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Application of SCOR flexibility metrics to assess the Industry 4.0-Readiness of Supply Chain Networks: an empirical study

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ABSTRACT

The development of Industry 4.0 (I4.0) necessitates flexible Supply Chain Networks (SCN). Therefore, this paper assesses the flexibility of SCN in context of I4.0. The assessment is based on a framework of metrics embedded in the Supply Chain Operations Reference (SCOR) model. The methodology employed integrates the Analytical Hierarchy Process (AHP) and the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) to weight the selected SCOR indicators and to determine the SCN I4.0-Readiness. The computations are based on empirically tested SCOR-data and expert judgements. The developed I4.0-Readiness-Assessment tool reveals a lack of SCN´s utilization of the full potential of I4.0.

Keywords: Industry 4.0, Supply Chain Networks, Flexibility Assessment

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1. Purpose

The proliferation of individualization, shortened product life cycles and technological innovations like Industry 4.0 (I4.0) connote with an enhanced cooperation and network formation to cope with these challenges. Hence, competition will no longer exist only between single companies but between entire Supply Chain Networks (SCN) (Huan et al., 2004). SCN require the ability to react promptly and suitably to a complex and changing environment. This ability is a key competence to SCN success and is called flexibility. In order to achieve flexibility, technological innovations, especially I4.0, are an important aspect. A lack of flexibility is the biggest obstacle and driver for the implementation of I4.0-technologies at the same time (Shafiq et al., 2015). Regarding a survey conducted by PricewaterhouseCoopers, 30% of the interrogated companies name an increase in flexibility as major driver of inter-company cooperation (PricewaterhouseCoopers, 2014). Therefore, it is crucial to assess the level of SCN flexibility and the connoting ability to participate in the fourth stage of industrialization, called I4.0-Readiness. Hence, the research question is: How can the SCN flexibility and thus the relating I4.0-Readiness be assessed?

Since a conceptual integration of flexibility assessment in a performance measurement framework is essential, the methodological approach of this paper is based on the Supply Chain Operations Reference (SCOR) model as reference framework with standardized terminology, processes and metrics (Ganga and Carpinetti, 2011). However, the SCOR model comprises over 500 metrics, so the selection of a relevant set of indicators is necessary. Hence, besides indicator selection the paper´s objective is the development of an integrated approach for the assessment of the I4.0-Readiness of SCN as a multi-criteria decision analysis (MCDA).

Among the variety of MCDA, two well-known and widely applied methods in the field of indicator selection are the **A**nalytical **H**ierarchy **P**rocess (AHP) and the **P**reference **R**anking **O**rganization **Meth**od for **E**nrichment **E**valuations (PROMETHEE) (Cho et al., 2012). The paper proposes a combination of those two methods: AHP is applied to structure the decision problem and to detect the importance of the respective indicators by determining weights. Afterwards the weights are integrated in PROMETHEE to assess the I4.0-Readiness of a specific SCN by comparing one SCN to reference SCN based on SCOR-benchmark data. Afterwards this paper introduces AHP, PROMETHEE and the integrated approach. The proposed integrated approach is applied by using statistically significant SCN data. The findings and a conclusion are formulated in the end.

2. Design, Methodology & Approach

The SCOR model, developed by the Supply Chain Council (SCC), comprises an integrated performance measurement system for SCN. The objective of the SCOR model is to understand, describe, measure and evaluate activities of a SCN based on a common framework, which facilitates benchmarks and identifies best practices (Huan et al., 2004).

The SCOR model consists of processes on three hierarchical levels: Level 1 contains the six distinct management processes plan, source, make, deliver, return and enable (SCC, 2014). Those management processes are further decomposed into process categories on level 2 and process elements on level 3 of the SCOR model.

Additionally to standardized processes, the model contains five performance attributes: reliability, responsiveness, flexibility, cost and asset (SCC, 2014). According to the SCC the performance attribute flexibility is defined as the agility of a SCN to respond to market changes in demand in order to gain or maintain its competitive advantage (SCC, 2014). Hence, it refers to both, the ability to efficiently adjust output quantity and to introduce new or modified products (Duclos et al, 2003; Stevenson and Spring, 2007). Both abilities represent the key challenges and requirements in the context of I4.0. Therefore, the SCN flexibility consists of two dimensions: SCN response time and SCN production flexibility.

Since flexibility is an important aspect to participate in the fourth stage of industrialization, these networks are called Industry 4.0-Supply Chain Networks (I4.0-SCN). A comprehensive literature based study reveals the following eight elementary characteristics of I4.0 SCN: inter-organizational information exchange, a temporary-order-related duration of cooperation, a high degree of dynamics, a cooperative relationship of the network partners, high degree of self-organization, a comprehensive interface compatibility, a hierarchical and polycentric network structure as well as a decentral form of coordination (Klünder et al., 2016). Those characteristics are applied for the operationalization of flexibility and thus the aspired assessment of the SCN-I4.0-Readiness. Thereafter, the paper assumes underlying relations between the SCOR metrics, the eight I4.0-SCN characteristics, the flexibility dimensions and ultimately the I4.0-Readiness of the SCN.

2.1 Preselection of Indicators

The selection of a relevant set of indicators for the flexibility assessment as key enabler and driver of I4.0 implementation is a many-layered and complex task as the SCOR model includes more than 500 indicators. In literature, 10 to 20 key indicators are regarded as a meaningful and sufficient number. Hence, a set of relevant indicators is prequalified by a three-stage procedure (Veleva and Ellenbecker, 2001).

Firstly, the statistically significant pool of SCN data, rose by the SCC and named SCORmark|benchmark, substantially narrows the number of applicable SCOR indicators. Secondly, the data corpus is sharpened by an analysis of the indicators flexibility- and industry 4.0-relevance. Thirdly, the selected set of indicators has to meet the requirements of standardization, transparency and usability and should comprise quantitative as well as qualitative measures in order to depict the complex and dynamic environment of SCN (Neely et al., 1997; Veleva and Ellenbecker, 2001). This leads to a set of 15 potential I4.0-Readiness-Indicators depicted in table 1.

Indicator	Definition	Unit
C1 Internet of Things Awareness	Degree of SCN's digital transformation	ordinal
C2 Technology Utilization	Percentage of SCN's equipment that is "intelligent"	%
C3 Cloud IT-Applications	Percentage of IT-systems which are integrated in a cloud system	%
C4 SC Skill Sharing	Ability to transfer specific logistic skills to other SCN members	%
C5 SC Know-How	Percentage of positions with documented skill standards	%
C6 SC Reconfiguration Willingness	Willingness of the SCN to achieve a new configuration of a SCN	ordinal
C7 Economic Dependency on the SCN	Importance of the participation in a SCN for SC participants' success	ordinal
C8 Upstream SC Strategic Alignment	Degree of interaction between direct SCN Customers indicating the amount of common network-directed activities	ordinal
C9 Downstream SC Strategic Alignment	Degree of interaction between direct SCN Suppliers indicating the amount of common network-directed activities	ordinal
C10 Degree of Collaboration	Degree of collaboration along the SCN	%
C11 Time needed to train Additional Labor	Amount of time needed to train additional labor to sustain 20% increase in quantities manufactured	time
C12 Manufacturing Cycle Time	Time required to turn raw materials into completed products	time
C13 Process Speed	Capability to monitor and measure the pace and speed of a process	ordinal
C14 Upstream Performance Capability	Extent to which the SCN is capable to monitor and measure the suppliers performance in real time	ordinal
C15 Downstream Performance Capability	Extent to which the SCN is capable to monitor and measure the distributors performance in real time	ordinal

Table 1 - Set of I4.0 - Readiness Indicators

2.2 Analytic Hierarchy Process

In order to determine the respective weights of the indicators, AHP is implemented. AHP consists of three steps: (1) hierarchy construction, (2) setting of priorities and (3) check of logical consistency (Macharis, 2004).

Firstly, the decision problem described above is converted into a decision hierarchy. Secondly, paired comparisons of criteria in terms of their importance for a parent element are executed. Those pairwise comparisons base on a standardized nine-point comparison scale. The nine-point scale represents equal (1), weak (3), strong (5), very strong (7) and absolute importance (9), the intermediate values (2, 4, 6, 8) and their reciprocals (Saaty, 2008). Here, the pairwise comparison of the criteria set, which is the set of indicators, C={ C_j |j=1,2,…,15} leads to an (15×15) evaluation matrix A=[a_{ij}] in which a_{ij} shows the preference weight of a_i in comparison with a_j (Macharis et al., 2004: Turcksin et al., 2011).

Equation (1):

$$A = [a_{ij}] = \begin{bmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \cdots & 1 \end{bmatrix} \quad , \quad \forall\, i, j = 1, 2, \dots, 15$$

The weight of an element is computed based on Saaty's approximate eigenvector procedure. Therefore, the comparison matrix A is normalized to find the relative weight of an element.

Equation (2):

$$w_i = \frac{\sum_{i=1}^{n} a_{ij}^*}{n} \quad \text{, where} \quad a_{ij}^* = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad \forall\, i, j = 1, 2, \dots, 15$$

Conclusively, a consistency check examines the validity of the pairwise comparisons. Here, λ_{max} represents the biggest eigenvalue of A and serves as validating parameter. The Consistency Ratio (CR) equals the ratio of Consistency Index (CI) and Random Consistency Index (RI). RI is appointed by Saaty's statistical significant simulation studies (Equation 3); e.g., given the 15 criteria in our study RI equals 1.59 (Saaty, 1998).

Equation (3):

$$CR = \frac{CI}{RI} \quad \text{, where} \quad CI = \frac{(\lambda_{max} - n)}{(n-1)}$$

By multiplying the CIs with the respective priority vector for each pairwise comparison matrix, adding the results for the entire hierarchy and comparing this index with the corresponding index obtained by the RI, the consistency ratio of the hierarchy (CRH) can be determined. The CRH should be in the neighborhood of 0.1, otherwise inconsistency is assumed (Saaty, 1980).

2.3 Integrated AHP-PROMETHEE-Approach

Due to an evaluation of strengths and weaknesses of several MCDA methods, AHP is enhancing and strengthening the calculations of the outranking method PROMETHEE (Dagdeviren, 2008). Thus, the combination of AHP and PROMETHEE guarantees the consideration of several desired quality criteria: A profound, scientific and appropriate methodology is pursued by the consideration of interdependencies and compensations between quantitative (tangible) as well as qualitative (intangible) factors. The methodological feasibility is ensured by the cost-effectiveness for data retrieval, avoidance of redundancies, comprehensibility for decision makers and the intertemporal reproducibility of the assessment. Moreover, a high measurability, reliability and significance of the database is necessary to produce quantifiable results with a high explanatory power. For this reason the process of determining the indicators´ importance regarding a superior criterion by weighting the indicators is transparent. The proposed integrated approach offers a high methodological flexibility necessary due to the strong momentum of I4.0 (e.g. Belton and Stewart, 2002; Franceschini et al., 2008).

Therefore, an integration of those methods is performed hereafter.

PROMETHEE is implemented to assess the I4.0-Readiness of a SCN in comparison to empirically determined SCOR benchmark networks. Since the multidimensional concept of I4.0-Readiness requires the consideration of various aspects, a finite and a priori known number of supply chains and a number of relevant assessment criteria characterize the decision situation. The assessment criteria (here 15 indicators) can be measured in different dimensions (incommensurability) but they have to be at least ordinal scaled. In this context, the word ‘assessment’ refers to a combination of decision-making criteria and personal preferences for the evaluation of decision-making alternatives. Therefore, an assessment is not independent from individual preferences and thus it is subjectively influenced. PROMETHEE helps to reveal these subjective assessment criteria.

Several steps of PROMETHEE were already achieved by the application of AHP. The set of criteria is clearly arranged hierarchically and accompanied with weighting factors w_j. Therefore, the PROMETHEE calculations start with the determination of deviations d_j between SCN a and b based on the pairwise comparisons (Brans et al., 1986; Behzadian et al., 2010).

Equation (4):

$$d_j(a,b) = g_j(a) - g_j(b)$$

For the transformation of incommensurable indicators into preference degrees P_j, preference functions ranging from 0-1 are applied. Brans and Mareschal (2005) present the Usual Criterion, U-shape criterion, V-shape criterion, Level criterion, V-shape with indifference criterion and the Gaussian Criterion to cover all use cases of practical relevance. The preference functions F_j were shaped by the indifference threshold value Q and the preference threshold value P as well as the Gaussian threshold value σ in case of the Gaussian preference function. The preference functions were applied to generate an overall preference index.

Equation (5):

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b) w_j\,, \qquad where \quad P_j(a,b) = F_j\left[d_j(a,b)\right] \qquad \forall\, j = 1,\ldots,15$$

The computation of positive Φ^+ and negative outranking flows Φ^- as part of PROMETHEE I leads to a partial ranking. A complete ranking, PROMETHEE II, is accomplished by the subtraction of the positive and negative outranking flow resulting in the net flow Φ^{net}.

Equation (6):

$$\Phi^+(a) = \frac{1}{m-1} \sum_{x \in A} \pi(a,x),$$

$$\Phi^-(a) = \frac{1}{m-1} \sum_{x \in A} \pi(x,a),$$

$$\Phi^{net}(a) = \Phi^+ - \Phi^-$$

The integrated assessment is especially in the context of the SCOR model an appropriate approach. AHP decomposes the complex decision-making problem hierarchically into sub problems. Due to the hierarchical structure of the AHP-PROMETHEE approach, the fundamental SCOR logic of decomposition and hierarchy generation is followed (Huan et al., 2004; Palma-Mendoza, 2014). Additionally, AHP's rank reversal problem, occurring by the introduction of new alternatives which might result in a revised ranking, is solved by the application of the standardized SCOR metrics (Huan et al., 2004); Macharis et al., 2004). As PROMETHEE is not providing a structured approach for the determination of weights, the integration of AHP delivers the relative importance of each criterion (Macharis et al., 2004).

3. Calculation and findings of the proposed methodology

3.1 Data Collection

The AHP calculations require pairwise comparisons of the selected indicators using Saaty´s fundamental scale (Saaty, 2016). Since the multi criteria decision problem of indicator se-lection has been decomposed and structured in hierarchically arranged sub problems, the pairwise comparison is a manageable task. For the given hierarchy experts conducted 1.296 pairwise comparisons on four hierarchical levels.

The first hierarchical level contains the SCN flexibility as overall goal of the decision process. The second and third levels comprise the determined flexibility dimensions and I4.0 SCN characteristics as criteria and sub criteria (Klünder et al., 2016). The fourth level of the decision hierarchy contains the 15 selected indicators as alternatives. The overall decision hierarchy is depicted in figure 1.

For the evaluation of indicators´ importance, a panel of 8 experts, one expert per characteristic feature, has specified their preference intensity based on a pairwise comparison of the indicators on each level of the hierarchical problem. As several experts with different areas of expertise are involved, the pairwise comparisons can be divided, hence the experts provide judgments in their area of expertise. Thus, the judgments are complementing each other (Saaty, 1990). Afterwards the geometric mean is calculated to aggregate the evaluations to an overall pairwise comparison (Mühlbacher and Kaczynski, 2013; Turcksin et al., 2011; Macharis et al., 2004).

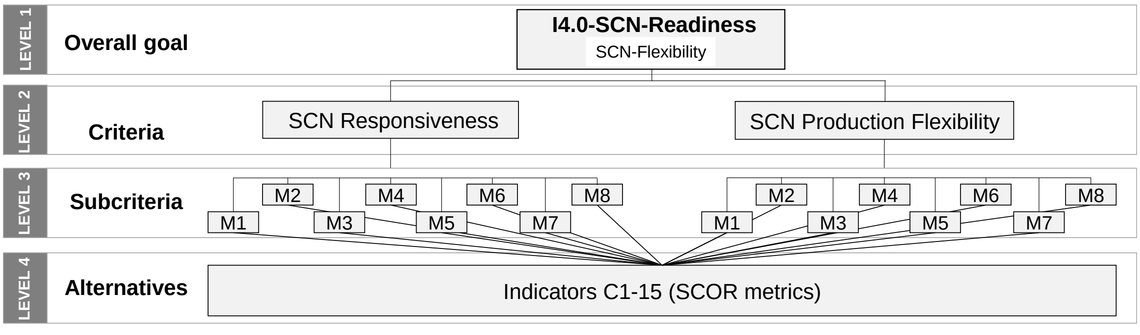

Figure 1 - AHP hierarchical structure

3.2 AHP calculations

Based on the established hierarchy and the collected data of pairwise comparisons, the respective weights of the alternatives and (sub) criteria can be calculated by using AHP. Hence, the expert judgments result in 8 pairwise comparison matrices with the dimension 15x15 on level 4, 2 matrices with the dimension 8x8 on level 3 and one matrix with the dimension 2x2 on level 1. Every matrix is expressing the importance of each individual alternative/criterion regarding an overarching objective. The results obtained from the AHP calculations based on the pairwise comparisons are provided in figure 2. The criterions C10, C1, C6 with calculated weightings of 0.10, 0.09 and 0.08 are identified as most important indicators for the evaluation of the I4.0-Readiness of SCN. As the consistency ratio for the whole hierarchy equals 0.10 the judgements could be classified as just consistent. In the light of I4.0's level of novelty and the complex multi-level hierarchy, judged by a high number of experts, the CRH is deemed adequate. The weights range from 0.03 to 0.10, indicating that some criteria are three times as important as other criteria. This emphasizes the necessity of the methodology.

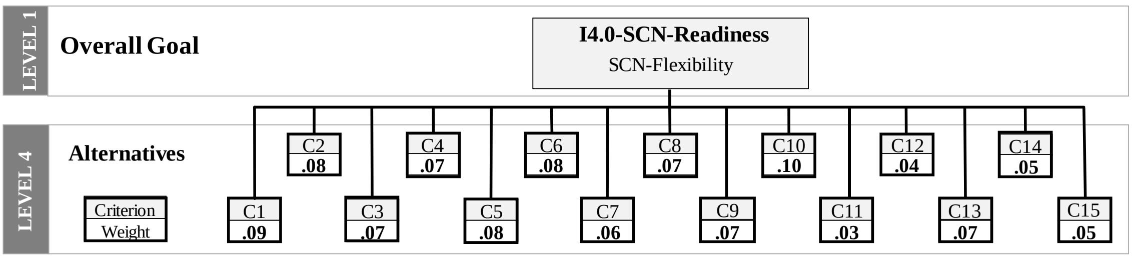

Figure 2 - Calculated weights (Level 4 on Level 1)

3.3 PROMETHEE

In order to perform the PROMETHEE calculations, two types of information are required: the relative importance of the considered criteria, namely the weights and the information on the decision maker's preference functions (Macharis et al., 2004). Since the weights have been generated in AHP, the first step in PROMETHEE is the definition of relative preference functions with specific thresholds for the respective indicators.

To preserve the quality of the significant empirical data, the V-shaped preference function is applied for all indicators. Depending on scale and graduation, the individual thresh-olds were set to get finely graduated prevalences. With the exception of 'time needed to train additional labor' (C11) and 'manufacturing cycle time' (C12) all criteria should be maximized.

The data section in table 2 comprises empirically significant benchmark data of rigid, median, average and advanced SCN determining different maturity levels of I4.0-Readiness. The benchmark has been derived from the statistically significant pool of SCORmark|benchmark data raised by the SCC. This study focuses especially on the auto-motive sector as the industry is highly innovative and networked. The row labeled ‘Ob-served’ displayed in table 2 represents an exemplary comparison SCN, that has to be re-placed by individual supply chain data of practitioners (see table 2).

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
Goal	⬆	⬆	⬆	⬆	⬆	⬆	⬆	⬆	⬆	⬆	⬇	⬇	⬆	⬆	⬆
Shape P	for the preservation of data quality *V-shape* is used for all criteria														
P	4	100	100	100	100	4	4	4	4	100	3	3	4	4	4
Data															
Rigid	Never heard	0	*0*	*low*	*low*	*medium*	*good*	*buy and sell*	*buy and sell*	*0*	*medium*	*27*	*medium*	*medium*	*medium*
Average	Never heard	*31,3*	*13,1*	*medium*	*much*	*very good*	*very good*	*Certi-fication*	*Certi-fication*	*17,7*	*few*	*18,7*	*good*	*medium*	*good*
Median	Never heard	*15*	*5*	*medium*	*much*	*very good*	*very good*	*Certi-fication*	*Certi-fication*	*5*	*few*	*20*	*good*	*medium*	*good*
Advanced	Plans	*52,5*	*10*	*much*	*high*	*very good*	*very good*	*Partner-ship*	*Partner-ship*	*32,5*	*few*	*1*	*very good*	*very good*	*very good*
Observed	Plans	*25*	*3*	*low*	*high*	*bad*	*very good*	*Coope-ration*	*buy and sell*	*12*	*medium*	*14*	*good*	*medium*	*very good*

Table 2 - Evaluation Matrix in PROMETHEE

Resulting from the design of the comparison SCN, the prototype of a rigid SCN is deter-mined as the most incapable SCN considering I4.0 requirements. Moreover, the net flow values given in table 3 disclose the dominance of the advanced SCN over the average and the median SCN. The calculation of the net flows allows a comparison between these prototypes and a specific SCN I4.0-Readiness. The net flows indicate a ranking of the observed SCN between the average and the median SCN.

		Φ^{+}	Φ^{-}	Φ^{net}
Benchmark Supply Chain Networks	Rigid SCN	0.0053	0.2636	-0.2583
	Median SCN	0.0720	0.1111	-0.0390
	Average SCN	0.0958	0.0887	0.0071
	Advanced SCN	0.3008	0.0005	0.3002
Comparison SCN	Observed SCN	0.1139	0.1239	-0.0100

Table 3 - PROMETHEE flows

A detailed analysis is enabled by the graphical representation of the multicriteria I4.0-Readiness via the ‘Graphical Analysis for Interactive Assistance (GAIA)-plane’. GAIA is a descriptive complement of PROMETHEE. The GAIA plane, resulting from the projection of the 15-dimensional space of criteria onto a two dimensional plane, depicts the position of the observed SCN by points whereas the vectors represent the indicators (Saaty, 2016). A Delta-Parameter of 95.6%, a measure of the graphics' reliability, states that the projection only eliminates 4.4% of the total information. Figure 3 reveals:

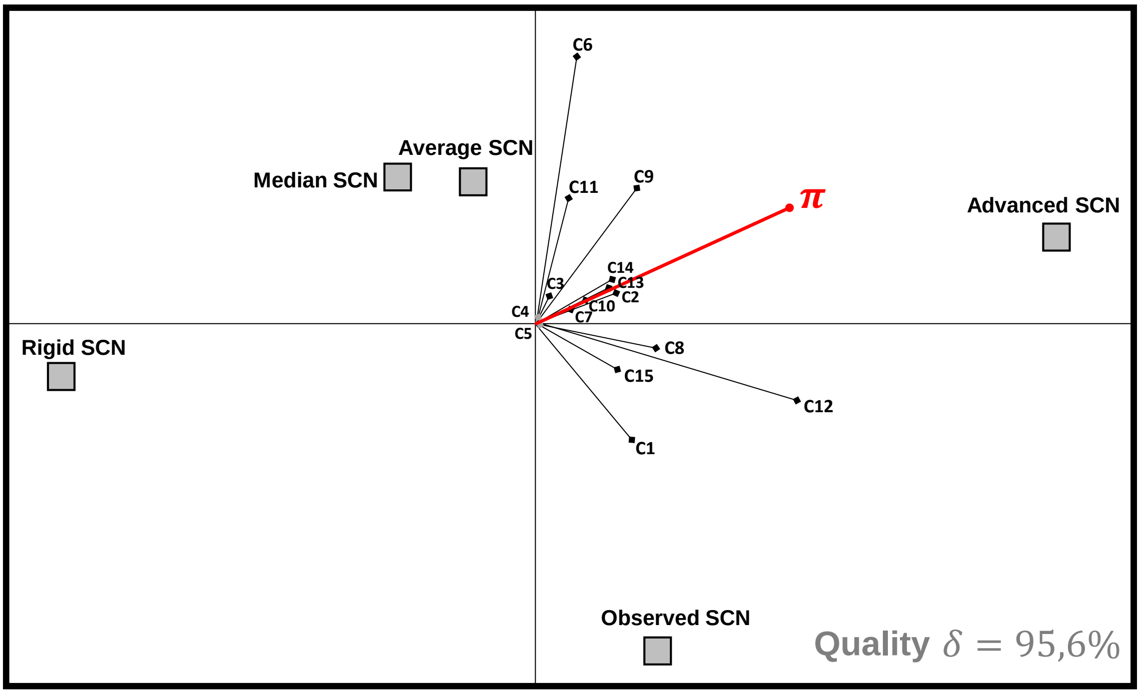

Figure 3 - GAIA plane

- All criteria utilized for I4.0-Readiness-Assessment express similar preferences by an orientation in an approximatively same direction.

- The axis' length of SCN's reconfiguration willingness (C6), the Manufacturing Cycle Time (C12) as well as the Upstream Strategic Alignment (C8) and Upstream Performance Capability (C14) illustrates that these criterions are highly discriminating. Even though AHP calculations reveal the highest perceived relevance of C10, PROMETHEE displays C6, C8, C12 and C14 are making the difference as they discriminate an unready from a ready SCN.

- The distance of SCN represents their affiliation, hence the observed SCN reveals an I4.0-Readiness likewise the median and average SCN.

- The location of a SCN in the direction of a criterion axis shows that the SCN performs particularly well on that criterion. Thus, the average SCN performs very well on criterions like 'Reconfiguration willingness (C6)', 'Time needed to train additional labor (C11)' or 'Economical Dependency on the SCN (C7').

- As the decision stick Π, plotted red in figure 3, is long, the PROMETHEE decision axis contains strong decision power. Different weightings move the decision stick Π in different orientations. Hence, Π provides a valuable tool for sensitivity analysis. A changed weighting in favor of C6, C7 and C11 for instance would rotate the decision stick counterclockwise and the average SCN would be the most capable SCN in I4.0.

Summing up the 'Observed SCN' should improve on all I4.0-Readiness Indicators with special respect to C6, C12 and C14.

4. Conclusion and Contribution

This paper has argued that realizing I4.0's full potential requires flexible and versatile SCNs. Hence, I4.0 connotes with an enhanced cooperation and concentration on core competences, therefore the value creation surpasses single companies and requires the formation of SCN. Thus, the SCN is the object of observation. In the context of SCN a well-known and often used framework is the SCOR model. Consequently, the metrics of the SCOR-model are applied as indicator for the 8 intangible and qualitative I4.0-SCN characteristics and hence have been applied to assess the flexibility and thus the I4.0-Readiness of SCN. This operationalization of qualitative characteristics via flexibility firstly enables a quantifiable assessment of I4.0-Readiness of SCN.

For conducting the I4.0-Readiness assessment, an integrated approach, combining the methods AHP and PROMETHE has been exploited. After the identification of a relevant set of indicators, AHP determines the weights of the importance of each indicator with respect to an upper level criterion. The implementation of AHP is based on a finely graduated hierarchical decomposition of the SCN-Readiness in four levels. The hierarchy re-quires 1.296 expert judgements and uncovers the importance of the relevant set of indicators. Afterwards the PROMETHEE approach determines the I4.0-Readiness of a SCN in comparison to benchmark SCN based on weights obtained in AHP.

This integrated approach broadens the perspective from challenges to necessary capabilities of SCN in I4.0. Statistically significant reference SCN enable practitioners to bench-mark their sector-specific I4.0-Readiness. By combining the strengths of AHP and PRO-METHEE into a single assessment tool, reliable and meaningful benchmarks were generated based on empirical SCOR benchmark data.

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