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Review

State of the Art Review on the Analytic Hierarchy Process and Urban Mobility

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Abstract: Cultural, economical, political, and social developments, added to population increases, favored the consolidation of cities. However, rapid city growth in the last decades has contrasted with the slowness in which states and municipalities responded to the new reality. In this sense, the analytic hierarchy process (AHP), a leading multiple criteria decision-making (MCDM) method, can be applied in the solution of common demands among municipalities, evaluating alternative plans for urban mobility. Since AHP has been applied to these specific decision problems, our research question is: How has AHP been applied to solve decision problems regarding urban mobility? The objective of this work is to identify the state of the art of AHP applications to urban mobility. To answer the research question, this paper presents a literature review (LR). State of the art review (SAR) is an LR approach expected to deliver results with medium comprehensiveness and results closer to exhaustive. With the support of graphical software, three clusters were identified, in the keywords network: AHP, Innovation & Public Management, and Urban Mobility. In the AHP cluster, research is driven by methodological subjects; on Innovation & Public Management, there is an open discussion on local *versus* national coordination; and the urban mobility cluster has hybrid or non-AHP applications of MCDM.

Keywords: AHP; literature review; state of the art review; urban mobility

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1. Introduction

The phenomenon of urbanization in the world has undergone two remarkable stages in history. The first stage started with the Industrial Revolution, at the end of the 18th century. The second stage started after World War II, in the 20th century [1]. The Industrial Revolution, among numerous changes in social and economic life, parted the places of residence and work. Then came the daily need to move people between these two places [2]. From the end of the 20th century, urbanization has resulted in serious transportation problems, especially in developing countries. Cultural, economical, political, and social developments, plus population increases, favored the consolidation of cities. However, the rapid city growth in the last decades, contrasted with the slowness in which states and municipalities responded to the new reality [3]. To make it worse, cities continued to grow, as did the mobility needs of their citizens [4].

Multiple criteria decision-making (MCDM) can be defined as the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process [5]. There are dozens of methods for MCDM [6]. The analytic hierarchy process (AHP) is a leading MCDM method [7–10].

In this sense, AHP, and other MCDM methods, can be applied for the solution of common demands among municipalities, evaluating alternative plans of urban mobility.

As a matter of fact, an abstract presented in the last International Symposium of the AHP had already noted the incipient literature on AHP and urban mobility [11]: exclusive searches on only one of these keywords ("analytic hierarchy process" *or* "urban mobility"), individually resulted more than a thousand documents in the Scopus Database. But a combined search on both keywords (with the Boolean operator *and*) resulted in only 18 documents.

Since AHP has been applied to urban mobility decision problems, our research question is: How has AHP been applied to solve decision problems regarding urban mobility? Answering that question, the main expected result is the current state of the art of AHP applications to urban mobility. The aim of this work is to deliver a state-of-the-art summary [12] of AHP applications, on this subject, from the last years. Therefore, the general objective of this work is to identify the state of the art of AHP applications to urban mobility. Specific objectives include:

- Confirm if AHP is the leading MCDM method on urban mobility.
- Describe how AHP is being applied to solve decision problems of urban mobility.
- Propose subjects for new research on AHP and urban mobility.

To answer the research question, and to attend to its objectives, this paper presents a literature review (LR) [13]. Indeed, there is a literature of LR on AHP [14–16] or MCDM [7]. There were general reviews, and even specific reviews, focusing applications of AHP and MCDM in specific subjects, as on supply chain management, for instance [8,9,17]. This work improves that literature with updated results and a focus on a previously unaddressed subject: urban mobility.

There are dozens of different LR approaches, including rapid review (RR), state of the art review (SAR), and systematic literature review (SLR), to name a few [18]. RR differs from SLR, as its name suggests, in that it requires shorter run times [19]. As the saying goes, "brevity is the soul of wit". This is the main attractiveness of RR, an LR approach consuming less time and money than SLR. However, a faster review may appear superficial, giving the impression that important sources may have been left out of the review. Therefore, SAR may present a compromised solution, not as costly as the SLR, and not as poor as the RR [20].

In addition to this Introduction, this paper has three more sections. Section 2 presents a brief introduction of AHP (Section 2.1), followed by a proposal of a four-phase method of SAR (Section 2.2). Then, phases of the SAR method are detailed indicating the use of database and software. Section 3 presents the results, phase by phase. Conclusions of this paper, and proposals for new research are presented in Section 4.

2. Methodology

In this section, the AHP [21], a method for MCDM, is introduced. Next, a four-phase method of SAR is proposed. Results of this SAR method applied in the LR of AHP on urban mobility is presented in Section 3.

2.1. Analytic Hierarchy Process

Developed in the 1970s [22], AHP is a leading MCDM method [7–10,15,16]. In addition to the many sessions dedicated to AHP at MCDM conferences, AHP is the only method with a regular event, since the 1980s at the International Symposium on the AHP (ISAHP) [23]. AHP is also the only MCDM method with an exclusive journal: the International Journal of AHP (IJAHP) [24]. IJAHP published two issues a year from 2009–2014, and it became a three-issue per year journal in 2015. These two exclusive venues support AHP to maintain its leadership as the top-applied MCDM method.

Application of most MCDM methods, including AHP, consists of three mains steps [25]:

1. Structuring: Identification of decision criteria and alternatives.
2. Measuring: Designation of weights for the criteria and scores for the alternatives.
3. Synthesizing: Synthesis of the results.

What makes one method different from another are the ways in which the steps are executed. In AHP, Step 1, Structuring, is executed with hierarchies: alternatives in the bottom level, criteria in the middle, and the decision objective at the top of the hierarchy. The assumption of the use of hierarchies are the independence among the criteria and the independence among the alternatives. Otherwise, to consider dependencies, another figure, different than hierarchy, would be required, as the networks, for instance, used in the analytic network process [26].

Step 2 is Measuring, and in AHP is executed with pairwise comparison matrices A. First, criteria are pairwise compared. Then, alternatives are pairwise compared, regarding each criterion. Weights for the criteria, and scores for the alternatives, are obtained with the normalization of the right eigenvector w of A, as in Equation (1), where $\lambda_{\max}$ is the maximum eigenvalue of A.

$$Aw = \lambda_{\max} w \tag{1}$$

Yet in Step 2, $\lambda_{\max}$ indicates the consistency of A. A consistent pairwise matrix A satisfies $a_{ij} = a_{ik}a_{kj}$, for all $i = 1, 2 \dots n$, $j = 1, 2 \dots n$, and $k = 1, 2 \dots n$, resulting in $\lambda_{\max} = n$, where n is the number of compared objects: Alternatives or criteria.

Inconsistent matrices have at least one comparison $a_{ij} \neq a_{ik}a_{kj}$, resulting $\lambda_{\max} > n$. Consistency ratio CR is a measure of inconsistency of comparisons matrices which compares the deviation $(\lambda_{\max} - n)$ to a random index RI, obtained with a simulation of 50,000 matrices computed by the Oak Ridge National Laboratory [21], as in Equation (2).

$$CR = \frac{\lambda_{\max} - n}{(n-1)RI} \tag{2}$$

It is desirable that $CR \leq 0.1$. Then, A may be accepted, meaning "conformity with previous practice" [27]. It means that there is no change of minds during the fulfilling of a pairwise comparison matrix.

In Step 3, Synthesis, overall scores for the alternatives are obtained adding scores for alternatives regarding each criterion, weighted by criteria weights. A non-mandatory procedure is the sensitivity analysis of these results [15].

The whole AHP application may be performed only with the use of spreadsheets. However, there is a variety of AHP software, including Decision Lens, Expert Choice, HIPRE, Make It Rational, PRIEST, and Super Decisions, to name but a few [15]. The development and availability of software are has been a positive trend in the growing applications of MCDM since the 1990s [7].

AHP applications are also varied on themes or subject area. The last ISAHP, for instance, received abstracts in eleven different "tracks" [23]:

1. Multi-criteria decision analysis theory and methodology.
2. Government policy and decision making.
3. Industrial and manufacturing engineering.
4. Business and innovation.
5. Healthcare decision making.
6. Ethics, social responsibility and sustainability.
7. Risk analysis and disaster management.
8. Supply chain management.
9. Information technology.
10. Entrepreneurship.
11. Applications in civil engineering and urban management.

Track 11, on civil engineering and urban management, had only one session for presentation. This was due to the low number of abstracts submitted to Track 11. None of the three abstract was on urban mobility, but, instead of this they focused on catalyst projects [28], the geographic information system (GIS) [29], and photovoltaic power plants [30]. Therefore, our abstract [11], cited in Section 1, presented in a poster session, was the only work

on urban mobility in the last ISAHP. In IJAHP there are only 18 documents with the word "urban", in abstract, keywords, title, or in the whole text. Unfortunately, almost all these documents are not on urban mobility. They are on other themes such as GIS, quality of life, sustainability, and water management. There is only one paper on urban mobility in IJAHP [31]. This is evidence that literature on AHP and urban mobility is insufficient.

2.2. Proposed Method for State of the Art Review

SAR is one of a dozen different LR approaches [32]. Compared with most common LR approaches, SAR is expected to deliver results with medium comprehensiveness and results closer to exhaustive (Figure 1).

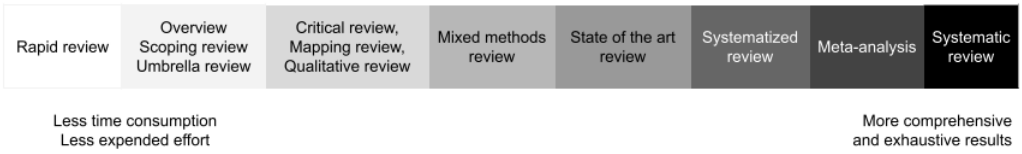

Figure 1. Comprehensiveness–exhaustiveness spectrum.

As presented in Figure 1, results from SAR are expected to be more comprehensive than critical, mapping or qualitative reviews of literature. However, results from SAR are expected to be not as exhaustive as the ones obtained with meta-analyses or with SLR. Since SAR intends to review more current works, the time span of SAR does not need to cover long periods as decades [33]. The choice for SAR is aligned with the research objectives presented in Section 1.

This paper presents a four-phase method of SAR, as in Figure 2.

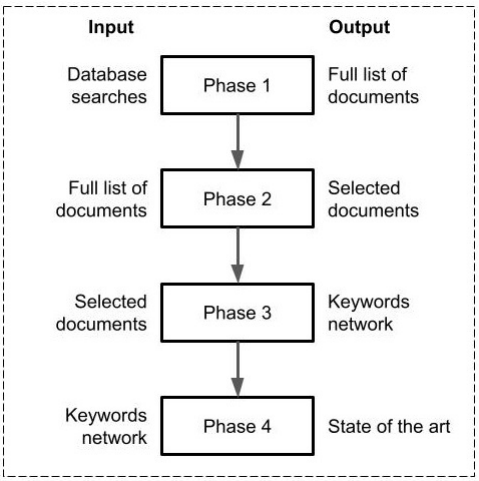

Figure 2. Proposed four-phase method of SAR.

In Phase 1, the Scopus Database (www.scopus.com, accessed from August to December 2020) was searched. Most of LR sourced the databases Clarivate's Web of Science or Elsevier's Scopus [34]. Despite both databases having similar contents, Scopus was selected for this research at first because it was free by institutional access. Despite expected similar content between Scopus and Web of Science, a second reason to exclusively search Scopus is the uniformity of search characteristics, such as search strings. Finally, the third reason to choose Scopus is its integration with the software tool used in Phase 3. Phase 1 was firstly carried out in the second half of 2020. Some results were updated one year after, as presented in Section 3.1.

In Phase 2, the documents list resulting from Phase 1 was screened to check its adherence with this work. Besides spreadsheets, no reference manager software was used. Title, abstract and keywords (TITLE-ABS-KEY) of documents were identified and manually

inserted in spreadsheets. In SAR, this procedure does not need to be formal as in SLR [35]. Therefore, Phase 2 could be performed from late 2020 to early 2021.

For Phase 3, the Software VOSViewer (www.vosviewer.com, accessed from January to June 2021) was used. VOSViewer is a software tool for literature that can be used to cluster publications and to analyze the resulting clusters [36]. Phase 3 was carried out in the first half of 2021.

Phase 4, like Phase 2, was also performed manually, without software support. This phase involved reading selected documents from Phase 2 and interpreting the clusters obtained with Phase 3. Phase 4 lasted until the second half of 2021.

Tubsections of Section 3 are numbered after the output of each phase of the proposed method of SAR.

3. Results

This section presents the results obtained with the proposed four-phase method of SAR, phase by phase, in separated subsections. Last subsection is divided in three subsubsections to clearly present our main results.

3.1. Full List of Documents

Table 1 presents results from the same TITLE-ABS-KEY searches on Scopus Database, with a time of almost one year between them.

Table 1. Total of documents resulted from searches in Scopus.

Search String	November 2020 [11]	October 2021 [37]	Increase
"analytic" *and* "hierarchy" *and* "process"	11,318	14,464	28%
"governance"	65,342	98,579	51%
"public" *and* "management"	2632	124,970	4648%
"urban" *and* "mobility"	1855	14,364	674%
Total	81,147	252,557	211%

Total documents from November 2020 increased 211% to October 2021. This increase was majorly pulled by new documents on public management. The reasons for this tremendous increase are not the subject of this work. Therefore, we will not speculate as to possible reasons for the growing number of documents on public management. An increase more than sixfold of documents on urban mobility is also highlighted in Table 1.

As presented in Table 1, the increase of documents on urban mobility is greater than AHP's. Since research results may last years for publication, this increase is not limited to research developed in the interval November 2020–October 2021.

3.2. Selected Documents

Not all 81,147 documents resulting from searches in Scopus were aligned with the scope of this work. There were documents on AHP, but not on urban mobility, and *vice versa*. For instance, the most cited document on AHP, published in the period 2015–2020, is an article on diabetes [38]. Next, it is a document on public health, and it is not a document on public management. It is definitely not a document on urban mobility.

Table 2 presents 103 selected documents with their main keywords. The use of keyword "AHP" instead of the keywords "analytic hierarchy process" is up to the journal. Some publishers adopted previous lists of keywords. However, the use of one keyword instead of another does impact data collection from databases such as Scopus. Some of the selected documents have both keywords "AHP" and "urban mobility", or "analytic hierarchy process" and "urban mobility". The Scopus database identifies one single keyword for analysis purposes. This identification was checked and confirmed with the reading of full texts, and not limited to TITLE-ABS-KEY.

Table 2. Selection of documents.

Main Keyword	Documents
Urban mobility	18
Analytic hierarchy process	17
AHP	15
Governance	14
Public management	11
Urban mobility technology	8
Smart cities	6
Sustainable urban mobility plan	6
Local productive arrangement	4
Public administration	4
Total	103

As presented in Table 2, "urban mobility" was the keyword with most selected documents. The combined keywords "urban mobility" and "urban mobility technology" had 26 documents. The combination of "AHP" with "analytic-hierarchy-process", surpassed them with 35 selected documents.

Figure 3 presents the distribution of selected documents by subject area. Documents were matched to a single area, by Scopus. Again, this identification was confirmed with the reading of full documents.

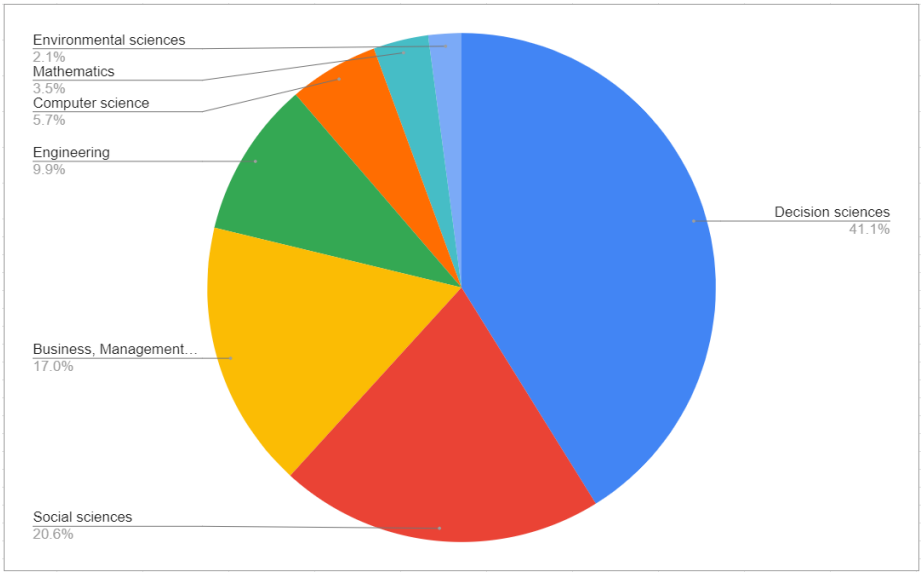

Figure 3. Distribution of documents by subject area.

The selected documents were published by journals on seven major areas, as presented in Figure 3. As was expected, Decision sciences and Business, Management and Accounting were the areas in which most of the works were published.

3.3. Networks of Keywords

Figure 4 presents a three-cluster network obtained with full-counting [36] of 16 keywords from the selected documents.

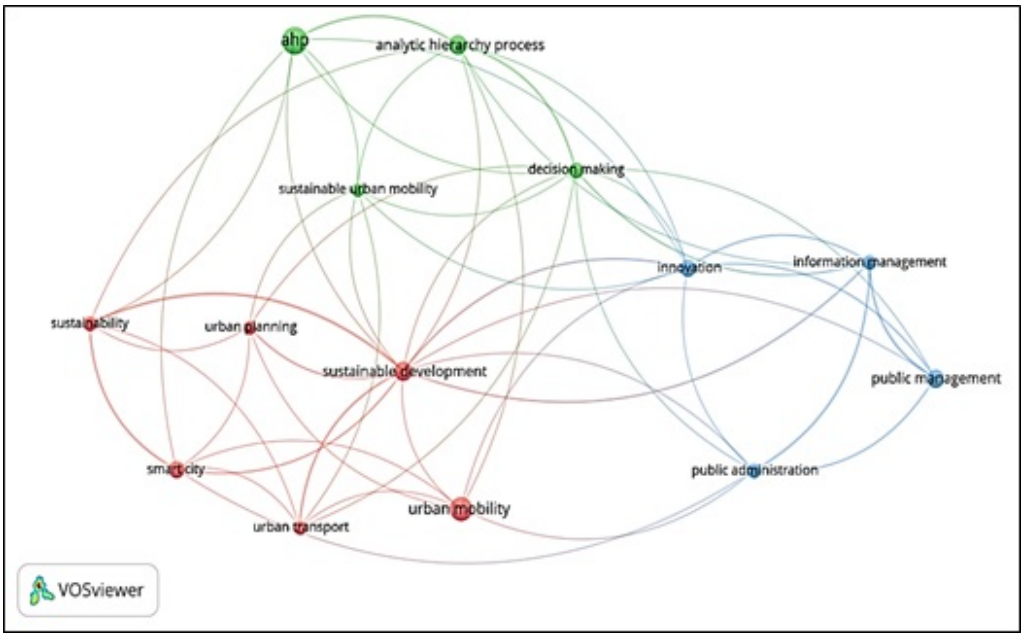

Figure 4. Keywords network (Source: www.vosviewer.com, accessed from January to June 2021).

As it can be seen, in Figure 4, the three keywords clusters are:

- Blue Cluster, with four keywords, as "innovation" and "public management".
- Green Cluster, also a four-keyword cluster, related to AHP and MCDM.
- Red Cluster, with six keywords, including "sustainability" and "urban mobility".

Visually, connections from each cluster and inside the clusters are balanced. There is no cluster with significantly less or more connections. AHP and Urban Mobility had the bigger circles, indicating that they were the most frequent keywords in the selected documents.

Sections 3.4.1–3.4.3 were numbered accordingly to clusters of keywords network.

3.4. State of the Art of AHP on Urban Mobility

3.4.1. Innovation & Public Management

From the early 21st Century, the European Union (EU) recognized that the importance of urban transportation meant that it should not be left to local governments [39]. Therefore, the development and implementation of sustainable urban mobility plans were supported at European and national levels. In Norway, under the Zero-growth goal, every growth in urban areas has to be absorbed by public transport, bicycle or walking, since 2012 [40]. Urban growth agreements were established to incentivize cooperation among local, regional and national governments.

On the other hand, London, in Europe, and Seattle, in North America, have already made efforts to steer and regulate smart mobility [41]. Conversely, both cities have set out strategic objectives on smart mobility. These objectives include long-term sustainable transport goals. The Belgian city of Ghent is another example of European efforts. Their experiments had transformed its "living streets", since 2013 [42]. These experiments, which include car sharing, cargo bikes, and communal activities, has been replicated locally in several cities in the Netherlands. Local efforts may be done by private or non-governmental organizations. In Bangalore, India, real-time information provided by mobile applications favoured the integration of mass and public transportation, aiming at last-mile connectivity. The solutions had highly perceived time savings among users [43]. The use of simulation software improved the efficiency of bus rapid transit (BRT) in the Brazilian city Sorocaba [44].

3.4.2. Analytic Hierarchy Process

Most of the selected documents presented pure AHP applications. Some documents presented combined AHP applications with other MCDM methods, such as the Data Envelopment Analysis (DEA) and the Technique of Order Preference Similarity to the Ideal Solution (TOPSIS).

A case study from Greece addressed the digital transformation of a local government [45]. The case involved a little explored area by local authorities, with slow adoption of technology. Most efforts were performed by the Greek central government. Another pure AHP application was presented in a case of partners selected for strategic alliances for innovation in India [46]. AHP was solely applied to measure the "liveability" of cities, in a Malaysian case [47]. That study started as the revival of a seminal AHP study on urban planning [48]. However, this newer study presented an incomplete hierarchy, i.e., without alternatives, and only had criteria and sub-criteria.

Sustainability's three Es (economically prosperous, environmentally sustainable and equally social) were decomposed in an MCDM model proposed for the analysis of smart cities [49]. This proposal included the integration of AHP and Fuzzy Sets Theory (FST).

Logistics and manufacturing are two top areas of AHP–DEA combined applications, according to an 2000–2019 LR [50]. The majority of 82 documents in that LR presented AHP–DEA applications without the integration of other approaches, such as the FST. Despite the extensive list, reviewers considered that "there is still space for AHP–DEA approaches, mainly in new-trend areas as green initiatives and corporate social responsability".

3.4.3. Urban Mobility

In Turkey, a major urban renewal movement shall renew eight million homes by 2040. Then, AHP was applied to the consideration of the identification of the weights of economic, environmental, and social factors of sustainability of urban areas. 323 professionals and 60 academics were consulted with AHP questionnaires, resulting in a guide for a wide range of urban renewal stakeholders, including local governments, citizens, contractors, architects, engineers, and urban planners [51].

AHP and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), another MCDM method, was combined to evaluate sustainable urban mobility scenarios by active stakeholder participation [52]. This AHP–PROMETHEE combined application refers to the case of Leuven, another Belgian city. The usage of an electronic group decision support system was considered a key factor for the success of this case study. AHP was applied to weight criteria and PROMETHEE to evaluate alternative scenarios.

A different mode to urban mobility, the Pedestrian Corridor (PC), offers a sustainable and environmentally friendly alternative to vehicular use. A well-designed and maintained pedestrian corridor can reduce vehicular use and encourage walking, which is beneficial for the environment and for the public health. AHP was solely applied to evaluate four alternate PCs in Union County, Pennsylvania [53].

4. Discussion and Conclusions

This final section is divided into four subsections, separating results discussions, practical implications, objectives achievement, and proposal of themes for future works.

4.1. Results Discussion

With the proposed four-phase method of SAR, presented in Section 2, it was possible to obtain the results, previously presented in Section 3. The first main result is that efforts for urban mobility do not have to be coordinated by national or regional governments. Despite EU concerns, there are also successful urban mobility innovation cases in America (Seattle, in the Unites States, and Sorocaba, Brazil), Europe (Ghent and Leuven, Belgium, and London, England), and Asia (Bangalore, India). On the other hand, there are countries with

well-integrated initiatives coordinated by national governments, as in Greece, Malaysia, and Norway.

AHP was both used solely or combined with MCDM methods. Combination or hybridism of MCDM methods is a trend in MCDM. In the joint literature of AHP,urban-mobility it is not a very well explored theme. For instance, only traditional MCDM methods as DEA, PROMETHEE, and TOPSIS have benn applied with AHP. Newer methods as Complex Proportional Assessment (COPRAS), the Full Consistency Method (FUCOM) and Step-wise Weights Assessment Ratio Analysis (SWARA) are not applied yet. At least, there is no publication with COPRAS, FUCOM or SWARA on urban mobility, in Scopus Database.

Sustainability's three Es is a model to identify criteria for MCDM analysis of urban mobility. Other models include Benefits–Opportunities–Costs–Risks (BOCR), Balanced Scorecard (BSC) or Mutually-exclusive-Collective-exhaustive (MECE). These AHP techniques for MCDM structuring maybe also useful for future research.

4.2. Practical Implications

Although aiming to deliver a state of the art review (SAR) of AHP applied to urban mobility, this paper presents practical implications on literature review (LR) for AHP researchers and also for urban mobility researchers. A systematic literature review (SLR) is perhaps the most common approach to LR. SAR is a newer approach with the advantage of being more quick, more simple, and less complex than SLR. The main disadvantage of SAR compared to SLR is its less exhaustive results.

SAR procedures are also less formal than the SLR. In practice, SAR application may be subject to the subjective judgments of researchers, for example, in the refinement of documents lists. This means that SAR applications do not require a formal protocol to be followed by more than one researcher.

This paper presented partial results of an ongoing major study on urban mobility. Results presented in this paper were very welcome for that major research. Therefore, the choice for SAR proved to be a good choice, in this case.

In conclusion, initially researchers have to decide what is a better fit to their research: a detailed, exhaustive, and formal literature review (with SLR) or a simple and quick review (with SAR). There will be research that is proper to SAR. And there will researcthat iss proper to SLR. Each case is different. This work presented a new approach for those who need the SAR, but only know the SLR.

4.3. Achievement of Proposed Objectives

The general objective of this work was to identify the state of the art of AHP applications to urban mobility. This objective was achieved with application of the four-phase proposed method of SAR. It is important to note that the objective was not to present an exhaustive and systematic review of the literature.

The first specific objective was to confirm if AHP is the leading MCDM method, also in terms of urban mobility. The achievement of this objective was aborted with the development of the SAR. This was due to the focus on AHP method, which is part of the major research cited in the last subsection. AHP is an MCDM method that fits properly in that research. The achievement of this specific objective may be subject of further research.

The second specific objective was to describe how AHP is being applied to solve decision problems of urban mobility. This was achieved with application of the four-phase method of SAR presented in this paper. Not only *how* AHP is being applied, but also *where* AHP is being applied was presented in Section 3.

The last specific objective was to propose subjects for new research on AHP and urban mobility. This objective was achieved, as presented in next subsection.

4.4. Themes for New Researches

The first theme for future research is to compare advantages and limitations of both models: city-based urban mobility development *versus* nation-based or regional-based urban mobility developments. "May the two models coexist?" is another question for future research. And AHP is a very suitable MCDM method to support this comparison.

One main result from this paper is the highlighting of AHP when either solely applied or combined with other traditional MCDM methods. The combination of AHP with newer MCDM methods application to urban mobility is a second theme for future research. For instance, FUCOM or SWARA may be combined with AHP in Step 2, Measuring (Section 2.1); COPRAS may be combined in Step 3, Synthesis (Section 2.1).

During the development of this research, the achievement of a specific objective was aborted: the confirmation as to whether AHP is also a leading MCDM method on urban mobility. As AHP is a leading MCDM in general, AHP also may lead to publication on urban mobility. This could be verified with bibliometrics or rapid reviews (RR).

At last, but not least, AHP may be useful to elucidate if there are proper alternatives to urban mobility to a specific situation. For instance, whether BRT is more suitable than PC for a more dense urban area under predetermined environmental or social limitations. This sounds like an interest problem to be solved with MCDM. From the areas explored in this paper, it is clear that case studies on MCDM applied to urban mobility is a promising idea for future research.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
BOCR	Benefits–Opportunities–Costs–Risks
BRT	Bus rapid transit
BSC	Balanced Scorecard
COPRAS	Complex Proportional Assessment
DEA	Data Envelopment Analysis

EU	European Union
FST	Fuzzy Sets Theory
FUCOM	Full Consistency Method
GIS	Geographic information system
IJAHP	International Journal of the Analytic Hierarchy Process
ISAHP	International Symposium on the Analytic Hierarchy Process
LR	Literature Review
MECE	Mutualy exclusive and collective exhaustive
MCDM	Multiple criteria decision-making
PC	Pedestrian corridor
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
RR	Rapid review
SAR	State of the art review
SLR	Systematic literature review
SWARA	Step-wise Weights Assessment Ratio Analysis
TITLE-ABS-KEY	Title, abstract and keywords
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution

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