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Cyber-Physical Spatial Decision Support System for Road Traffic Management

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Abstract

Nowadays, most of growing cities in the world are witnessing an unprecedented increase in road traffic congestion because of population mobility and sporadic events like accidents and natural disasters. As these congestions generally result in substantial casualties and economic losses, tremendous investments are being spent on efficient solutions for road traffic management. Abundant works have proposed solutions to help road traffic stakeholders in making decisions about ongoing events at the individual and collective levels. However, not enough success is yet achieved when it comes to collecting, processing, and delivering the right data, from the right location, at the right time to the right user. We argue in this paper that the divide should be effectively closed between a real world where road traffic and its related events are happening and a world where decisions are being taken. To this end, we propose to use the emergent technologies of Cyber Physical Systems along with multi-agent system mechanisms for additional autonomy, flexibility, and control of the different aspects of the highly dynamic and uncertain field of road traffic management. Within this scope, we propose an architecture of a Cyber Physical Spatial Decision Support System (CPSDSS) through which we explain how various road traffic challenges could be monitored and controlled.

Keywords: *Road Traffic; Cyber Physical System; Spatial Data Warehouse; Spatial Decision Support System; SOLAP; Cyber Physical Spatial Decision Support System; Multi-Agent Systems*

1. Introduction

Because of several constraints, including limited road network capacity and random en-route events, road traffic congestion is posing serious problems in most big cities worldwide [1]. In order to deal efficiently with these problems that range from financial losses to human fatalities, advanced traffic monitoring and control tools (e.g., SCATS and SCOOT) are being used widely in hundreds of major cities in the world. However, due to increasing road traffic and dynamic spatio-temporal events, additional proactive mechanisms remain needed to prevent traffic congestions. Since road traffic data commonly have spatial components (e.g., location), Spatial decision support systems (SDSS) are relevant candidates, as they are designed to help decision makers solve complex spatially related problems [2]. Their growing use in several applications, including urban planning, natural resource management, and transportation [3] is being facilitated by continuous technological advances [2]. However, due to spatial data complexity, the commonly used GIS (Geographic Information System) tools are not well enough for decision-makers to make right choices [5]. For large amounts of data, SDSSs commonly rely on Spatial Data Warehouses (SDWs) [4] to store spatial data. For online processing, SDW may use a variety of techniques, including Spatial On-Line Analytical Processing (SOLAP) [6]. Both technologies, SDW and SOLAP, are based on Spatial Multidimensional Models (SMMs) that reflect the structure according to which data are stored in the SDWs and define the way SOLAP tools are used to navigate and carry out multidimensional analysis of these data [7].

The acquisition of spatial data for road traffic management had been mostly revolutionized with the use of spatially distributed Wireless Sensor Networks (WSN) which are capable of collecting data on events of interest (e.g., accidents) and objects of interest (e.g., cars) in real-time. It has also been revolutionized with the increasing use of sophisticated mobile phones and their associated facilities

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(including GPS - Geographic Positioning System) as well as with other electronic devices, like surveillance cameras, Radio-Frequency Identification (RFID) readers, radars, and satellites. All these tools are allowing huge amounts of road traffic related data to be collected, increasing thereby the challenges of their structuring, storage, and processing. These challenges include the acquisition of the right data at the right time, integration of spatial data from different sources into the same application or repository for visualization and analysis [8], the construction of convenient SMMs for SDWs, and the implementation of convenient SOLAP tools for personalized navigation and analysis of road traffic data. To meet these goals, we argue that current SDSSs for road traffic management must close the gap they have with the physical world where the traffic scenario is taking place. Indeed, current solutions focus on data processing on a virtual world and marginalize the process of controlling and monitoring data acquisition by physical devises on the ground. We argue in this paper that the emergent concept of Cyber Physical Systems (CPSs) provides an efficient option for closing the divide between both worlds. For instance, by relying on communication and computing cores, and by using a variety of networked sensors, actuators, and embedded devices to sense, monitor, and control the physical world [9], a CPS provides a good framework for collecting, integrating and analyzing heterogeneous spatial data for decision-making purposes [10]. We therefore believe that CPS tools can extend SDSSs by allowing them to proactively control the road traffic data acquisition process instead of remaining reactive tools that operate on the available data only, regardless their quality, freshness, and accuracy. Additional missing functionalities can also be implemented on SDSSs to extract spatial knowledge from real-time sensor data and archive data on interesting road events and situations.

In this paper, we propose an architecture of a platform marrying SDSS and CPS technologies, that we call Cyber-Physical Spatial Decision Support System (CPSDSS). The platform ultimately aim to integrate archive and real-time heterogeneous spatial road traffic data and deliver personalized services to road traffic stakeholders. In the reminder of the paper, Section 2 outlines concepts and works related to SDSSs. Section 3 investigates the challenges of combining SDSS and CPS technologies and presents our proposed architecture for the CPSDSS platform. Section 4 highlights important opportunities related to the proposed platform.

2. Related work

2.1. Spatial Decision Support Systems

Given that spatial decision situations are typically complex and involve many stakeholders, they often require the use of an iterative, interactive, and participative [11] decision process. Such a process can be supported by several tools, technologies, or systems such as GIS, expert systems, remote sensing, and Spatial Decision Support Systems (SDSS) [2].SDSSs have a multidimensional nature, they often integrate multidisciplinary technologies and they are often domain and problem specific [2]. For these reasons, there is no common agreement on what is exactly a SDSS [3].

SDSSs have been used in a wide variety of applications, including aquaculture [12], agriculture [13], land use planning [14], business [15], forestry [16], and public healthcare [17]. In the domain of road traffic management, several SDSS-based solutions have been proposed. For example, Hasan [18] presented a comprehensive framework for an Intelligent Decision Support System (IDSS) for Traffic Congestion Management System. The proposed IDSS uses a state of the art transportation network equilibrium modeling and provides an easy way to use GIS-based interaction environments. The IDSS reduces the dependability on the expertise and level of education of the transportation planners, transportation engineers, or any transportation decision maker. Rajabifard et al. [19] have presented an Intelligent Disaster Decision Support System (IDDSS) that integrates a vast range of road network, traffic, geographic, economic and meteorological data as well as dynamic disaster and transport models.

2.2. Spatial Data Warehouses and Spatial Multidimensional Models

In SDSSs, Spatial Data Warehouses (SDWs) are commonly used to store and provide access to large volumes of historical, conventional and geo-referenced data. Basically, these repositories result from the confluence of two technologies, namely spatial data handling and multidimensional data analysis. Spatial data handling technology is essentially provided by two kinds of systems: spatial database management systems (SDBMS) and geographical information systems (GIS). The technology of spatial data handling has made significant progress during the last decade, fostered by the standardization initiatives promoted by OGC (Open Geospatial Consortium) and ISO/TC211, as well as by the increased availability of off-the-shelf geographical data sets that have broadened the spectrum of spatially-aware applications. Conversely, multidimensional data analysis has become the leading technology for decision making in the business area.

In a SDW, data are organized as an n-dimensional spatial datacube reflecting a multidimensional structure that will also define the way data will be handled. The datacube is composed of a number of facts and defined by dimensions and measures. Dimensions constitute the axes of analysis. Each dimension is organized into one or several hierarchies, each of which is composed of different levels. An instance of a level is a member. Furthermore, measures are quantitative indicators that are analyzed against members of dimension levels. Values resulting from combinations between members of different levels, along with their measures, are called facts [4].

For effective data analysis, a refined multidimensional model that keeps the user as the focal point and achieves a clear abstraction of the data for all stakeholders in the system is needed [20]. Several multidimensional models have been proposed in the literature, without respecting always this recommendation. Each model largely depends on the nature and quality of the acquired data and their intended use. For example, Bimonte et al. [21] defined a spatial multidimensional model with measures and dimensions represented as complex objects. Pedersen and Tryfona [22] proposed a model focusing on the problems of aggregations in the presence of different topological relationships existing between spatial measures. Miquel et al. [23] handled the problem of integration of the spatiotemporal data in geospatial data warehouses. The authors proposed two approaches for the multidimensional modelling of heterogeneous spatial data and applied them to the domain of forestry.

In the context of road traffic, our literature review revealed the existence of two works proposed by Bauzer-Medeiros et al. [24] and Park et al. [25], respectively. In the first work, the authors proposed a multidimensional model for the treatment of spatiotemporal data collected by hundreds of sensors placed on the main highways of a city. The model allows to analyze the state of the traffic (debit) and the rate of activity (occupation) in a given day, during a fixed schedule, for certain weather conditions. In addition to the absence of explicit capture of hierarchies in dimensions, this work does not include spatial measures. In the second work, the authors suggested a multidimensional model to elicit comprehensive analysis results that fits various purposes. This model is only based on the use of archive data.

2.3. Spatial On-Line Analytical Processing

The analysis of spatial datacubes is performed with SOLAP (Spatial On-Line Analytical Processing) tools that are mainly built to support rapid and easy spatiotemporal analysis and exploration of data following a multidimensional approach [26]. SOLAP includes many operators such as roll-up (moves up along one or more dimensions towards more aggregated data), drill-down (moves down dimensions towards more detailed, disaggregated data), slice, and dice (performs a selection and projection operations on a cube).
Several commercial SOLAP solutions are available on the market, including JMap® Spatial OLAP Extension [26], GOAL [27], and SOVAT. Other products supporting some SOLAP requirements are also available, such as KHEOPS Technologies and ProClarity [28]. Nevertheless, despite the huge research and development efforts on SOLAP, several issues remain open, including handling multiple representations of the same objects. This is particularly because of the absence of a consensus on a formal SMM for spatial data warehousing [29].

2.4. Gaps

To the best of our knowledge, current SDSSs for road traffic management are not yet performing well enough, particularly when it comes to supporting simultaneous requirements from several stakeholders. Indeed, current solutions are not yet capable of conveniently integrating data from several sources and including multiple representations of the same objects, according to different scales, perceptions, and semantics. This is particularly because existing spatial multidimensional models are domain-oriented and lack flexibility to express personalized perceptions of several stakeholders. Furthermore, current solutions do not include appropriate mechanisms to make an efficient integration of real-time data and archive data as well making an effective joint use of both data types to generate personalized contents and services. These solutions do not also maintain a close oversight of data collection tools, their sampling frequencies, accuracy, and authenticities.

3. Toward a CPSDSS for traffic management

Current SDSS-based solutions for road traffic management are mainly focusing on processing, storing, and visualizing the data collected about objects and events of interest. These solutions do not give much attention to controlling data collection mechanisms. We argue that the gap between the physical world where road traffic is taking place and the virtual world where management actions are taken could be appropriately be filled with Cyber Physical System technologies. In order to leverage the connection between both worlds, we argue that flexible and intelligent mechanisms are needed to act and react to environmental changes while using optimized resources. To meet this goal, we propose the architecture of a platform combining SDSS and CPS for road traffic management technologies. In what follows, we outline some challenges related to our platform, that we can *CPSDSS*. Some of these challenges are depicted in Figure 1 below.

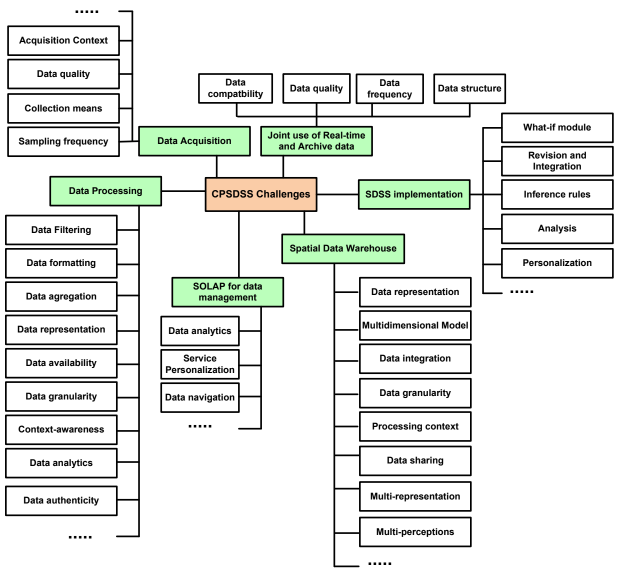

Fig. 1. **CSPDSS challenges**

3.1. Challenges

Data acquisition –Wireless Sensor Networks (WSNs), smart phones, surveillance cameras, RFID readers, radars, and satellites are examples of tools which are currently being used to collect real-time data about road traffic objects and events. These tools are making increasing amounts of data to be available at predefined and/or random moments. These data could be collected according to predefined structures or collected without any prior structures. Data can also be collected according to different formats, granularities, and qualities. All these parameters commonly result in inconsistency, heterogeneity, and availability problems that must be solved, otherwise, appropriate decisions could not be always inferred from data.
Data processing – The abovementioned problems are commonly posing big challenges to process road traffic data. Indeed, the data collected should be filtered and evaluated according to their semantics, current contexts as well as current and expected requirements of road traffic decision-makers. Data may also need to be aggregated in order to avoid unnecessary redundancy and checked for authenticity to identify potential malicious activities. Furthermore, processing should be optimized by executing the right actions, on the right data, at the right time. Some intelligent mechanism should be deployed in order to achieve this goal and deliver the right decision at the right time to the right user.

Joint use of real-time and archive data – Archive data are not sufficient to make appropriate analysis about ongoing situations. Real-time data are actually more important especially when dealing with a hazardous situation. Heterogeneity and inconsistency are frequent challenging problems that arise when real-time data are intended to be used with archive data. For instance, both data types may differ on several features, including quality, granularity, and format. Since transforming real-time data to match the characteristics of the archive data cannot be achieved within acceptable timeframes, especially due to the increasing amounts of new collected data, efficient mechanisms remain necessary to allow decisions to be made based on both data types. Some research works have addressed this issue but results remain in their early stages [30].

Integrating multi-view spatial data – In the multidisciplinary field of road traffic management, several stakeholders are collecting and using data for their individual needs. Enabling these stakeholders to collaborate would increase the efficiency of their actions. We argue that a common data repository could allow this collaboration. However, data coming from different sources are commonly inherently different in terms of representations, granularity, quality, resolution, scale, semantics, and formats. They are also stored according to different data models, which makes them difficult to merge. A new spatial multidimensional model is generally necessary to represent all the data while capturing the multiple views of the different stakeholders. In order to create such model, Viswanathan and Schneider [31] listed 25 basic requirements for an effective multidimensional model for data warehouse design. These requirements include handling different levels of granularity, user-defined aggregates, handling data imprecision, and support for spatial hierarchy, dimension, and measures. Some of these requirements are not easy to respond since they are about capturing specific views and requirements of each stakeholder.

Updating the Spatial Data Warehouse within acceptable time windows –Road traffic stakeholders continuously collect data for their own decision-making process. In order to upload the new collected data into the SDW, a heavy Extract-Transform-Load (ETL) process must be carefully applied. When the SDW is meant to integrate all the stakeholders' data sources for an enhanced and informed collaboration, requests to update this common repository could conflict. In order to avoid such problems, effective mechanisms to schedule the integration of new data into the SDW are still needed. These mechanisms give priority to requests based on current ongoing road traffic events. .

Efficient SOLAP tools for data management – SOLAP has three essential features [32]: (1) data visualization via cartographic (maps) and non-cartographic displays (e.g., 2D tables); (2) data exploration; and (3) data structuring. It is operating on data which are structured according to a specific multidimensional model. Creating a new model that capture the need of several stakeholders according to multi-scales and multiple-views and personalizing the visualization of data to support their specific requirements will necessitate the extension and/or the redefinition of some SOLAP tools, such as spatial measures, spatial aggregation, and spatial hierarchy [7].

Designing and implementing efficient SDSS – Despite the fact that they are increasingly accepted tools in spatial decision-making processes, the successful design, development, delivery, and use of SDSS still presents many challenges [2]: limited success (many SDSSs are either prototypes, conceptual frameworks, or utilized only in academic exercises), lack of efficiency (there is sometimes little evidence that SDSSs have been utilized to aid real spatial decision-making situations or that any given SDSS has been used repeatedly), and difficulty to execute cross-discipline collaborations to solve complex spatial problems. We highlighted in a previous work [3] additional challenges, including: high multi-disciplinary requirements (several expertise in database management system, geographic information systems, computer operating systems, remote sensing and Internet searching for data gathering, graphics, as well as specific domain knowledge are needed), validation of results (when the SDSS simulates a highly dynamic environment as during crisis response, it is a big challenge to validate the simulation models in use), lack of standards for enabling Web-based SDSS, and lack of comprehensive GIS functionalities for some applications displaying results on maps.

3.2. Proposed CPSDSS architecture

Because of multiple individual limitations of current technologies used in SDSSs, we intend to create a new platform that alleviates spatial decision-making processes by integrating several technologies and tools for spatial data acquisition, modeling, storage, and analysis. The expected platform will combine CPS and SDSS technologies to merge and analyze heterogeneous real-time and archive data about road traffic while capturing the needs of several stakeholders. We call our expected platform *Cyber-Physical Spatial Decision Support System for Road Traffic Management* (CPSDSS-RTM).

In Figure 2, we depict our architecture for CPSDSS-RTM. The traditional SDW process of Extract-Transform-Load will be monitored by an intelligent component (IETL) in order to solve conflicting requests to update the road traffic data warehouse and schedule the updates at convenient times. At predefined times or based on requests, it integrates data coming from stakeholders' data sources and generate a common SDW. From this common repository, some specialized databases (also called datamarts) are generated for specific needs. The architecture includes an Intelligent Control Module (ICM) that will collect data from the physical road traffic assets and decides whether the freshly collected data will be used for real-time decision-making or will be scheduled for integration with the archive data. This module is also responsible for monitoring the communication between the cyber and physical worlds of the CPS. To this end, it controls the data collection process (sampling frequencies, data quality, sensors and resources involved, road traffic areas of interest, etc.) based on predefined schedules, ongoing events, and current requirements of individual stakeholders. Based on these parameters, the Spatial Decision Support Module (SDSM) may use the archive data only (stored in the datamarts or in the SDW) or integrated the real-time data to deliver the required assistance to road traffic stakeholders. To this end, it includes a revision and integration module that checks relevant parameters of the input data (archive and/or real-time data), including their formats, quality, representations, and semantics. The inference module will then apply what-if, optimization, goal-seeking, and statistical models to generate decisions. Prior to delivering these decisions to the right stakeholder, a reporting and analysis module is used as a user interface to generate a personalized content that fits the specific profile and needs of the stakeholder. On the physical world of the CPS, sensors and actuators are organized into clusters based on several criteria, such as geographic location and processing and communication capabilities. Within these clusters, some intelligent mechanisms are embedded to improve local decisions regarding data collection and forwarding. Details about the intelligent components are out of the scope of this paper.

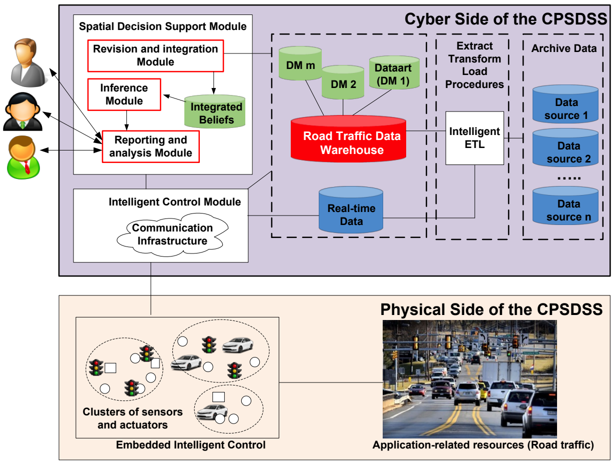

Fig. 2. The proposed architecture for the CPSDSS platform

4. CPSDSS Opportunities

In order to implement the proposed architecture, several technologies and tools must be used. In this regards, the IETL could be implemented using FME, GeoKettle and Talend. The Hadoop MapReduce is a relevant option to process massive structured and unstructured data as well as to perform complex transformations for integrating data into the SWD. PostgreSQL and Postgis are examples of technologies that could be used for the implementation of the SDW. OLAP server (Mondrian) and Carto server (MapServer) could be used for data processing and personalization. The java-based JadeX platform could be used to implement the necessary intelligent components of our architecture, including some parts of the SDSS, the Intelligent Control Module, and some embedded control mechanisms. An appropriate implementation of the proposed platform would open doors for several opportunities that we outline in what follows.

Seamless Integration with Big Data – Thanks to their capabilities to collect data, anytime, anywhere about a variety of objects and events of interest, sensors are providing decision-makers with huge volumes of data about road traffic events. These volumes are growing sporadically and rapidly with a variety of structured and unstructured data for which common authenticity and semantic checks must be performed. As these volumes could reveal important knowledge about road traffic events and objects of interest, Big Data techniques must be deployed for a thorough analysis of their value.

Seamless Integration with Internet of Things – Ubiquitous computing technologies (e.g., WSN, RFID, etc.) used for reporting data about road traffic events and objects are continuously evolving. These technologies are being increasingly integrated into a wide range of Real World Things (RWTs). Thanks to their embedded communication facilities, the RWTs have evolved into the Internet of Things (IoT) concept. Several studies are focusing on the mobility of RWTs to collect more data about the right events/objects of interest, from the right location, at the right time. To this end, the RWTs networking capabilities are being used to implement efficient approaches allowing these RWTs to collaborate and achieve services going beyond their individual capabilities. For instance, road traffic authorities could deploy some RWTs with extended processing capabilities to collect and aggregate data from several sources while on-the-move and then infer limited decisions about local events. The scope of these decisions should be carefully investigated and analyzed in order to avoid conflicts between decisions and prevent any security thread that would come from these RWTs. Furthermore, the IoT objects could be deployed to increase resource availability, enhance participatory data acquisition and processing, and maintain efficient communication between the cyber and the physical components of the CPS.

Service personalization – When several stakeholders are expected to use the same data repository, an efficient mechanism is needed to capture their multiple views. In a related work [8], we investigated this issue in a general context. Additional investigations remain needed in order to allow the expected CPSDSS-RTM platform to generate decision services to stakeholders according to their requirements and priorities.

CPSDSS and cloud-computing – Because of the increasing complexity of road traffic management, on-premise resources are becoming insufficient. A shift to a hybrid mix where cloud-computing services and resources are also used to improve the performance of the CPSDSS is attracting increasing attention. In this regards, moving data and processing to the cloud would result into several opportunities, including a simplified and effortless data integration and faster response to ongoing road traffic events.

Intelligent CPSDSS – Road traffic management is inherently complex, due to dynamic events, changing requirements, dynamic resource availability, and common needs for real-time decision making. For an efficient monitoring of these issues, the CPSDSS platform should be extended with flexibility, autonomy, intelligence, and context awareness capabilities. We argue that the paradigm of multi-agent systems is a convenient option because of its proven capabilities to solve complex problems within highly dynamic, constrained, and uncertain environments. In this regard, software agents could be assigned several tasks, including controlling data acquisition, monitoring data integration, and personalizing services delivered by the CPSDSS-RTM platform.

5. Conclusion

In this paper, we addressed the increasingly complex problem of road traffic management. We highlighted the shortcomings of current Spatial Decision Support Systems (SDSSs) that are not yet capable of appropriately integrating and supporting multiple views and requirements of the different stakeholders involved in the road traffic management process. We particularly outlined the existing divide between the physical world where the traffic scenario is taking place and the virtual world where data are processed and decisions are made.

In order to fill this gap, we proposed the architecture of a platform marrying the use of SDSSs and Cyber Physical Systems (CPSs) technologies. Within this architecture, some decision-making activities could be shifted to low-level components, namely sensors and actuators. For an intelligent, flexible, and autonomous control of the data acquisition process and the decision-making process, we proposed and investigated the use of the multi-agent system paradigm. Our future works will focus on implementing our platform and assessing its performance.

References

[1] S. Djahel, N. Jabeur, R. Barrett and J. Murphy, "Toward V2I communication technology-based solution for reducing road traffic congestion in smart cities," Networks, Computers and Communications (ISNCC), 2015 International Symposium on, Hammamet, 2015, pp. 1-6. http://dx.doi.org/10.1109/ISNCC.2015.7238584

[2] Sugumaran, R. and Degroote, J. (2014). Spatial Decision Support Systems: Principles and Practices, CRC Press

[3] Jabeur, N., Haddad, H., Sahli, N. (2011) "Sensor Network and GeoSimulation: Keystones for Geospatial Decision Support Systems". Book: Efficient Decision Support Systems: Practice and Challenges. INTECH Open Access Publishers, ISBN 978-953-307-441-2, pages 337-356. http://dx.doi.org/10.5772/17004

[4] Surabhi, M. (2014). Spatial Data Warehouses. Available at: http://www-users.cs.umn.edu/~smithal/. Last visited November 29, 2014

[5] Boubaker, B., Jabeur, N., Alimazighi, Z. (2015) "An Intelligent ETL Grid-Based Solution to Enable Spatial Data Warehouse Deployment in Cyber Physical System Context", Journal of Procedia Computer Science, Vol. 56, pp: 111 – 118. http://dx.doi.org/10.1016/j.procs.2015.07.176

[6] Codd, E. F., S. B. Codd and C. T. Salley. 1993. Providing OLAP (On-Line Analytical Processing)to User- Analysts: An IT Mandate. Hyperion white papers, 20p.

[7] Boulekrouche, B., Jabeur, N., Alimazighi, Z. (2014). "Spatial Multidimensional Model and Multiple Geometric Representations: a survey, conceptual model and definitional framework". Surabhi, M. (2014). Spatial Data Warehouses. Available at: http://www-users.cs.umn.edu/~smithal/. Last visited November 29, 2014

[8] Boubaker, B., Jabeur, N., Alimazighi, Z. (2016) "Toward integrating grid and cloud-based concepts for an enhanced deployment of spatial data warehouses in cyber-physical system applications, International Journal of Ambient Intelligence and Humanized Computing, Vol. 7 (4), pp: 475-487. http://dx.doi.org/10.1007/s12652-016-0376-1

[9] C. Lin, S. Zeadally, T. Chen, C. Chang, "Enabling Cyber Physical Systems with Wireless Sensor Networking Technologies", International Journal of Distributed Sensor Networks, Volume 2012, 2012

[10] Rajkumar, R., Lee, I., Sha, L., Stankovic, J. (2010). Cyber-physical systems: the next computing revolution. In Proceedings of the 47th Design Automation Conference. ACM, New York, NY, USA, pp. 731-736. http://dx.doi.org/10.1145/1837274.1837461

[11] Goel, R. K. 1999. Suggested framework (along with prototype) for realizing spatial decision support systems (SDSS). Paper presented at Map India 1999 Natural Resources Information System Conference, New Delhi, India

[12] Nath, S. S., J. P. Bolte, L. G. Ross, and J. Aguilar-Manjarrez. 2000. Applications of geographical information systems (GIS) for spatial decision support in aquaculture. Aquacultural Engineering 23(1–3):233–278. http://dx.doi.org/10.1016/S0144-8609(00)00051-0

[13] Colby, M. M., and Y. J. Johnson. 2002. Potential uses for geographic information system-based planning and decision support technology in intensive food animal production. Animal Health Research Reviews 3(1):31–42. http://dx.doi.org/10.1079/AHRR200238

[14] Witlox, F. 2005. Expert systems in land-use planning: An overview. Expert Systems with Applications 29(2):437–445. http://dx.doi.org/10.1016/j.eswa.2005.04.041

[15] Keenan, P. B. 2005. Concepts and theories of GIS in business. In Geographic information systems in business, ed. J. B. Pick, 1–19. Hershey, PA: Idea Group Publishing. http://dx.doi.org/10.4018/978-1-59140-399-9.ch001

[16] Baskent, E. Z., and S. Keles. 2005. Spatial forest planning: A review. Ecological Modelling 188(2–4):145–173. http://dx.doi.org/10.1016/j.ecolmodel.2005.01.059

[17] Haddad, H., Moulin, B. and Thériault, M. (2015). An Integrated Approach for Communicable Disease Geosimulation based on Epidemiological, Human Mobility and Public Intervention Models. Spatial and Temporal Dynamics of Infectious Diseases, Dongmei C. et al. (Eds.), John Wiley & Sons, Inc, ISBN: 9781118629932

[18] Hasan, M. 2010. "A Framework for Intelligent Decision Support System for Traffic Congestion Management System," Engineering, Vol. 2 No. 4, 2010, pp. 270-289. http://dx.doi.org/10.4236/eng.2010.24037

[19] Rajabifard, A., Thompson, R.G., Kaviani, A., Griffin, G., Chen, Y. 2015. "A decision support system for improving the management of traffic networks during disasters", 37th Australasian Transport Research Forum (ATRF 2015), Sydney, Australia, 30 Sept – 2 Oct, 2015.

[20] Viswanathan, G., Schneider, M. (2011). On the Requirements for User-Centric Spatial Data Warehousing and SOLAP. DASFAA Workshops, volume 6637 of Lecture Notes in Computer Science, page 144-155. Springer. http://dx.doi.org/10.1007/978-3-642-20244-5_14

[21] Bimonte, S., Tchounikine, A., Miquel, M. (2007). Spatial OLAP: Open Issues and a Web Based Prototype. 10th AGILE International Conference on Geographic Information Science 2007 Aalborg University, Denmark, pp: 1-11

[22] Pedersen,T., &Tryfona, N. (2001). Pre-aggregation in spatial data warehouses. LNCS: 2121, Proceedings. of the 7h Int. Symposium on Advances in Spatial and Temporal Databases, 460-480. http://dx.doi.org/10.1007/3-540-47724-1_24

[23] M. Miquel, Bédard Yvan, and A.Brisebois, " Conception d'entrepôts de données géospatiales à partir de sources hétérogènes". Exemple d'application en foresterie. Ingénierie des systèmes d'information, page(s): 89-111, 2002

[24] C. Bauzer-Medeiros, O. Carles, F. Devuyst, B. Hugueny, M.Joliveau, G.Jomier, M. Manouvrier, Y. Naija,G. Scemama, and L. Steffan, " Vers un entrepôt de données pour le trafic routier", Note de recherche, 2006

[25] Park, D., Yu, J., Park, J.S., Kim, M.S. (2013). NetCube: a comprehensive network traffic analysis model based on multidimensional OLAP data cube. INTERNATIONAL JOURNAL OF NETWORK MANAGEMENT Int. J. Network Mgmt 2013; 23: 101–118. http://dx.doi.org/10.1002/nem.1818

[26] Bedard, Y., Rivest, S. &Proulx, M.-J., 2006, Spatial On-Line Analytical Processing (SOLAP): Concepts, Architectures and Solutions from a Geomatics Engineering Perspective. Book chapter in Data Warehouses and OLAP: Concepts, Architectures and Solutions, EDA Group

[27] Kouba, Z., Matousek, K., &Miksovsky, P. (2000). On Data Warehouse and GIS integration. In Proceedings of DEXA 2000, Lecture Notes in Computer Sciences 1873 (pp. 604-613). http://dx.doi.org/10.1007/3-540-44469-6_56

[28] Stevens, M., Vitos, M., Lewis, J., & Haklay, M. (2013). Participatory monitoring of poaching in the Congo basin. GISRUK 2013, 21st GIS Research UK conference, April 2-5, 2013, Liverpool, England, UK

[29] Ahmed, T. O., Spatial On-line Analytical Processing (SOLAP): Overview and Current Trends, International Conference on Advanced Computer Theory and Engineering, 2008. http://dx.doi.org/10.1109/icacte.2008.217

[30] Yan F. (2012). The Research of Active Data Warehouse Based on Multi-Agent. Proceedings of Congress on Engineering and Technology (S-CET), pp:1-4

[31] Viswanathan, G., Schneider, M. (2011). On the Requirements for User-Centric Spatial Data Warehousing and SOLAP. DASFAA Workshops, volume 6637 of Lecture Notes in Computer Science, page 144-155. Springer. http://dx.doi.org/10.1007/978-3-642-20244-5_14

[32] Rivest, S., Bedard, Y., Marchand, P.: Toward better support for spatial decision making: defining the characteristics of spatial on-line analytical processing (SOLAP).Geomatica-Ottawa 55(4) (2001) 539–555