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Evaluation of spatio-temporal forecasting methods in various smart city applications

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ABSTRACT

Together with the increasing population and urbanization, cities have started to face challenges that hinder their socio-economic and sustainable development. The concept of smart cities, therefore, has emerged during the last years as a response to these problems. Advanced measurement and communication technologies enabled through smart cities have particularly played a key role in dealing with such economic, social and organizational challenges faced during the growing of cities. In this sense, using historical information provided with the mentioned technologies, various forecasting tools have been incorporated into smart city environment in order to manage more effectively its essential components such as smart grids and Intelligent Transportation Systems (ITS). For a further improvement in forecasting accuracy and hence in the management of these smart systems, recently, the information available in space has been also introduced in forecasting tools in addition to that in time. These advanced forecasting approaches, called *spatio-temporal* methods, have the capability of making use of all the available data collected from different locations. The potential benefits of these approaches have been underlined in various recent studies in the literature. In this paper, a comprehensive overview and assessment of forecasting approaches including both spatial and temporal information have been presented for the purpose of supporting the ongoing efforts for exploiting the available information in smart city applications. With this objective, the spatio-temporal forecasting methods presented in the literature are classified considering their implementation areas and model structures. Furthermore, the similarities and peculiarities of the methods classified are examined in detail, resulted in the compiling of valuable reference information for future studies on improving these approaches.

1. Introduction

A gradual increase has been occurring in the amount of people living in urban areas at the last decades due to various opportunities of large cities including better jobs with higher salaries, better education particularly at university level, wider social environments and higher living standards. According to the latest United Nations report, the population in urban areas, which is about 4 billion today, is expected to surpass 6.5 billion by 2050, resulting an increase of 12% in the proportion living in urban areas [1]. The increasing of the population and urbanization in metropolises and even growing cities, therefore, complicates the satisfaction of the fundamental needs of the people in these regions, such as housing, utilities (water, electricity and gas), medical care, welfare, education and employment.

In order to deal with such economic, social and organizational challenges to be faced during the growing of cities, a wide range of studies and projects has been presented during the last decades. These investigations have particularly focused on the applications of various smart systems in cities for the purpose of alleviating the impacts of the mentioned problems. For a specific example, advanced measurement, communication and control technologies have significantly contributed to providing and using of clean water, electricity and gas in a more effective way. Furthermore, the applications on Intelligent Transportation Systems (ITS) have decreased the time wasted in traffic and thereby reduced the corresponding carbon emissions. Besides, the efficiency of electric power systems has been increased and the integration of renewable energy sources to these systems has been facilitated, together with the studies on smart grids. The comfort level of households in residential houses has been also considerably improved thanks to the advancement in smart home technology. All these smart systems and more have reached their targets to some extent and contributed to more livable environments providing also many new opportunities to people in order to meet their requirements in an easier and quicker way. For the purpose of further exploiting the superior features of the smart systems in a feasible and sustainable way, all these independent smart systems need to be integrated in the context of a

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comprehensive framework.

With this objective, the concept of Smart City has been envisioned in the last years. A smart city has been generally defined as a developed urban area that uses Information and Communication Technologies (ICT), human capital and social capital in order to promote sustainable socio-economic growth and a high quality of life. Among the essential components of smart cities, forecasting is of significant importance since the efficient operation of smart systems is generally based on the knowledge about the plausible future conditions of these systems. It is well-known that high-accuracy renewable energy generation forecasts can allow further exploitation of renewable sources and electric load demand forecasts help the energy generation and consumption balance maintain at a minimum cost in electrical grids. More accurate forecasts both on supply side (solar and wind power) and demand side (electric load) can help power system operations and are particularly of great importance for smart grid technologies, such as Distributed Generation (DG) and Demand Response [2,3]. Besides, the forecasts of various traffic characteristics such as traffic flow and speed can minimize the effects of congestion, delay, security and environmental problems on the transportation network by using this information in intelligent traffic management. Furthermore, the forecasts of traffic characteristics might contribute to the smart energy management within smart cities as the relevant results can be utilized for better managing of the charging operations of (EVs) and even in the use of EVs as mobile storage units via Vehicle-to-Grid (V2G) technologies.

Considering the benefits of forecasts for the mentioned areas, a large number of studies on the development and application of forecasting approaches has been presented in the literature. These studies generally adopt two kinds of modelling approaches: (i) physical models that consider the mathematical description of the physical processes for the forecasts of the related variable, and (ii) statistical models that take historical data into account in order to estimate the future values. The latter approach is generally more effective in modelling the time-varying conditions in short terms and therefore provides better forecasting results up to one or two days. It can be therefore indicated that statistical approaches are more appropriate for the dynamic management of smart systems.

The statistical approaches have generally achieved reasonable forecasting results in the literature using different models such as Autoregressive (AR)-based models and machine learning methods. In order to increase the accuracy of forecasts, particularly for the longer prediction horizons, combined or hybrid models that integrate two or more models with a forecasting model for the purpose of a higher accuracy have shown significant achievement in the last decades. Taking advantage of different models can generally enable to accomplish a higher forecasting performance compared to that of single models. It can be indicated that these models can reach the possible highest accuracy level with the existing input data set; however, for a further improvement in forecasting accuracy, it is obvious that new input data are required to be included in the models. With this objective, the models that exploit all the available time series data from different locations have gained increasing interest in the last decade. The advanced measurement and communication tools, which have been recently available widely thanks to smart cities, have also contributed to development of these models by enabling the procurement and transferring of detailed data from different sources in a wide area.

These methods, called *spatio-temporal* models, combine two different forecasting approaches: (i) temporal modelling in which the expected future values are forecasted using the historical data from exactly same point, and (ii) spatial modelling in which the data are imputed at sites where no information is available. These models, therefore, consider the spatio-temporal interdependence structure in an area of interest instead of focusing on the data from only one point. The underlying idea behind these models is that the effects of a phenomenon at a given point in a system (meteorological system, traffic system, etc.) might propagate to nearby locations during a certain period due to the inertia of these systems. In other words, any information from a different location has a potential to contribute to the modelling of a target variable at a certain point. In general it is considered in the concept of these models that the data highly-correlated with the target variable will have a favorable impact on forecasting accuracy. The studies in the literature of spatio-temporal forecasting are, therefore, mostly focused on the determination of the most informative input data among a set of candidate variables from a variety of measurement sites. In addition to an improvement in forecasting accuracy, this selection process also decreases the computational times caused by such excessive data.

In this paper, the spatio-temporal forecasting methods that can be used in a smart city context are investigated in terms of their model structures, main features and peculiarities. For the purpose of examining the applications of these methods in detail, the methods are classified regarding the type of variable to be forecasted using these methods. Spatio-temporal forecasting methods are classified into three classes in this study; the forecasting approaches for renewable energy generations, for load demands and for traffic characteristics, regarding their application fields and each class is separately evaluated in different sections. Section 2 includes the studies that deal with the renewable energy forecasts, namely, wind forecasts and solar forecasts. Section 3 examines the effectiveness of spatio-temporal load demand forecasts. The implementations of traffic characteristics forecasts based on both spatial and temporal data are elucidated within Section 4. Section 5 provides insights about the effectiveness of using spatio-temporal methods for forecasting applications and summarizes the most important remarks about these approaches. Conclusions are drawn in the last section.

2. Renewable energy forecasting approaches

Generating electricity from renewable sources has gained gradually increasing interest in the last two decades due to their environmentally friendly and cost-effective operations compared to the conventional energy sources. Together with the higher penetration of renewables, particularly wind and solar energy sources, a new uncertainty problem has appeared in power system scheduling in addition to the uncertainty comes from demand side. This problem can be considerably mitigated using the renewable power forecasts on the supply side. The forecast of renewable power on demand side, which is generally produced by residential renewable energy sources connected to distribution systems, can also enable the exploitation of the energy potential at this level and therefore provide economic benefits to producing consumers known as prosumers.

2.1. Wind speed/power forecasting approaches

A rapid growth in wind energy generation has been experienced in many parts of the world in the past decade. The installed wind power capacity throughout the world reached over 430 GW at the end of 2015, with an annual growth rate of almost 22% during the last decade [4]. The projections for the next 15 years show that wind energy will provide over 19% of the total electricity supply in the world [4]. The integration of such a high-capacity intermittent energy resource into power systems poses various challenges in operating and managing of these systems since its energy cannot be dispatched in the traditional sense. For the purpose of maintaining power system reliability in the case of high wind power penetration levels, several preventive actions are generally taken. Among these precautions, wind power forecasts are of significant importance due to their effectiveness and cost-efficiency.

The studies in the literature of wind forecasting generally adopt two different procedures to forecast wind power: (i) indirect wind power forecasting, that is, the methods that forecast wind speed and convert the forecasted values to wind power forecasts using power curves, and (ii) direct wind power forecasting, that is, the methods that directly