.) (2010) *Compressed Air Systems: A Techno-economic Evaluation Approach*, *Reports from the IWU, Sustainable Production for Resource Efficiency and Ecomobility: International Chemnitz Manufacturing Colloquium ICMC 2010 – Proceedings*, Verlag Wissenschaftliche Scripten, Chemnitz.

Park, Y., Geum, Y. and Lee, H. (2012) 'Toward integration of products and services: taxonomy and typology', *Journal of Engineering and Technology Management*, Vol. 29, No. 4, pp.528–545.

Radgen, P. and Blaustein, E. (2001) (Eds.): *Compressed Air Systems in the European Union: Energy, Emissions, Savings Potential and Policy Actions*, LOG_X Verlag GmbH, Stuttgart.

Reiskin, E.D., Johnson, J.K. and Votta, T.J. (2000) 'Servicizing the chemical supply chain', *Journal of Industrial Ecology*, Vol. 3, Nos. 2 and 3, pp.19–31.

Roy, B. (1991) 'The outranking approach and the foundations of ELECTRE methods', *Theory and Decision*, Vol. 31, No. 1, pp.49–73.

Roy, R. (2000) 'Sustainable product-service systems', *Futures*, Vol. 32, Nos. 3–4, pp.289–299.

Saaty, T.L. (1990) 'How to make a decision: the analytic hierarchy process', *European Journal of Operational Research*, Vol. 48, No. 1, pp.9–26.

Schröter, M., Buschak, D. and Jäger, A. (2010) *Nutzen statt Produkte kaufen – Verbreitung und Effekte neuer Produkt-Dienstleistungs-Konzepte im deutschen Verarbeitenden Gewerbe*, Mitteilungen aus der ISI-Erhebung Modernisierung der Produktion Ausgabe 53. Fraunhofer ISI, Karlsruhe.

Seslija, D., Stojiljkovic, M., Golubovic, Z., Blagojevic, V. and Dudic, S. (2009) 'Identification of the possibilities for increasing energy efficiency in the compressed air systems', *Mechanical Engineering*, Vol. 7, No. 1, pp.37–60.

Sorrell, S. (2007) 'The economics of energy service contracts', *Energy Policy*, Vol. 35, No. 10, pp.507–521.

Spengler, T., Geldermann, J., Hähre, S., Sieverdingbeck, A. and Rentz, O. (1998) 'Development of a multiple criteria based decision support system for environmental assessment of recycling measures in the iron and steel making industry', *Journal of Cleaner Production*, Vol. 6, No. 1, pp.37–52.

Stoughton, M. and Votta, T. (2003) 'Implementing service-based chemical procurement: lessons and results', *Journal of Cleaner Production*, Vol. 11, No. 8, pp.839–849.

Taylor, B. (2006) 'Encouraging industry to assess and implement cleaner production measures', in *Journal of Cleaner Production*, Vol. 14, Nos. 6–7, pp.601–609.

Tukker, A. (2004) 'Eight types of product-service systems: eight ways to sustainability? Experiences from SusProNet', *Business Strategy and the Environment*, Vol. 13, No. 4, pp.246–260.

Tukker, A. and Tischner, U. (2006) 'Product-services as a research field: past, present and future. Reflections from a decade of research', *Journal of Cleaner Production*, Vol. 14, No. 17, pp.1552–1556.

Turcksin, L., Bernardini, A. and Macharis, C. (2011) 'A combined AHP-PROMETHEE approach for selecting the most appropriate policy scenario to stimulate a clean vehicle fleet', *Procedia – Social and Behavioral Sciences*, Vol. 20, pp.954–965.

US Department of Energy (2003) *Improving Compressed Air System Performance – A Sourcebook for Industry, Energy Efficiency and Renewable Energy*, US Department of Energy; Washington D.C.

Wang, J.J., Jing, Y.Y., Zhang, C.F. and Zhao, J.H. (2009) 'Review on multi-criteria decision analysis aid in sustainable energy decision-making', *Renewable and Sustainable Energy Reviews*, Vol. 13, No. 9, pp.2263–2278.

Weber, L. (1997) 'Some reflections on barriers to the efficient use of energy', *Energy Policy*, Vol. 25, No. 10, pp.833–835.

Weißfloch, U. (2013) *Multikriterielle Bewertung von Produkt-Dienstleistungssystemen zur Steigerung der Energieeffizienz von Druckluftsystemen*, Fraunhofer Verlag, Stuttgart.

Williams, A. (2007) 'Product service systems in the automobile industry: contribution to system innovation?', *Journal of Cleaner Production*, Vol. 15, No. 11, pp.1093–1103.

Williamson, O.E. (2000) 'The new institutional economics: taking stock, looking ahead', *Journal of Economic Literature*, Vol. 38, No. 3, pp.595–613.

Wise, R. and Baumgartner, P. (1999) 'Go downstream – the new profit imperative in manufacturing', *Harvard Business Review*, Vol. 77, No. 5, pp.133–141.

Woodward, D.G. (1997) 'Life cycle costing – theory, information acquisition and application', in *International Journal of Project Management*, Vol. 15, No. 6, pp.335–344.

Zhou, P., Ang, B.W. and Poh, K.L. (2006) 'Decision analysis in energy and environmental modeling: an update, *Energy*, Vol. 31, No. 14, pp.2268–2286.