Composite Index Creation Using AHP and DEA: Efficiency Optimization for Industries

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Abstract

While there already exists tools that can be implemented to improve inefficiency. The problem lies in determining where the inefficiencies reside. The contribution this paper provides includes demonstrating an outline to create a composite index for the purpose of determining inefficiencies. This objective leads to the numerical presentation of a composite index which will quantify the healthcare industry's inefficiencies. The healthcare industry has benefitted from operational efficiency improvements, both in medicine and administration. The outputs of this index will provide healthcare administration a means of justifying internal and external decisions made for specified operational improvements. The Analytical Hierarchy Process and the Data Envelopment Analysis are the methodologies incorporated in the composite index. The index integrates sub-indices that are aggregated and weighted to determine the overall efficiency of a hospital. The index is applied using real data from ten Canadian hospitals which has been provided by the Canadian Institute for Health Information (CIHI). The index demonstrates the level of efficiency for each composition of the index and the overall efficiency of a hospital can be standardized to the efficiency of all hospitals using this system.

Keywords Analytical Hierarchy Process, Data Envelopment Analysis, composite index, health care industry, and application.

1. Introduction

Each industry implements tools to determine how efficiently they operate. In the healthcare industry there is a need for priority setting, management science tools, and optimizing efficiency in the health care industry. (Bota et al., 2000) Therefore, a determinant tool incorporating a multi-criteria decision-making process was created to address this issue. This tool can be used to create, and monitor, the results that management would like to see within their business, or in the case presented in this paper, the hospital. These results will lead to enhanced quality of care, cost-effectiveness, improved teachings, etc. Hospitals present a deficiency in quantitatively pinpointing inefficiencies within their setting. (Baltussen and Niessen, 2006) It is for this reason that the health care industry was chosen for running this model. Inclusively, this research provides hospital management with a determinant tool which improves the experience, care, and management provided by the health care industry.

The purpose of this research is to provide industries with a superior tool for determining inefficiencies. It is important to determine where these inefficiencies lie, because once an inefficiency is pinpointed it can be analyzed and eliminated. The internal management team should then be able to utilize methods of improving their efficiency in select areas which will then affect overall efficiency. Wherea,s it is difficult to quantify efficiency, the methodologies incorporated in this study are ideally suited for this resolve, as they are measurable, verifiable methods. (Borisov et al., 2012) The composite index can then be used to compare and standardize the relative levels of efficiency between businesses across and industry. The purpose of this research is to provide industries with a superior tool for determining inefficiencies. It is important to determine where these inefficiencies lie, because once an inefficiency is pinpointed it can be analyzed and eliminated. The internal management team should then be able to utilize methods of improving their efficiency in select areas which will then affect overall efficiency. Whereas it is difficult to quantify efficiency, the methodologies incorporated in this study are ideally suited for this resolve, as they are measurable, verifiable methods. (Borisov et al., 2012) The composite index can then be used to compare and standardize the relative levels of efficiency between businesses across and industry.

1.1 Contribution

This paper provides a detailed outline on how to create a composite index that determines inefficiencies of a company, and then its industry, through the incorporation of both AHP and DEA. It explains why these methodologies were ideal for this process, how to build a composite index manually on excel or similar software, while providing a numerical example using real data. While the example is based on the healthcare industry, the steps in creating a composite index can be scaled for a single business, or any industry seeking another means of determining overall efficiency.

2. Literature Review

Since the exposure of the Analytical Hierarchy Process (AHP) in the 1980's by Saaty, there have been hundreds of papers incorporating this methodology in academic research. The eigenvector method of calculating priorities in AHP makes it one of the best methodologies to use for weighing composite aspects of an index. AHP is a methodology which was designed to solve complex decision problems containing multiple criteria. The combination of both qualitative and quantitative analysis allows decision making to be more objective and consistent. The articles reviewed contain arguments that either positively or negatively criticize AHP as a quantitative method. The discussions against the application of AHP for its relative inconsistency have been disputed on an algorithmic level. However, AHP is still widely applied for multiple purposes, both in its designated form as well as with modifications. The methodology has been applied in the field of medicine, but as demonstrated in the literature, there remains a gap in weighting the priorities of healthcare.

The volume of published research discussing, applying and evaluating AHP lead to an overview of the methodology, AHP, is provided by Vaidya and Kumar, 2004. The methodology is deemed a flexibly integrated, widely used, multiple criteria decision-making tool. It is defined as a pairwise comparisons method with an Eigen value approach. This made AHP a tool capable of being incorporated within different fields of research and application. The steps required for the process are outlined and the application of this methodology is analyzed. It is discussed within the scope of its integration within different fields, incorporation into business analysis tools, using it in conjunction with other methodologies, etc. Approximately one hundred and fifty application articles are referenced, and the concluding remarks of the article highlight the growing importance, use, and effectiveness of AHP (Vaidya & Kumar, 2004). Mathematical discrepancies for AHP have been criticized. The priority vector derived from the principal eigenvalue method in AHP and its consistency ratio were originally analyzed in Bana e Costa & Vansnick (2008). The drawback of AHP is that it fails to meet the condition of order preservation (COP) in most cases. The authors argue that meeting this standard is imperative for providing the fundamentals required in any decision aiding technique. It provides an example to demonstrate the violation of COP and criticize the mathematical derivation of the priority vector (Bana e Costa & Vansnick, 2008). Nonetheless, the mathematical discrepancies have been disputed in articles like Kulakowski (2015), where the evaluation and criticism of AHP continued by addressing the consistency of this methodology. It is mathematically analyzed through theorems which correspond with potential inconsistencies present in the methodology. This includes meeting the standards of conditions of order preservation (COP). Due to this, the author presents precise criteria for determining when this standard is met. Inherently, this article explains that AHP not meeting these mathematical standards would make it an insufficient approach at turning expert judgements into priority vectors (Kulakowski, 2015).

The methodology is continuously applied in different frameworks and provides positive results, such as in Li et al. (2011) where a scientific method is derived by combining AHP with qualitative and quantitative input to derive an objective judgement. A performance evaluation for University X's faculty was created. The authors provide an accurate and consistent manner of evaluating the relative performance of faculty members within a college/university setting. This index incorporation of AHP uses an unmodified methodology to complete the objectives set forth in the scope (Li et al., 2011). The application of AHP has spanned into multiple methods of incorporating it in existing tools, such as a composite index. In Niemira (2001) it was used to determine the cyclical turning points of macroeconomic activity. It was developed to create a newer statistical technique for the variant component weighting to be paired with the current cyclical-indicator, the Traditional-NBER method. This article underscored a need to research variable weighing of the components of an index. Therefore, the author improved upon the effectiveness of the methodology, AHP, for an ameliorated manner of approaching the cyclical turning points. This was required so that the mathematical inconsistencies would be taken into consideration for accurate computation of turning points (Niemira, 2001).

Other manners of applying AHP require modifying the original methodology to fit the task. The research presented in Saaty et al., (2011) is another example of incorporating an adjusted AHP methodology to evaluate heterogeneous elements. This example created an AHP model which determines the relative importance of criteria to each other within clusters. This was created to extend the use of the scale within AHP and it categorizes the criteria into clusters in ascending order of importance. It is another index that adjusts for a different evaluation of data that needs further categorization, displaying the versatility of this methodology as well as its success in quantifying the weighting of qualitative data. In the case of this article, it was applied to altruistic acts. (Saarty, et al., 2011) Additional application of AHP would be the protocol presented in Liberatore et al., (2003) which incorporates AHP as a decision aid for the binary decision of having a screening examination. This article also presents modifications to the methodology which were deemed appropriate for the requirements of the study's components. The purpose of this study was to demonstrate both the implementation and development of a decision-counseling protocol for the sole purpose of cancer screening. One of the components of the study included AHP-based counseling sessions. The authors claim for using the AHP was that it was both a widely used approach as well as it had been previously successfully applied to medical decision making. The final factors that led the researchers to implement AHP were its practicality in both measuring and allowing inconsistencies of judgements and that it simplifies the process of making judgements using pairwise comparisons (Liberatore et, al. 2003).

One of the challenges of AHP is setting priorities. There is a need for transparent, rational approaches to setting priorities, especially within healthcare settings. Baltussen & Niessen (2006) demonstrate the development of a multi-criteria approach to priority setting would be necessary, especially in the case of health interventions. It has been identified as one of the most important issues in health system research. The current rational approaches to priority setting do not take into consideration all the criteria that are relevant to policy makers. This article multi-criteria tool that can be applied to set priorities for health care interventions. Their incorporation allows for an efficient manner of determining the relative importance of criteria from relevant stakeholders to determine resource allocation. However, this article is pertinent as it discloses the importance of adjusting healthcare priorities to include multi-criteria decision-making tools (Baltussen & Niessen, 2006).The Netherlands applies an MCDA (multi-criteria decision analysis) approach to setting priorities for its public health care policy making. There are two cases that are discussed within the article itself, the first one ranks health problems by importance dependent on their impact on public health while the second one discussed efficiency improvements. The processes impacted policy, and the effectiveness of MCDA methodologies to set priorities for health policy was concluded. (Bota et al. 2000)

The outcome of Nobre et al. 1999, is that multi-criteria decision-making methods which incorporate fuzzy set approaches would be the ideal set of tools for the health care industry. This one incorporates TODIM, a Portuguese methodology which "the matrix *V*, representing the value judgement of the DM, is normalized across alternatives obtaining a matrix *p* criteria x *n* alternatives *W*, which is called the decision matrix…" (3347) This methodology allows for differences between decisions to be identified considering the dimensions of the decision problem according to the decision maker. This study demonstrated that priorities incurred through altered decision-making methodologies are relatively accurately weighted according to the designated decision makers. (Nobre et al. 1999) DEA (Data Envelopment Analysis) is defined as a linear programming application. Its aim is evaluating the efficiencies of similar decision-making units. The DMU's (Decision Making Units) are characterized in terms of their inputs and outputs, not their operating details. DMU considered efficient if it gets the most output from its inputs. Efficiency defined as the value of its outputs divided by the value of its inputs. The purpose is to identify efficient DMUs when there are multiple outputs and multiple inputs. There is a need to use weighting factors to produce an overall efficiency measure when the inputs and outputs are treated as multidimensional. Inputs are obtained from historical data and the weights are determine in the analysis. The efficiency measure is then the ratio of weighted outputs to weighted inputs. (Powell

& Baker, 2012)There a re criticisms for using DEA, including in the field of health care. A study that investigated the inefficiency differences in Pennsylvanian hospitals. The study used data from acute care hospitals in Pennsylvania, specifically the financial data compiled for reporting to the Health Care Cost Containment Council. It was a two-stage approach to analyse factors affecting hospital inefficiency. They incorporated the stochastic frontier technique to estimate the mean inefficiencies for the hospitals, as opposed to Data Envelopment Analysis (DEA). The article exclaims that this methodology was the first widely used frontier approach in efficiency studies of health care organizations in the United States. The Stochastic Frontier Analysis (SFA) was later widely adopted due to the criticism that DEA was unable to separate noise from inefficiency. (Rosko & Chilinerian, 1999)

There is, increasingly, health care research which incorporates DEA. The authors, Borisoz et al.,evaluated overall performance in providing health care for EU states at the regional level, in terms of technical efficiency. This study made the decision to use DEA as a diagnostic tool because of its relevance in the field of health care. It is used to measure health care efficiencies of transitioning economies and then incorporated the findings into a discussion regarding potential policy implications of the former. It demonstrated a manner of evaluating relative efficiencies of health care systems within the EU so that the most, and least, efficient systems could be identified. Those systems at the lower end of the spectrum could improve by learning from the leading EU states health care systems to correct their efforts. (Borisov et al., 2012) Nonetheless, the mathematical discrepancies have been disputed in articles like Kulakowski (2015), where the evaluation and criticism of AHP continued by addressing the consistency of this methodology. It is mathematically analyzed through theorems which correspond with potential inconsistencies present in the methodology. This includes meeting the standards of conditions of order preservation (COP). Due to this, the author presents precise criteria for determining when this standard is met. Inherently, this article explains that AHP not meeting these mathematical standards would make it an insufficient approach at turning expert judgements into priority vectors (Kulakowski, 2015). The methodology is continuously applied in different frameworks and provides positive results, such as in Li et al. (2011) where a scientific method is derived by combining AHP with qualitative and quantitative input to derive an objective judgement. A performance evaluation for University X's faculty was created. The authors provide an accurate and consistent manner of evaluating the relative performance of faculty members within a college/university setting. This index incorporation of AHP uses an unmodified methodology to complete the objectives set forth in the scope (Li et al., 2011).

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2.1 Data Envelopment Analysis

DEA (Data Envelopment Analysis) is defined as a linear programming application. Its aim is evaluating the efficiencies of similar decision-making units. The DMU's (Decision Making Units) are characterized in terms of their inputs and outputs, not their operating details. DMU considered efficient if it gets the most output from its inputs. Efficiency defined as the value of its outputs divided by the value of its inputs. The purpose is to identify efficient DMUs when there are multiple outputs and multiple inputs. There is a need to use weighting factors to produce an overall efficiency measure when the inputs and outputs are treated as multidimensional. Inputs are obtained from historical data and the weights are determine in the analysis. The efficiency measure is then the ratio of weighted outputs to weighted inputs. (Powell & Baker, 2012)

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3. Method to Developing Composite Index

The methods applied to create an internal determinant tool for industries incorporated both methodologies from the literature review. In this case, AHP was the first mathematical model that was extensively applied to different forms of indexes. Once the mathematical model and the manners in which AHP was applied to different indexes was studied, it was determined that it would be the ideal model for this work. AHP grants the model the possibility to incorporate expert individualized opinion of the hospital staff into the composite index. However, once it was determined that the model would be unable to allow hospitals to compare their efficiency relatively, a second model was to be incorporated. In this case, DEA was studied for its properties to compare the relative efficiency of units according to outputs and inputs.

The steps to recreating this composite index are outlined below. Figure 3.1: index structure demonstrates the partial composition of the hierarchy. Once the hierarchy has been formed, management should outline three random experts from staff that will fill out a single questionnaire together which will determine the relative importance for each composite. This will be the base for the pairwise comparison matrices, which will determine the priority vectors for each composite. The reasoning behind having three random experts from staff undergo a questionnaire together is that one expert alone would provide priorities specific to only one individual, where the chance of skewing the results becomes higher. Whereas, by including two additional experts they bring along a better understanding of the overall business setting. The questionnaire will ask the experts how important a composite relative to another composite at the same level of hierarchy. The rating scale for this importance is demonstrated in Table 3.1: AHP rating scale. The steps taken to develop, and successfully implement, the composite index have been outlined in Table 3.2: steps to creating composite index.

Numerical Rating	**Scale**
1	Equally important
2	Equally to moderately important
3	Moderately important
4	Moderately to strongly important
5	Strongly important
6	Strongly to very strongly important
7	Very strongly important
8	Very to extremely strongly important
9	Extremely important

Table 3.1: AHP rating scale

Once the survey is completed by the experts then the weights are calculated using AHP. The consistency ratio for each composite is determined. If a composite has a consistency ratio above 0.1 then the experts must be asked to determine relative importance for those composites that were inconsistent. Once this process is complete the data is included in the worksheet with the priorities. The data within a composite is added together to get a total amount. This total is multiplied by the weight of each portion of the single composite. This provides the most efficient number for the portion. This "perfect" efficiency number for a portion is divided by the actual number which provides a decimal number. The user must calculate the deviation from 1 to provide a percentage of efficiency for the composite. The deviation from 1 is used because to reach efficiency you want to be as close to `1, or 100%, as possible. But if you are below or above this number you have not reached efficiency. The average percentage of these efficiencies is taken to get an efficiency level for the composite. This is then repeated up to the overall efficiency composite at the highest level of the hierarchy. The final step incorporated DEA to standardize the efficiency across an industry. These steps should be taken to re-create the composite index, either for hospitals themselves, other industries or so that further research can be done into the composite indexes themselves.

4. Hospital Case

The creation, and application, of the composite index required data from a finite number of hospitals. There are six small hospital, three big hospitals, and one educational hospital where the composite index was applied. They were received through the Canadian data conglomerate, Canadian Institute for Health Information, CIHI, which is a non-profit organization that holds essential information on the Canadian healthcare system.

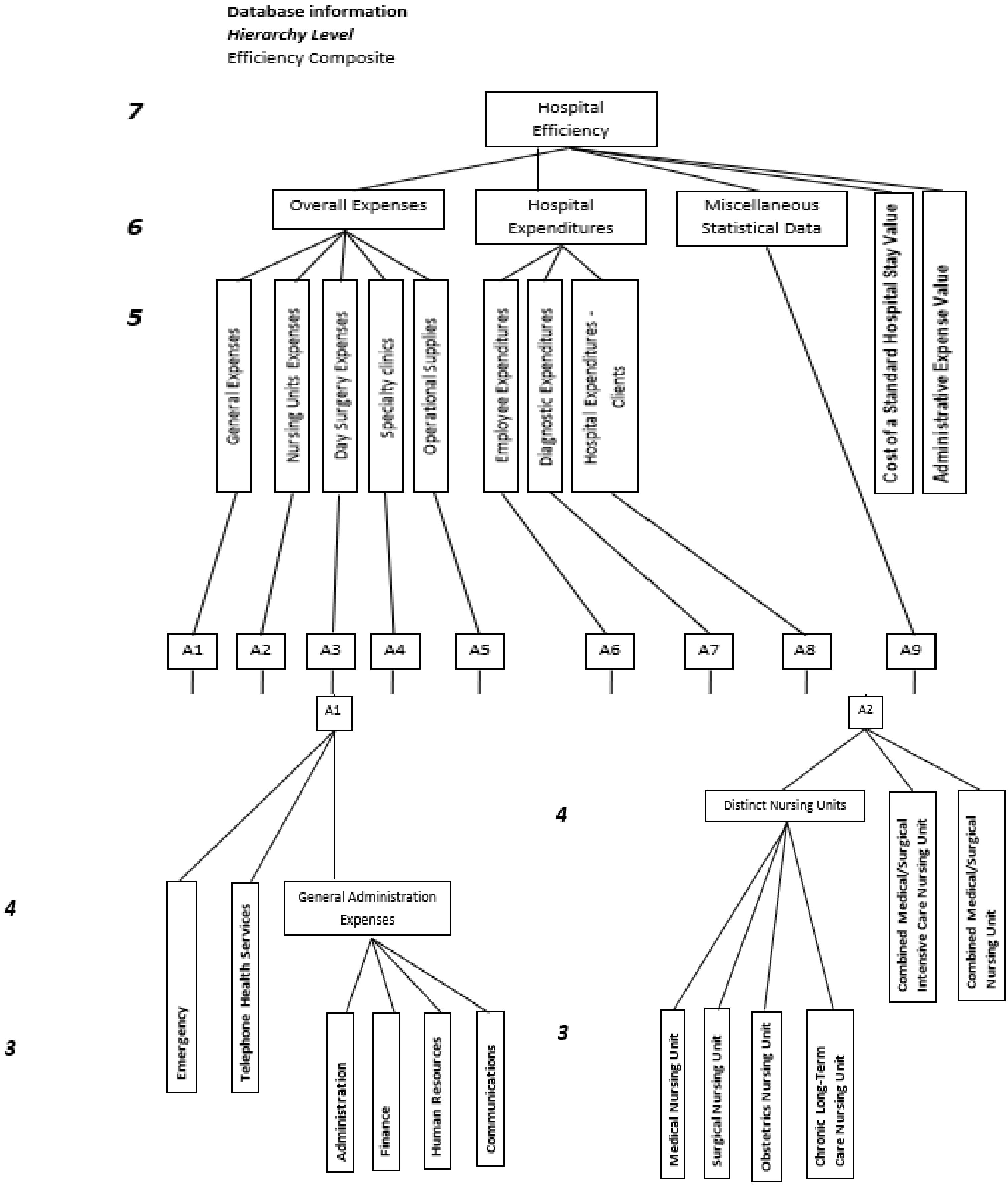

Figure 3.1: index structure

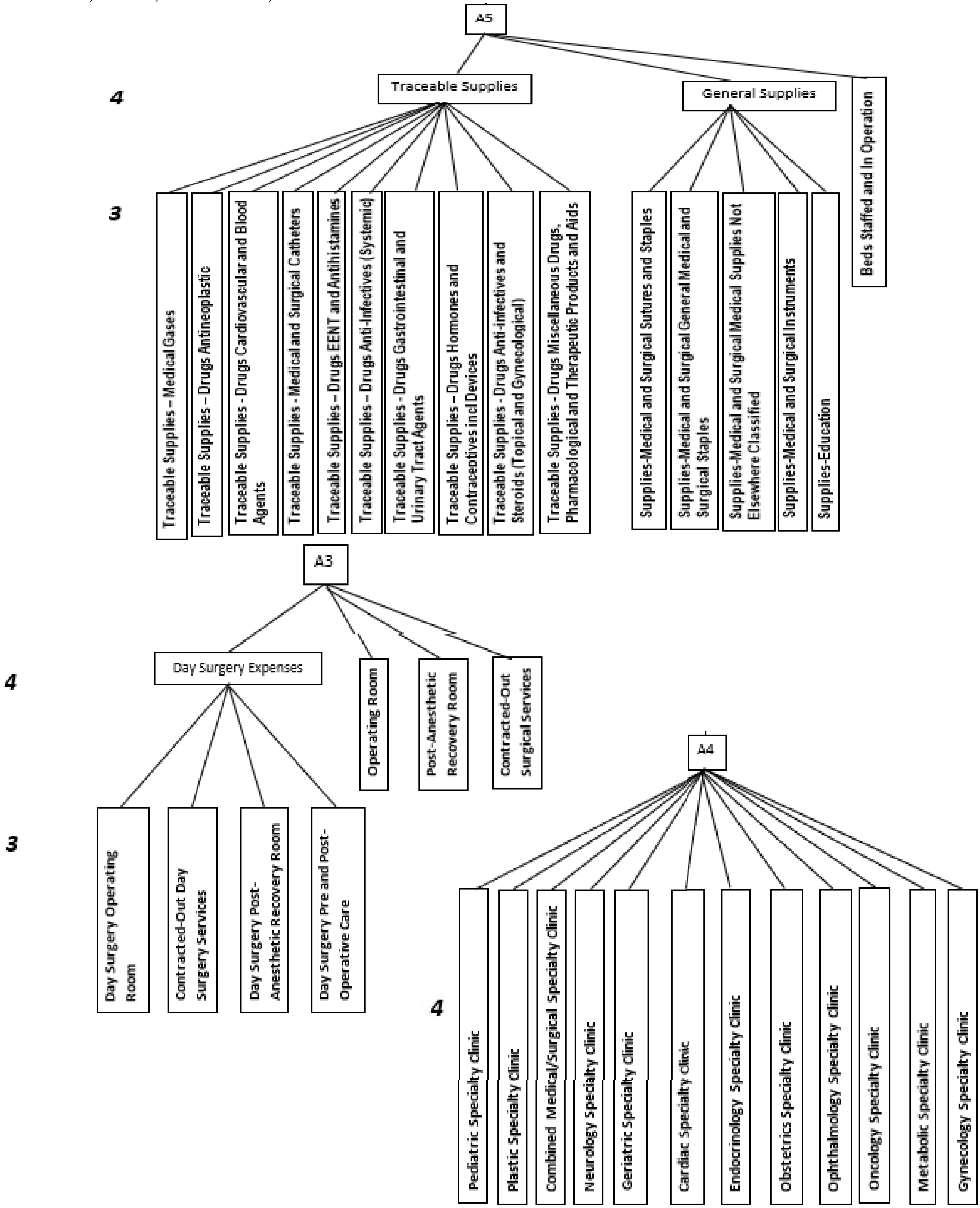

Figure 3.1: index structure

4.1 Data Background

There were one hundred and eleven indicators requested for the purpose of applying this composite index. The indicators were chosen according to the type of data that most hospital classifications would have available, as well as what would be most important to priority setting for a hospital. Under Regulation 964 Public Hospitals Act, these twenty-two different classifications for hospitals in Canada; from Group A to Group V. The classification depends on the number of beds, specific units, and its purpose. This creates a barrier in comparing hospitals as they are not all based on a standardized acute hospital with all the same departments. It is for this reason that this composite index can be incorporated in each type of classification, as portions of the composite index could be removed or added as is needed, while DEA is used to calculate the relative efficiency of the hospitals. From the total number of indicators, forty-one did not have information from any of the ten reporting hospitals. The composite index including these indicators is included in Figure 3.1: index structure.

The composite index is applied to Hospital X, the first preliminary hospital. After all the problems were solved with the original model, nine other hospitals, Hospital A through J had similar composite indexes built and run with their respective data. Hospital X is classified as a small hospital, under CIHI, according to the number of beds. Figure 4.1: level 1 setup for registered nurses shows how the composite is setup for level 1 of the hierarchy, registered nurses. It has the pairwise comparison matrix, priority vector, and consistency ratio. Figure 4.2: registered nurses composite presents the mathematical information computed for the composite.

Table 3.2: steps to creating composite index

Step 1: Review recommended composites that can be included in your composite index.
Step 2: Create hierarchy using the composites and recommended structure for the index.
Step 3: Create surveys with pairwise questions for experts.
Step 4: Survey three experts together for pairwise matrices.
Step 5: Compute the weights using the pairwise matrices, as demonstrated in AHP.
Step 6: Calculate the consistency ratio for each matrix.*
Step 7: Incorporate the data into worksheet for the composite index.
Step 8: Add your alike data for the portions of the composite together to get a total amount.
Step 9: Multiply the weight of each portion of the single composite by the total data provided for that composite to give you a perfect (most efficient) number for each portion.
Step 10: Take the most efficient number for each portion and divide it by the actual to get a decimal.
Step 11: Calculate the deviation from 1 for each portion to get the efficiency of each portion.**
Step 12: Multiply the efficiency of each portion by its respective weight to get the efficiency relative to priority.
Step 13: Sum the efficiencies relative to priority to get the overall efficiency for the composite.
Step 14: Repeat steps 8 through 13 for each composite working upwards towards overall efficiency.
*****Step 15:** Make overall efficiencies of a business in an industry available to conduct DEA so that efficiency levels can be determined relative to other businesses in the same industry.
**If the consistency ratio determines inconsistency in the pairwise matrices, above 0.1, or 10%, then conduct steps 3 through 6 for those specific composites until it is corrected.*
*** The deviation from 1is calculated by taking the first number before the decimal and dividing the decimal number by it.*
****This step can only be applied if additional businesses overall efficiency levels are made available. Either through a database or some kind of program.*

Each component of the index is set-up as demonstrated the first two figures below and calculated in the same manner. Hospital X was determined to be running at 11% efficient with the current priorities. A hospital manager can then look down the levels to see where their largest inefficiencies lie so that they can adjust their strategies to account for operational improvements in those specified areas. Hospital X has an overall efficiency of 11%, however, while this demonstrates its internal level of efficiency, it does not indicate the relative efficiency with other hospitals.

Registered				
	UP Casual	UP Part-Time	UP Full-Time	
UP Casual	1	0.25	0.25	
UP Part-Time	4	1	2	
UP Full-Time	4	0.5	1	
SUM	9	1.75	3.25	
	UP Casual	UP Part-Time	UP Full-Time	Priority
UP Casual	0.111111111	0.142857143	0.076923077	0.11029711
UP Part-Time	0.444444444	0.571428571	0.615384615	0.543752544
UP Full-Time	0.444444444	0.285714286	0.307692308	0.345950346
	UP Casual	UP Part-Time	UP Full-Time	Total
UP Casual	9.066420664	0.459767964	0.722647059	10.24883569
UP Part-Time	36.26568266	1.839071856	5.781176471	43.88593098
UP Full-Time	36.26568266	0.919535928	2.890588235	40.07580682
UP Casual	0.992673993		Lambda	3.068579569
UP Part-Time	0.951566952			
UP Full-Time	1.124338624		CI	0.034289784
			CR	0.059120318

Figure 4.1: level 1 setup for registered nurses

Figure 4.3: scaled efficiencies of Hospitals shows the relative efficiency calculated using DEA, which demonstrates that Hospital X is performing at 53.8% efficiency relative to the other nine hospitals. These internal efficiencies will differ, as they incorporate individualized priorities, and compositions of the index. Nonetheless, both efficiency values provide important information to hospital management.

	Weight	**Hours**	**Perfect Efficiency**	**Levelled**	**Deviation**	**Weighted Efficiency**
UP Casual	0.11029711	6013	30166.81115	5.01693184	0.199325012	0.021984973
UP Part-Time	0.543752544	109038	148719.0395	1.363919363	0.733181174	0.398669129
UP Full-Time	0.345950346	158454	94619.14937	0.597139544	0.597139544	0.206580632
	TOTAL	273505			**Efficiency**	63%

Figure 4.2: registered nurses composite

Finally, these ten hospitals had their relative efficiencies determined using DEA. For this study, the outputs indicated were *Administration Expense Value* and *Inpatient Discharges*, while the inputs were *Total Hospital Expenses* and *Total UPP and MOS hours.* These indicators were chosen because the composite index only incorporates statistical and administrative data. Therefore, total expenses and hours were the main inputs of the overall index, whereas for outputs, the administration value and inpatient discharges corresponded appropriately to the inputs. Once DEA is applied, the relative efficiency was calculated by setting the highest efficient hospital to 100% efficiency, and following suit with the other hospitals. In Figure 4.3: scaled efficiencies of hospitals, Hospital D is operating at the highest rate, which DEA determined to be approximately 65%. All efficiencies were then divided by Hospital D's efficiency to determine the relative efficiency once the scale was modified for the highest efficiency to be 100%.

DMU	Efficiency
Hospital X	0.538305158
Hospital A	0.499692873
Hospital B	0.389145559
Hospital C	0.65232731
Hospital D	1
Hospital E	0.365621536
Hospital F	0.542093403
Hospital G	0.754337204
Hospital H	0.72971337
Hospital I	0.184531797

Figure 4.3 scaled efficiencies of hospitals

As the example of Hospital D has shown, the hospital with the highest efficiency relative to the other hospitals becomes the one operating at 100%. The relative efficiency of hospitals is important as it demonstrates how the hospital is performing relative to other hospitals. It provides a manner of comparing the relative efficiency at which hospitals are operating. If all hospitals are operating around the same individualized level of 45% efficient, then relative to one another, it will be close to 100% efficient. But, if a specific hospital is running at 85% efficient and its relative efficiency Is at 60%, it indicates that improvements need to be made to be able to function at a similar level to other hospitals. It is a manner of standardizing the care that is provided by the healthcare industry.

5. Discussion

As a contribution to both the academic community and the workforce, this article provides a detailed guide on how to create an ameliorated method to measure efficiency. It explains the logic behind its development, the steps required to build this form of composite index, as well as a numerical example based in the health care industry. The work done can be applied to other industries and can also be programmed into software to create a program that industry can use as opposed to building themselves. The index demonstrates a manner of using multi-criteria decision-making methodology to determine inefficiencies in a hospital setting. It incorporates an individualized approach at determining priorities as localized staff determine the importance level for comparison matrices. The composite index is adjustable and therefore can be used by all hospitals, no matter the classification. Finally, the relative efficiency calculation allows for all the hospitals to be compared despite their differences in classification. In this manner, management has two important statistics, an internal efficiency level and the external relative efficiency level of the hospital. These statistics can be used to justify strategic planning, operational improvements, budget cuts, etc.

The goal of this work was not only to demonstrate the effectiveness of such a tool to determine individualized inefficiencies, but also to provide additional means for an industry to not only pinpoint their inefficiencies but to standardize them across it. In this way, a business can determine how efficient they are operating according to one another. Nonetheless, this standardization would require that the index be turned into a program that could conduct this external analysis while having the internal aspect remains with the business itself. The steps and example were included in this paper so other industries may incorporate it, as well as for future research in creating a program with the composite index already installed for easier use.

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