Hybrid Recommender Systems:
The Review of State-of-the-Art Research
and Applications

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Abstract—**To date, recommender systems are a popular instrument to make personalized suggestions and provide information about items for users. There are many techniques that can be applied for personalization in recommender systems. All these techniques have complementary strengths and weaknesses. A hybrid recommender system combines two or more recommendation techniques to gain better system performance and mitigate the weaknesses of individual ones. Classification of hybrid recommender systems used in this paper is based on the classification proposed by Burke [1]. The need of a systematic review in the area arises from the requirement to summarize all the information about actual methods and algorithms that are used in hybrid recommended system. These materials will be used to support further research activities aiming to develop the auto-switching hybrid recommender system.**

I. INTRODUCTION

Recommender systems (RS) is a tool that suggests items that are useful to a particular user. They have become fundamental applications in electronic commerce and information access. To date, different techniques and different methods are used to perform recommendation. The most known classification includes content-based, collaborative, knowledge-based techniques [2]. Different methods are combined in hybrid recommenders to optimize the prediction quality and resolve the bottlenecks of individual techniques.

Consequently, it is meaningful to classify the research papers according to data mining techniques. Classification of hybrid recommender systems, used in this paper, is based on Burke's classification of hybridization methods [1]. There are different strategies by which hybridization can be achieved and they are broadly classified into seven categories:

- Weighted – *implementing different methods separately and then combining their predictions.*

- Switching – *certain switching criterion is used by the system to interchange between two recommender systems operating on the same object.*

- Feature Combination – *features from different recommender systems data sources are put into a single recommendation algorithm.*

- Cascading – *one recommender system refines the results given by another.*

- Feature Augmentation – *the output of one system is used as an input feature to another; for example, using the model generated by one to generate features that are used by another.*

- Meta Level – *a model learned by one recommendation is used as input to another. Its difference from Feature Augmentation is that the entire model is used as input.*

- Mixed – *incorporates two or more techniques at the same time, e.g.: Content-based and Collaborative Filtering.*

The topic of hybrid methods is still quite actual, therefore, the purpose of this paper is to examine the state-of-the-art directions of their applications and research in this field to obtain information about the most common and "popular" methods of hybridization in recommender systems as well as to identify methods that lack attention of the community.

This paper surveys the background of actual hybrid recommenders through a review of actual work to:

- evaluate and interpret all available research relevant to a particular research question;

- find some pattern or phenomenon of interest, to present a fair evaluation of a research topic;

- discuss what metrics are usually used to compare recommender algorithms.

This report covers three phases of a literature review: planning the review, conducting the review and reporting the review. It is organized as follows: Section 2 describes the review process. Section 3 reports the review results. Section 4 summarizes the research results.

II. RESEARCH PROCESS

The main objective is to summarize all actual base of theoretical and practical experiments in area of implementation and development of hybrid recommender

TABLE I. SUMMARY OF RELEVANT REVIEW PAPERS ON HYBRID RECOMMENDER SYSTEM

Title	Author(s)	Abstract
Short systematic review on e-learning recommender system.[69]	W.M. Chughtai, A.B. Selama, Imran Ghani	This paper reviews the landscapes of current state-of-art recommender systems in e-learning environment. This paper is limited to discuss four types of filtering approaches, their benefits, limitations and cold-start problem with respect to recommender systems. The review of domain and previous research improvement provide timely and useful insight about recommender systems and cold-start issue in e-learning recommender system domain.
A systematic review of scholar context-aware recommender systems [70]	Zohreh Dehghani Champiria, Seyed Reza Shahamirib, Siti Salwah Binti Salima,	The paper provides a review the relevant articles in the field of scholar recommendations, explore contextual information influential in scholar recommendations, examine recommending approaches. This review has been conducted to identify the contextual information and methods used for making recommendations in digital libraries as well as the way researchers understood and used relevant contextual information from the years 2001 to 2013 based on the Kitchenham systematic review methodology. The results indicated that contextual information incorporated into recommendations can be categorised into three contexts, namely users' context, document's context, and environment context. Researchers have understood and exploited relevant contextual information through four ways, including citation of past studies, citation of past definitions, self-definitions, and field-query researches; however, citation of the past studies has been the most popular method.
Recommender System: Review[71]	Akshita, Smita	This paper discuss various techniques proposed for recommendations including content based, collaborative based and other techniques. To improve performance, these methods have sometimes been combined in hybrid recommenders. It also discuss about growing area of research in the area of recommender systems that is mobile recommender systems.
A literature review and classification of recommender systems research [74]	Deuk Hee Park, Hyea Kyeong Kim, Il Young Choi, Jae Kyeong Kim	210 articles on recommender systems from 46 journals published between 2001 and 2010 are reviewed. These articles are categorized into eight application fields (books, documents, images, movie, music, shopping, TV programs, and others) and eight data mining techniques (association rule, clustering, decision tree, k-nearest neighbor, link analysis, neural network, regression, and other heuristic methods). Research provides information about trends in recommender systems research by examining the publication years of the articles, and provides practitioners and researchers with insight and future direction on recommender systems.
Systematic Review of Linked Data-based Recommender Systems [73]	Cristhian Figueroa, Iacopo Vagliano, Oscar Rodríguez Rocha, Maurizio Morisio	This paper presents a systematic literature review to summarize the state of the art in recommender systems that use structured data published as Linked Data for providing recommendations of items from diverse domains. It considers the most relevant research problems addressed and classifies RS according to how Linked Data has been used to provide recommendations. Furthermore, it analyzes contributions, limitations, application domains, evaluation techniques, and directions proposed for future research.
User and Context Information in Context-Aware Recommender Systems [72]	Sergio Inzunza, Reyes Juárez-Ramírez, Alan Ramírez-Noriega	A Systematic Literature Review- This paper present a review conducted to identify what user's and context's information it's considered relevant by researchers to generate contextual recommendations from 2012 to 2015, based on Kitchenham systematic literature review methodology. The results indicated that there is a large set of possible user's and context's information that can be used to do recommendations. This review can be taken as basis for future context-aware recommender systems development, as well as development of contextual user models.
The Use of Machine Learning Algorithms in Recommender Systems [68]	Ivens Portugal, Paulo Alencar, Donald Cowan	A Systematic Review - This paper presents a systematic review of the literature that analyzes the use of machine learning algorithms in recommender systems and identifies research opportunities for software engineering research. The study concludes that Bayesian and decision tree algorithms are widely used in recommender systems because of their relative simplicity, and that requirement and design phases of recommender system development appear to offer opportunities for further research.

systems (HRS). To plan the research, we defined the list of research questions:

- Which are the actual statements of the field of hybrid recommender systems?

- What types of hybrid recommender systems are presented? Do they still fit the classification schema proposed in [1] despite the fact that almost 10 years passed since publication of that paper?

- What kind of input data is usually used in RS?

During research, we used the ScienceDirect – search interface for journals and books from Elsevier. It is one of the world's premier publishers in science, technology, proceedings of the ACM Recommender Systems Conference (RecSys) – a leading conference "mainly focused" on recommender systems, and IEEE Xplore Digital Library – a powerful resource, delivering full text access to the scientific highest quality technical literature in engineering and technology.

To identify the keywords, we found some relevant topics and defined the relevant words that could be used to describe the topic: "hybrid recommender system", "combining techniques", "recommender system".

From a more general viewpoint, the following papers were included:

- The subject of the paper is recommender system algorithms and their combination (not an integration of the RS with different resources) and the problem of input information interpretation.

- Articles on the topics, published during last 5 years.

The following papers were excluded:

- Informal literature surveys (no defined research questions, no search process, no defined data extraction or data analysis process).

- The researches connected with integration of RS with different resources.

The ScienceDirect database search for query "(Hybrid recommender systems)" gave 678 results; to narrow the search, we used the query "(Hybrid recommender system) and ABSTRACT(combination) AND LIMIT-TO(year, "2017,2016,2015,2014,2013")" that gave 31 results. The second query "(TITLE-ABSTR-KEY (hybrid recommender systems) and TITLE-ABSTR-KEY(combining techniques)" gave 12 more results.

Searching through the RecSys conference materials, we used programs of the last conferences to find topic which included the keyword "Hybrid recommender systems", after the 2013 the all topics in the section «Hybrid recommender systems and cold start problem» was included; that gave 16 additional papers.

In the IEEE Xplore Digital library source we searched for documents containing "hybrid recommender system" in title and published in 2012-2017, that gave 38 papers. This query was narrow enough, so we decided to learn all of them.

After initial screening, according to the defined criteria and information from abstracts, we left 64 papers of 93 for thorough examination.

In addition, to analyze the need of research, we have found several review papers dedicated to recommender systems in the television domain, scholar context-aware recommender systems, network-based recommendation algorithms etc. None of these reviews considered the field of the hybrid recommender systems or the question of their actual classification. The most appropriate reviews of search are summarized in the Table I.

The papers presented in the table argue the actuality of the review, demand to analyze the area of hybrid recommended system, summarize all information about existing methods and algorithms, used in recommended system.

The main aim of this review is to draw more general conclusions about lack of researches in the area of hybrid recommended systems. These materials will be taken as a prelude to further research activities.

III. REVIEW RESULTS

A. Distribution by year of publication

The research papers analysis by year of publication demonstrate that publications related to recommender systems steadily increased in 2013 and 2016. The amount of research papers decrease due to the development of mobile technologies that have began to be used everywhere and recommender systems research apparently extended a new application field.

B. Application area

Distrubution of papers among application areas is shown in Fig. 1. The main application area of the hybrid recommender

systems is e-commerce, but a lot of papers didn't have any specialization and could be used in different cases. While learning the purposes of recommender systems, we found, that 53% of papers present novel approaches for developing hybrid recommender systems, the other papers are dedicated to the implementation of HRS in some specific areas or for some specific resources, like for example Foursquare[23].
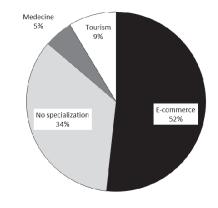

Fig. 1. The scope of the hybrid recommender system

C. Hybridization techniques

69% of HRS are Weighted according to the Burke's classification, i.e. resulting list of recommendations is calculated by the weighted formula, 16% are based on Feature Combination, several HRS employ Cascading and 2 systems are Switching.

Paper [19] presents a new Inferential Ontology-based Semantic Similarity (IOBSS) measure to evaluate semantic similarity between items in a specific domain of interest by taking into account their explicit hierarchical relationships, shared attributes and implicit relationships. Further, the paper proposes a hybrid semantic enhanced recommendation approach by combining the new IOBSS measure and the standard item-based Collaborative Filtering approach.

Another paper [10] presents the results of learning the influence of the different types of information to the item recommendation. Author defines that tags, social contacts, and user-item interaction data – are more effective to achieve useful recommendations. Aiming to determine whether and how combining such information sources may enhance over individual recommendation approaches. Analyzing the obtained results, the authors of [10] conclude that exploiting social tagging information by content-based recommenders offers high coverage and novelty, and combining social networking and collaborative filtering information by hybrid recommenders provides high diversity. Different approaches – content-based, collaborative filtering, and social – have low overlap and relative diversity values between them, which leads to the conclusion that meta-hybrid recommenders combining the above strategies may provide valuable, balanced item suggestions in terms of performance and non-performance metrics, for different contexts depending on the needed level of personalization.

The literature research allowed to find only 2 papers, connected to these type of hybrid recommender paper: first one [13] proposes a switching hybrid algorithm that combines the conjectured strengths of content-base (CB) and demographics-based (DB) techniques. System uses content-based technique, when it is requested to predict a rating for a new item, while it uses demographics-based technique, when predicting a rating for a new user or a new contextual situation. Second paper [6] propose a method to combine the estimated relevance for a resource along with its quality. In order to generate recommendations they use the switched algorithm (between content-based approach and collaborative filtrating (CF) approach) that depend on the results of matching similarity measures among vectors. Particularly, they use the standard cosine similarity measure, but define it in a linguistic context.
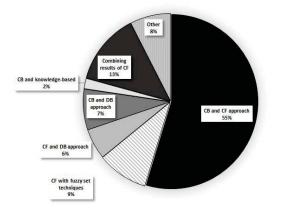

Fig. 2. Types of hybrid recommender system

The bottlenecks of the Burke classification of recommender systems consist in the lack of the type for systems, that use different algorithms of recommendations, but all of them have the same type. Authors define their systems as a hybrid, but, for example, the hybrid recommender system proposed in [33] is based on the computing the Relative Feature Frequency and the Modified relative Feature frequency, then computing all the user and all the features for the Relative Feature Score. The hybrid system computes the similarity in preference and the similarity in opinion using different algorithms. According to Burke's classification this system can be classified as belonging to a Cascading type, or couldn´t be a hybrid recommender system at all.

D. Evaluation

While analyzing the approaches to evaluate systems in presented papers, we found, that the most popular metric to evaluate the results of recommendation is Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) (Fig 3).

Learning of papers gives us the answers to the research questions.

E. Algorithm combination to hybrid recommender systems work

The most popular combination was the collaborative techniques and the different type of the content based methods. Popular are the fuzzy-based personalized recommender systems, for example [2], for ANFIS to extract knowledge (fuzzy rules) from users' ratings and preferences on items' features. In this paper, they use fuzzy techniques to handle vagueness, uncertainty, and fuzziness, and to model humans' behavioral complexity in expressing their opinions.
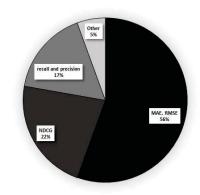

Fig. 3. The metrics to evaluate recommender system

Analizing the algorithms, that are used for hibridization, we discovered, that the most useful combination is the Content-based and collaborative approach (55%), actual algorithm to date are the set of fuzzy techniques (Fig 4).
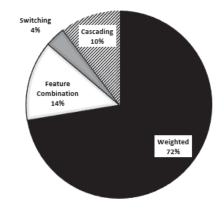

Fig. 4. Algorithms of hybridization

F. Input data

The most popular input date is the information about users' preferences and item features. But, to date, all available information, all types of data, are used.

Some systems work with demographic information of users and ontological item-based semantic information, others with geolocation data, frequency of tags applied to item, content (items), annotated with freely chosen words (tags) (the

whole set of tags constitutes an unstructured collaborative classification scheme that is commonly known as folksonomy), RDF Dataset, Facebook API to support re-rating of profile items through an array of sliders, Wikipedia, Facebook and Twitter [2],[19],[34],[62],[21].

One of the most actual and complex combination of the input data is presented in the paper [53], a system algorithm that works with Airbnb dataset. Accommodation reviews, descriptions and images, available on the website, are the major factors that are collected through a web crawler program, the review scores are used as a reference to filter out the low quality accommodation prior to the implementation of the proposed recommender system.

The most interesting discovery is Environment External Connector [5]. This connector is responsible for converting the data from the external environment into useful information for the proposed by the authors system called Invenire. Thus, Invenire can abstract representations of the types of information from different data sources.

The second discovery is the algorithm, that computes the accumulated Mean Absolute Error (MAE), Root Mean Squared Error (RMSE) and correlation for each technique. The accumulated values of RMSE for techniques are used to compose the fitness function that is used to evaluate the results. To compute the accumulated RMSE for each technique the proposed algorithm produces a matrix for each user. Predictions are generated for user using some technique applied over the matrix. Thus, the sum of these components guide the algorithm through search space.

V. CONCLUSION

In this paper we presented the results of researching the most common and "popular" methods of hybridization systems. We summarized the state-of-the-art recommendation methods and tried to determine their type, according to algorithmic principles and Burke classification.

We showed that hybrid recommender systems are still popular and are used for different problem solutions. We also learned the types of the input date, different logic of work, types of evaluation.

The vast majority of presented papers comply with Burke's classification of the hybrid recommender systems, but we also found the bottlenecks in classification. The problem is in the comparing the systems, that use the different algorithms of recommendations, but in the same time have one type (for example, different algorithms are combined as a part of Content-based recommender system). According to the same paper of Burke [1], hybrid recommender systems combine two or more recommendation techniques to gain better performance with fewer of the drawbacks of any individual one. This definition doesn't give us the answer how we can define the systems with different algorithms within one type. If we decide, that such systems are hybrid, we can define the systems as «Cascading».

There are different concepts in order to combine such recommendation algorithms in an efficient way, but contrary

to the area of weighted HRS, the question of switching hybrid approaches is still actual. In future work, the number of sources will be extended to obtain more information.

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