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Application of the Analytic Hierarchy Process to Facilitate the Cross-Impact Balance Analysis

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Abstract: The Cross-Impact Balance (CIB) analysis is an instrument, which supports transparently the development of consistent qualitative scenarios by consulting various experts and stakeholders (see Weimer-Jehle 2006). This article introduces an extension to the CIB analysis with the analytic hierarchy process (AHP), a multi criteria-analysis tool, which solves the issue of possible weighting problems within the CIB.

Keywords: Scenario Analysis, Cross-Impact Balance analysis, Electricity Markets

1 Introduction

Extensive scenario studies are commonly conducted to describe possible future developments of complex interdependent systems, like the energy system. During the last decades, a variety of scenario techniques have been elaborated to competently consult and inform politics, businesses and the public. In this context, the Cross-Impact Balance (CIB) analysis was developed (see Weimer-Jehle 2006) on the basis of standard cross-impact methods, allowing for larger methodological flexibility and transparency.

The CIB analysis supports transparent construction of consistent scenarios, based on judgements of interdisciplinary experts and stakeholders about selected system elements and their systemic interactions (see Weimer-Jehle 2006). Among others, the effectiveness of CIB was proven in multiple studies focused on development or validation of scenarios for the energy sector (see e.g. Schweizer & Kriegler 2012; Vögele S. et al. 2017). These systems are often complex and sometimes comprise of a large number of system elements or even different subsystem levels (Hansen et al. 2014). Thus, CIB analysis turns to be complicated by the consistent and thorough weighting of their multiple cross-impacts.

This article introduces an extension to the CIB analysis with the AHP, a multi criteria-analysis tool, which solves issues of possible weighting problems or imbalances within the CIB. The new approach was initially applied in the CIB scenario construction process of the BMWi founded *4NEMO* project. This article shows the underlying idea of the approach, displays potential implementation methods and discusses possible advantages of this novel approach.

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2 Methodology

2.1 Cross-Impact Balance Approach

The CIB allows to formalize our knowledge about systems of different complexities, taking into consideration their elements, further called ‘descriptors’, which qualitatively or quantitatively describe the system under investigation. Each descriptor can have two or more ‘states’ that reflect the nature of its possible future changes, which complicates the evaluation process for large matrices. Experts are asked to give their judgements – they assign specific impact weights that characterize mutual relationships of descriptors and their states. Afterwards, the obtained evaluations of all identified ‘cross-impacts’ are collected in the cross-impact matrix and the CIB algorithm defines combinations of descriptor states in such a manner that they reflect logics of experts’ judgements coded in the matrix (see Weimer-Jehle 2009). This functions flawless if considered descriptors are either not large in their number, or the described system does not include assumptions on any sub-systems or hierarchical structures.

If just one or some of the descriptors have a comparatively lower impact than others, their weights can be adjusted at the evaluation step. However, with large matrixes displaying complex systems, considering different ‘importance’ values while evaluating interrelations between the descriptors’ states will significantly complicate the overall approach:

1. The descriptor’s relative ‘importance’ does not necessarily vary only for one descriptor within the descriptor list. Sometimes the list may be represented as a hierarchy of elements with regard to their importance. This makes it hard to adhere to this hierarchy for large CIB matrixes.
2. Complex systems lead to a complex set of scenarios containing a significant amount of elements. Furthermore, the choice of the system’s borders plays a major role. Many systems that are analyzed with scenario methods may be seen as a subsystem embedded in an extensive/global system[1]. The hierarchy of these impacts from the larger systems on the local investigated systems has to be taken into account, while estimating the weights of cross-impacts.

Both effects support a trend towards more extensive CIB studies and a stronger divergence within the ‘importance’ of the respective descriptor lists. In order to solve the challenge of arbitrary descriptor weightings in large CIB matrices, the current article presents the AHP introduced by Saaty (1980) as an intermediary step within the CIB.

[1] Or vice versa, the system under consideration contains one or more subsystems.

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2.2 The Analytic Hierarchy Process in the Context of CIB

AHP has become one of the most applied multi criteria analysis (MCA) tools in decision making, where there is a need to consistently include experts' evaluation. Since it was introduced by Saaty (1980), AHP was widely implemented to evaluate scenarios, where it served as an intermediate step to achieve weights of the 'criteria' (in CIB-context: descriptors), which were subsequently transferred to other MCA tools (Buchholz et al. 2009). Meanwhile, MCA tools offer only a ranking of the scenarios and fail to account for interdependencies between the criteria, for which CIB analysis is an exemplary tool.

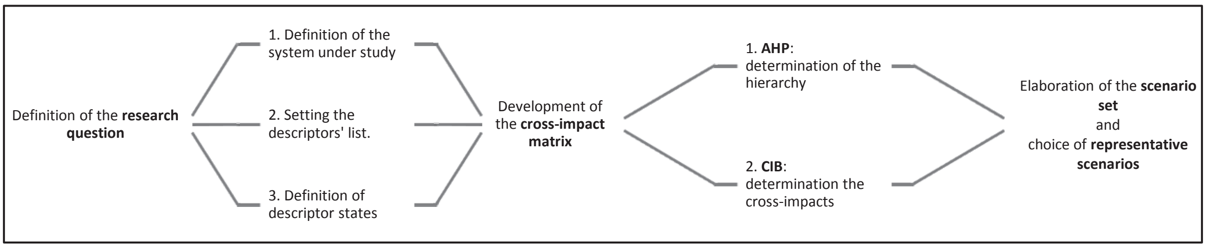

Figure 1: Steps in CIB and AHP complementary process

The complementary AHP step allows to identify and display the hierarchy of the CIB descriptors. It helps to reveal their perceived ability to influence other system elements and the system as a whole. Within the AHP, weightings are obtained by pairwise comparison of the descriptors by experts with regard to their relative importance within the system under investigation. The AHP provides descriptors' weights in a range from 1-100%, revealing their internal hierarchy. It becomes especially relevant if extraordinary large CIB matrices are taken into account.

The identified individual weights of all descriptors allow not to focus on their relative importance during the following phase of the CIB analysis, when evaluating cross-impacts between the descriptors. Hence, in the following phase only the distribution and balancing of impact weights between the descriptor states have to be taken into account, while the impact weight that one descriptors poses on the overall system can be neglected. However, AHP ratings cannot be integrated directly into the CIB analysis. Therefore, this article suggests two different approaches of implementation. The first approach introduces a method to implement AHP ratings ex post to an already existing CIB matrix. Each judgement field will be multiplied by a specific multiplier that individually evaluates the impact factor for each cross-impact of two descriptors. The second approach shows how the AHP can be integrated directly into the CIB process, in order to facilitate the judgement procedure.

2.3 Methods of implementation

2.3.1 Multiplying Approach

The method is based on the previous presented AHP ratings for the different descriptors. Evaluation of cross-impacts between two descriptors given by experts at the CIB workshop are subsequently multiplied by a factor, which represents their identified relative importance. It is essential to differentiate between active (impacts exerted by a descriptor) and passive (impacts exerted onto a descriptor) influences within the cross impact matrix. Thus, the term for the multiplier has to take this differentiation into account.

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The multiplier for each judgement field within the cross-section consists of two parts (see Eq. 1). The first part represents the combination of the AHP weightings for both descriptors. The second part ensures that the influence from weak active descriptors on important passive descriptors becomes limited. Otherwise a minor and less important descriptor would have an unreasonable high influence on the scenario room.

$$w_{(i,j)} = r_n^i * r_n^j + {r_n^i}^2 * \frac{r_n^j}{\left(1 - r_n^i\right)} = r_n^i * (r_n^j + \frac{r_n^i * r_n^j}{1 - r_n^i}) \tag{1}$$

where

$w_{(i,j)}$ multiplier for judgement field of a cross impact between the active and passive descriptors, where i denotes an active descriptor and j – a passive descriptor, $i, j \in \mathbb{N}$ and $i \neq j$, where $i, j = 1 \dots n$

r_n AHP rating for a descriptor D_n

Figure 2 shows the application of Eq. 1 to a CIB matrix, where each judgement field is multiplied by the factor of the respective cross-impact.

			D_1		D_2		D_n	
			r_1		r_2		r_n	
			v_1^1	v_2^1	v_1^2	v_2^2	v_1^n	v_2^n
D_1	r_1	v_1^1			$J(v_1^1, v_1^2) \cdot w_{(1,2)}$	$J(v_2^1, v_2^2) \cdot w_{(1,2)}$	$J(v_1^1, v_1^n) \cdot w_{(1,n)}$	$J(v_2^1, v_2^n) \cdot w_{(1,n)}$
		v_2^1			$J(v_2^1, v_1^2) \cdot w_{(1,2)}$	$J(v_2^1, v_2^2) \cdot w_{(1,2)}$	$J(v_2^1, v_1^n) \cdot w_{(1,n)}$	$J(v_2^1, v_2^n) \cdot w_{(1,n)}$
D_2	r_2	v_1^2	$J(v_1^2, v_1^1) \cdot w_{(2,1)}$	$J(v_2^2, v_2^1) \cdot w_{(2,1)}$			$J(v_1^2, v_1^n) \cdot w_{(2,n)}$	$J(v_2^2, v_2^n) \cdot w_{(2,n)}$
		v_2^2	$J(v_2^2, v_1^1) \cdot w_{(2,1)}$	$J(v_2^2, v_2^1) \cdot w_{(2,1)}$			$J(v_2^2, v_1^n) \cdot w_{(2,n)}$	$J(v_2^2, v_2^1) \cdot w_{(2,n)}$
D_n	r_n	v_1^n	$J(v_1^n, v_1^1) \cdot w_{(n,1)}$	$J(v_2^n, v_2^1) \cdot w_{(n,1)}$	$J(v_1^n, v_1^2) \cdot w_{(n,2)}$	$J(v_2^n, v_2^2) \cdot w_{(n,2)}$		
		v_2^n	$J(v_2^i, v_1^1) \cdot w_{(n,1)}$	$J(v_2^n, v_2^1) \cdot w_{(n,1)}$	$J(v_2^n, v_1^2) \cdot w_{(n,2)}$	$J(v_2^n, v_2^2) \cdot w_{(n,2)}$		

Figure 2: Exemplary application of the AHP weightings in the CIB-matrix

D_n descriptors, where n is the total number of descriptors

m number of variations for descriptor D_n, with $m = \{1, 2\}$ (applicable only to the current example)

v_m^n variation m of descriptor D_n, with $n = \{D_1, D_2, \dots, D_n\}$

$J(v_m^i, v_m^j)$ Judgement field with impact strength defined by experts' of v_m^i on v_m^j

Initially, each judgement field of two variations is assessed by experts' judgement $J(v_m^i, v_m^j)$. In a subsequent step, each judgement field within one cross-impact is adjusted by the multiplier, described in Eq. 1. This procedure results in judgement fields of the identified cross-impact that simultaneously reflect the experts' judgement on the mutual interrelation between the variations and the relative importance of this field.

2.3.2 Scaling Approach

In the current chapter the ex-ante application of the AHP ratings is performed as a thought experiment. However, the approach presented here is based on the CIB evaluations and AHP

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ratings obtained within the experts' interviews (see Figure 3). We assume a variety of approaches can be implemented to translate the AHP ratings into a scale prior to the CIB workshop with experts, providing them with the pre-determined scale for each cross-impact identified. Within the current work, two different scales will be taken into consideration:

1. scale from "3" ("-3") to "5" ("-5") applied to the CIB cross-impact matrix (*AHP 5*),
2. scale from "1" ("-1") to "10" ("-10") applied to the CIB cross-impact matrix (*AHP 10*).

The choice of the first scale was driven by the original scale used for the cross-impact evaluation within the CIB expert workshop (from "-5" to "+5", where negative ratings represent restricting influences and positive – supporting). Thereafter, the AHP ratings were normalised with respect to the desired scale and thus, descriptors ranked high by the AHP were given proportionally high values (maximum of "5") from the chosen desirable range. Accordingly, low ranked descriptors received the lowest value in the range, thus varying from a maximum of "3" to "-3" for the investigated cross-impacts. This scale is closest to the scale initially defined at the CIB expert workshop. Within this scale minor changes occurred to the judgements of the cross-impacts: e.g. proportionally up-lifting entries in the fields where experts gave low evaluations without considering the descriptors' ability to alter the overall system.

As discussed before, a strict differentiation between active and passive descriptors with regard to the assigned impact factor is necessary. In order to take this differentiation into consideration, we assumed that the impact of the active descriptor on the passive descriptor will be augmented by the passive descriptors' ability to affect the overall system. For example, if active descriptor D1 has an overall (AHP) weight in the system of 2.3 % and the passive descriptor D2 – 4 %, then the influence of D1 on D2 has to be proportionally augmented by D2's weight on the system - amplifying the influence of D2 by 4 %.

3 CIB for the European electricity market

In order to demonstrate the impact of implementing the AHP to CIB, this article will refer to a CIB matrix that was developed for the BMWi founded 4NEMO project. Among other goals, this project aims at an extended integration of economic and social dynamics and related uncertainties into energy system modelling approaches. There are seven participating models within this project. In order to maximize comparability, project internal socio-economic scenarios are developed as a subsequent step, using the CIB analysis (see e.g. Weimer-Jehle 2009; Weimer-Jehle 2006). This poses a particular challenge, since the scenarios developed using the CIB must sufficiently cover the exogenous input factors of seven models.

This section will provide a brief outline of the initial CIB matrix and the resulting scenarios and will serve as a point of reference for assessing the implementation methods of the AHP. The chosen scope for the scenarios covers the development of the European electricity market until 2050. Single countries are not depicted individually, therefore the assumed developments within the respective descriptors' variations will always be true for every considered country and can be interpreted as a general trend for Europe.

The descriptor list contains 22 items, whereas each descriptor has two to four variations and a total of 85 identified cross-impacts. In a subsequent step, the AHP was applied in order to assess each descriptors' ability to give meaningful information about the system under examination. Figure 3 shows the CIB matrix in combination with the results of the AHP ratings.

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Examination of the assigned hierarchy reveals a general tendency of experts' perception to focus stronger on energy policy and social developments rather than pure technical factors.

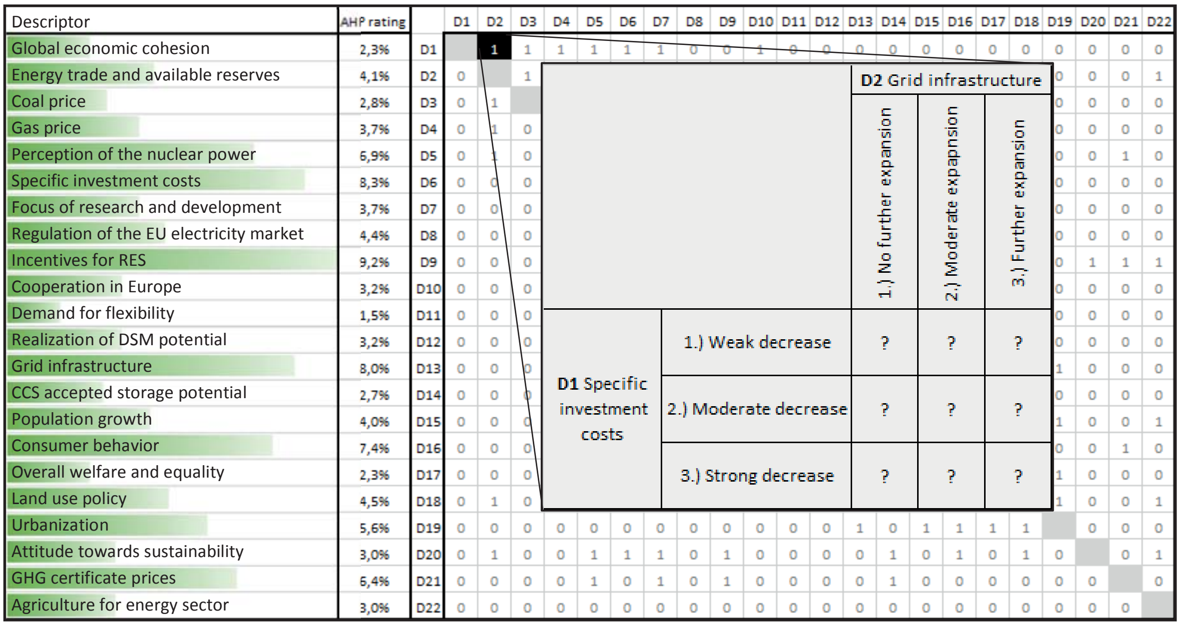

Figure 3: Cross Impact Matrix with exemplary judgement field in combination with descriptors' AHP rating

Applying the algorithm to the described CIB matrix creates a scenario room of 26 consistent scenarios. Figure 4 depicts the occurrence of variations by descriptor in relation to the overall amount of scenarios. While most descriptors show a relatively balanced distribution of variations, the descriptors "Perception of nuclear power", "Urbanization" and "Accepted CCS storage potential" show a non-varying state throughout all developed scenarios. More specifically, this means that all scenarios share a set of specific assumptions about the development of those factors:

1.) The technology of nuclear power generation is perceived as high risk technology[2]
2.) The rate of urbanization within Europe will stay stable at 0.2%/a
3.) Lacking acceptance for CCS technology hampers utilization of available storage potentials

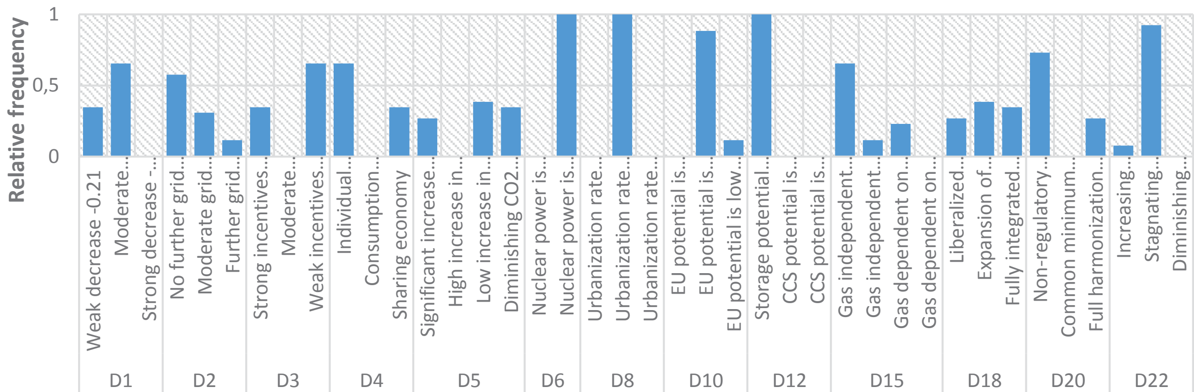

Figure 4: Relative frequency of variations per descriptor

[2] There is no differentiation between public perception and perception of political decision makers.

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4 Results

4.1 Multiplying approach

The implementation of the AHP to the CIB matrix as described in section 2.3 results in a significant reduction of consistent scenarios: while the original CIB matrix produced 26 scenarios, the AHP adjusted matrix leads to two scenarios. Consequently, the number of descriptors, which show no variation strongly increased and only two descriptors show variations. Figure 5 displays the structure of this scenario room.

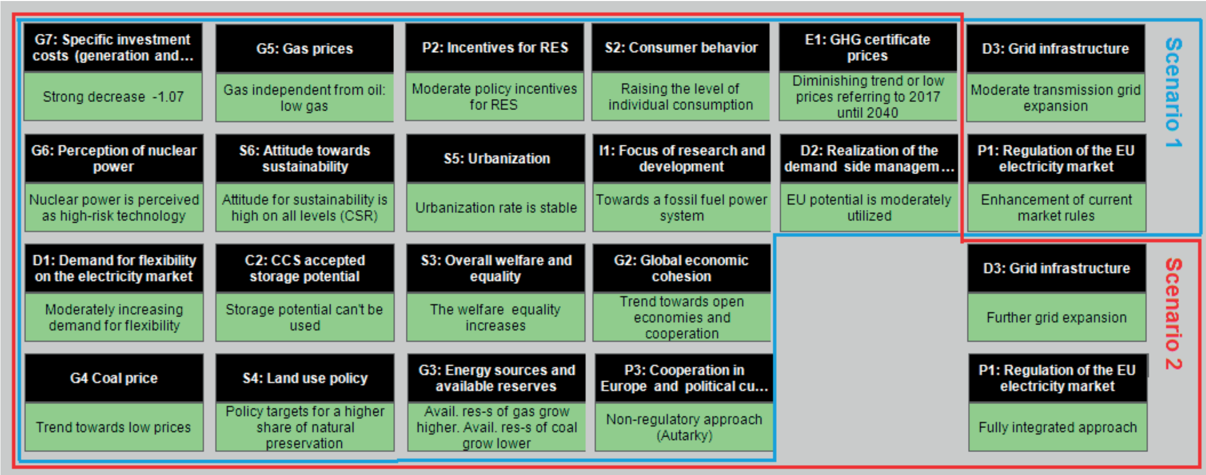

Figure 5: Scenarios for the AHP multiplication

Due to the high amount of non-varying descriptors, these two scenarios are very similar and have a high internal consistency. Even with higher degree of freedom for inconsistencies of single descriptors, the results prove to be stable. This indicates that the scenarios with AHP extensions can be tighter in terms of their internal argumentation and are therefore less assailable. On the other hand, this approach limits the CIB's ability to depict and reveal unknown future pathways and scenario options.

The resulting scenarios are not included in the original CIB set. Furthermore, a detailed comparison of the AHP scenarios with the original scenario set reveals that there seems to exist little similarity between those two sets. The closest scenarios of the original CIB matrix share 14 equal variations with the AHP scenarios. This indicates, that this implementation method does not refine the original scenario sets, but alters the direction of the scenarios significantly.

The ex-post implementation of the AHP ratings opens the opportunity to suit the descriptor assessment in order to the underlying research questions and to shift the focus of the scenarios. With the AHP extension it is possible to change the main emphasis of the scenarios and to transfer matrixes with already existing impact judgements into new scenario studies. However, the resulting scenario set is highly dependent on the chosen form of calculation of the multiplier and the internal scaling of the judgement fields. Furthermore, those factors show reciprocal effects as well. Therefore, further research in form of comprehensive sensitivity analysis will be necessary in order to fully evaluate this approach.

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4.2 Implementation of the AHP to the CIB process

Each entry in the CIB matrix received a specific value defining the range and the maximum possible entry for supporting or restricting influences on the passive descriptor. The major driver is to see how the choice of the implemented scale can alter the scenario room. Change in the scales allowed to consistently explore the boundaries of the scenario room and bring in new variations of descriptor states that did not occur in the original matrix (see Figure 6). Other variations' frequencies were suppressed within the same process.[PM1] However, the scenario room with the *AHP 5* resulted in the largest spectre of variations among the scenario sets under consideration.

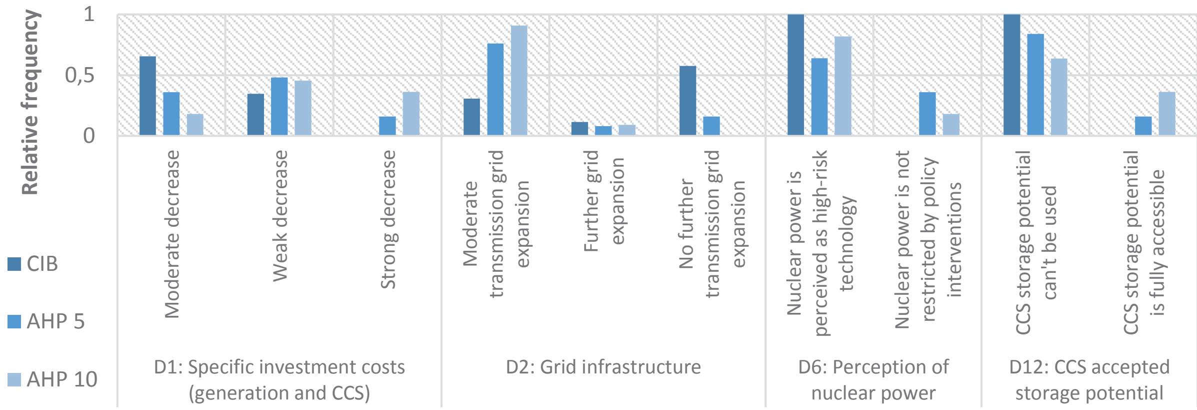

Figure 6: Relative frequency of variations per descriptor (not sure, if needed)

In order to evaluate the achieved scenario rooms by the correspondence analysis (CA), the authors defined three visions of the future (see Table 1). They do not refer to any particular scenario developed by the CIB analysis, however they follow the narratives and analysis represented in (Perera et al. 2013) and the so-called EU winter package (European Commission 2016).

Table 1: Visions of the future defined for the purposes of the CA analysis of scenario rooms

	Green vision	Yellow vision	Black vision
Policy incentives for RES	Strong	Moderate	Weak
GHG certificate prices	High to significant increase in CO2 prices	Diminishing trend or low prices referring to 2017 until 2040	Low increase in CO2 prices
Attitude towards sustainability	Attitude for sustainability is high on all levels (CSR)	Attitude for sustainability is high on all levels (weak CSR)	Low requirements for sustainability
Focus of research and development	Towards low carbon power system	Towards low carbon power system	Towards a fossil fuel power system
Global economic cohesion	Trend towards open economies and cooperation	Trend for bilateral/supranational cooperation	Trend towards national protectionism and international competition
Gas prices	Gas independent from oil: high gas	Gas dependent on oil: high gas	Gas dependent on oil: low gas
Coal price	High coal price +2.5% p.a.	Stable prices +0% p.a.	Trend towards low prices
Cooperation in Europe and political culture	Full harmonization approach	Common minimum EU rules on cooperation + bilateral cooperation	Non-regulatory approach (Autarky)
Regulation of the EU electricity market	Liberalized electricity market	Enhancement of current market rules	Fully integrated approach

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The CA evaluates the obtained scenario rooms with regard to their proximity to the visions defined above. Three scenario rooms are formed by the original results from the CIB matrix filled in by the experts (denoted as CIB on the figure below) and two comparative cross-impact matrixes compelled with the help of the AHP-derived scale (see Figure 7). The CA conducted within this paper relies on the R packages "ca" and "factoextra" by Kassamara & Mundt (2017) and Nenadic &Greenacre (2007), respectively.

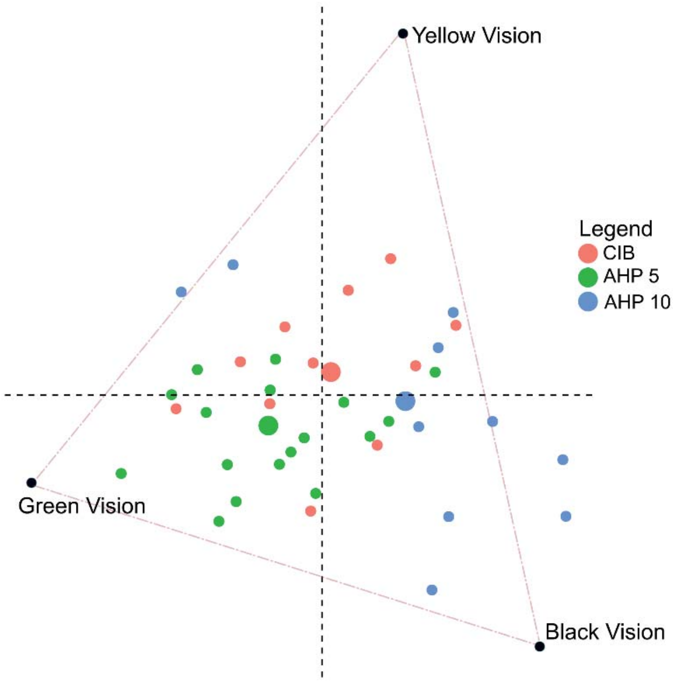

Figure 7: Correspondence analysis applied to the analysis of the three investigated scenario rooms

The pattern of the original CIB scenario room has a clear centered position but is distributed mainly along the Green to Yellow visions diagonal. AHP results implemented through two different scales allowed for a greater variety within the scenarios and shifting the central scope of the respective scenario rooms towards the green or black vision[PM2]. Since the initial ratings of the experts were not changed in their direction (supporting and restricting impacts being the same) but rather re-scaled, the AHP-based tool provided with a transparent method to explore the CIB matrix boundaries ex-post, or to offer a judgement field specific scaling ex-ante within the process of the CIB analysis. The thick points on Figure 7 depict the centroids or a position of an average profile for each of the three scenario groups. Thus, the original CIB tends to represent a central scope of the scenarios that do not offer "extreme[PM3]" combinations of descriptor states. *AHP 5*, although being very close to the expert's CIB, aligns more to the Green vision. In the *AHP 10*, where descriptors ranked low received only a minor ability to outbalance impacts of the top list descriptors, bring in scenarios close to the business as usual terms defined by the Black vision.

5 Conclusion

The opportunity of the AHP–CIB tandem is to eliminate the limitations of both approaches without making the process more complicated. It can help to incorporate expert judgments in a consistent manner and avoids misunderstandings during the judgement procedure on the

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intensity of the impacts in the CIB matrix. This article introduced two different methods of applying the AHP to CIB analysis: (1) implementing the AHP rating to the CIB matrix and (2) including the AHP to the CIB process.

As demonstrated in section 3, the first approach condensates the scenario cluster, without losing the information on the initial experts' judgements. However, the significant reduction of scenarios limits the CIB's ability reveal unknown future pathways and scenario options but delivers more stable and less assailable results.

The second approach requires direct integration into the CIB process. This method can either serve as an internal consistency check in order to assist the experts' judgement process, or it can be used to determine the maximum impact evaluations of each individual cross-impact. On the one hand, this allows for additional transparency and consistency during the process of the cross impact assessment. On the other hand, this approach restricts the experts' capability in evaluating the cross impacts by providing them with the pre-determined scale. The results of this approach show that it allows to consequently and transparently change the boundaries of the scenario room within the CIB analysis and gives a better overview and control over the CIB results. This allows to explore the scenarios without making considerable changes to the number of identified cross-impacts, but rater altering relative weights of their impacts within the matrix in a consequent manner. Increased variations' frequencies may be considered as one of the positive outcomes of the applied method. The approach brings in considerable benefits at the stage of planning and organization of the CIB experts interviews. It offers a transparent way to group descriptors with respect to their impacts, highlighting specific impact fields where experts' judgements are most critical and capable to drive the subsequent CIB analysis.

To sum up, implementation of the AHP to the CIB analysis can facilitate the CIB analysis and simultaneously increase the level of transparency and consistency within this method. Furthermore, possible imbalances within the CIB matrix can be eliminated. This article indicated two paradigmatic methods of implementation, but in order to reach a comprehensive assessment on the full potential of the combination of CIB and AHP, further research will be necessary. However, the process of the CIB and the evaluation of the overall quality of the resulting scenarios will still be strongly dependent on experts' assessments.

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