Investigating the Application of Multi-Objective Optimisation and Multi-Criteria Decision Making to Future Concepts of Intelligent Mobility and Telecommunications

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***Abstract*—Designing an urban environment involves a multitude of diverse principles, among which vehicle dynamics, pedestrian dynamics and telecommunications play a very important role. However, these are rarely considered together in studies for intelligent mobility. On top of that, optimising such a multidisciplinary system is a very challenging task because of the number of principles and interfacing among the participating components. This work introduces a scalable research methodology that combines all of the above, so as to assess the effectiveness of the application and to provide an alternative approach to design an urban environment that could be equally applied at scale. This is expected to provide deeper insight to traffic planners and researchers both in academia and industry, so as to generate new designs that could yield higher performance solutions in intelligent mobility problems.**

I. Introduction

A. Background

Over the last years, the trend of urbanisation clearly emphasises the need to focus on the design and deployment of smart cities [1], towards improving CO2 emissions and energy saving. Gradually, through digitalisation of services, the infrastructure changes and becomes more efficient, at the expense of lack of sustainable development. As this damages investment activity, the means of technology are required to generate information and make appropriate decisions, which require higher levels of well-structured monitoring processes and structural conditions.

The future of intelligent mobility comprises of a multitude of challenges from social, environmental, technological and economic perspectives, as described below. The high volume of traffic in urban environment ought to be minimised. Consequently, the energy footprint and CO2 emissions of urban transport should be minimised. The concept of vehicle-to-vehicle and vehicle-to-infrastructure communication via using Vehicular Ad Hoc Networks (VANETs) is considered as an approach to positively contribute towards the mitigation of the aforementioned issues. This is an upcoming trend, which has the potential to lead to greater levels of automation, towards complete autonomous driving. A number of technologies are listed in [2], whose applicability ranges from the present to 2050. However, these are governed by the high costs of experimentation (e.g., conducting surveys) and also scarcity of means.

Making decisions through simulation is an emerging technology [3]. However, the cost of ownership and use of specialised software packages is excessive, which, in practice, enables only established organisations to conduct research studies. Optimisation is the natural extension of simulation, towards a more effective design that would serve the same principles. However, optimisation methods are rarely employed. On top of that, Multi-Objective Optimisation (MOO) [4] is a particular extension, required by decision makers, that can reveal a number of solutions, so as to better appreciate the complexity of instances of real-world applications. As a follow-up technology, Multi-Criteria Decision Making (MCDM) [5] is a method to complement MOO, so as to rank optimum solutions. This can help to make more informed decisions, while considering human-in-the-loop approaches. It has the potential to automate the decision making process of self-configuring the infrastructure, towards optimising the flow of vehicles and optimally using available resources, so as to achieve the environmental and social and economic targets. This will benefit the use of resources and is expected to minimise the number of accidents. Finally, it is anticipated to lead to more effective land use. It could also give to legal authorities the means to investigate and make more decisions via simulation. Starting from the lowest level of urban traffic, the modelling and optimisation of traffic junctions in an urban environment is expected to be assist in the design and management of sustainable solutions to meet the future needs of intelligent mobility [4].

B. Aims and Objectives

The aim of this research is to introduce and demonstrate through application a flexible methodology that combines MOO and MCDM, so as to be applied to instances of urban transport with respect to the environmental, economic and technology aspects, towards enabling intelligent decisions under uncertainty in the design of smart interactions, as an incremental unit of future cities and intelligent mobility. The products of this research (i.e., methods and tools) are developed to be freely used in a variety of ways by any number of stakeholders and could link to either research and commercial tools and methods. The list of objectives comprises of the following:

1) Model the mobility of an urban environment
2) Model the communication among modelled entities
3) Optimise the aforementioned modelled world.
4) Identify important parameters that affect the performance of the system.
5) Utilise diverse sources of data to correlate behaviours and patterns in transport.
6) Make a decision based on uncertainty that considers stakeholders opinions
7) Enable a transparent interfacing among all the entities/simulated principles

C. Project Methodology

The methodology is based on a specific category of MOO methods, which is complied with stochastic MCDM methods; metaheuristic optimisation, which is know to deliver satisfactory solutions to real-world problems [6], whereas MCDM methods such as The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [5] can consider a number of thresholds (i.e., preference, indifference and veto) so as to accurately rank a number of solutions.

For ease of integration into other systems and processes, the methodology is structured by following The Open Group Architecture Framework (TOGAF) [7], as depicted in Fig. 1. This framework was selected for its maturity, openness and wide applicability in large-scale projects.

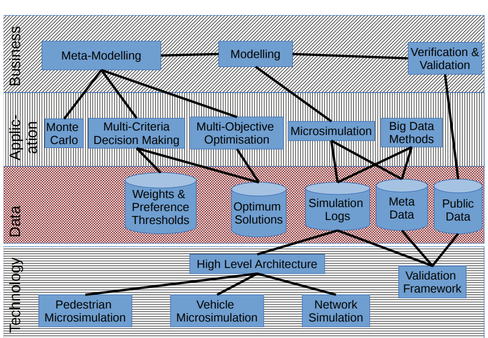

Fig. 1. Research methodology represented in TOGAF

At the top level, modelling represents the abstractions of real world that focus on intelligent mobility principles by using microsimulation. The modelled system is going to be used by other models that implement Monte Carlo, MCDM and MOO algorithms. Finally verification and validation (by following the approaches in [8]) serve as a separate and distinct step, which should take place after setting up the model and before employing meta-modelling, so as to generate sensible results and increase the confidence to the final solution. After running a number of instances of microsimulation, the results could be further used by applying big data methods, so as to extract additional knowledge, which could generate meta data. The latter could be used in conjunction with thresholds of weights and preferences (from MCDM methods), so as to make more informed and strategic decisions. The diverse modules for microsimulation will operate under a well-established communication protocol that has been successfully used by military applications, so as to increase the span of possible applications and interoperability, as described below.

Regarding the application layer, the microsimulation should be verified before employing the following methods. Monte Carlo ought to be applied at the beginning of the methodology, so as to better understand the microsimulation and extract any sensitivities by using the latter as a black-box. Then, this knowledge could be used to accordingly specify an optimisation algorithm, so as to identify the areas of highest performance and deliver a range of non-dominated solutions. These non-dominated solutions will be used in a MCDM application, so as to sort them based on stakeholders' preference.

The methodology comprises of the following items, which match the aforementioned objectives 1-1:

1) Employ vehicle and pedestrian microsimulation tools, so as to model the behaviour, interactions and movement of pedestrians and vehicles
2) Employ network simulators, so as to implement the fundamentals of vehicle-to-x (V2X) communication
3) Employ metaheuristic optimisation algorithms, so as to carry out optimisation studies that can consider the complexity of studies and delivery decent results within acceptable time-frames, with the potential to be used in real-world applications
4) Employ principal component analysis methods [9], so as to identify the most energetic parameters in a dataset
5) Employ statistical learning and big data mining techniques to process and analyse collections of publicly available data that are acquired by sensors and other sources
6) Employ MCDM methods based on Monte-Carlo, so as to model the probabilistic nature of the problem
7) Implement a framework based on structured data, so as to enable a multitude of similar systems to integrate in the process that could potentially increase the fidelity of the results

D. Contribution To Knowledge

- Assess the impact of using an optimisation methodology based on metaheuristic optimisation algorithms, so as to optimise the design of smart intersections in an urban environment, considering the diversity of attributes of a synthetic population.
- Design, demonstrate and benchmark a flexible systems' architecture against state-of-the-art tools in intelligent mobility, so as to enable the aforementioned application.
- Demonstrate the potential to apply the proposed methodology to larger instances of urban transport problems and/or introduce future mobility concepts [10].
- By applying this suggested methodology, alternative solutions are expected to emerge in instances of urban mobility problems, so to demonstrate the potential of employing it on a family of problems and ultimately improve the return on investment in terms of research and solution performance.

E. Structure

So far, a number of challenges in intelligent mobility have been presented. In response, a prototype methodology has been introduced to enable intelligent decisions in an urban environment to suggest alternative solutions, so as to reduce the impact on the environment and economic factors by combining principles from the fields of systems engineering, traffic modelling and telecommunications. The next section will report and present the progress and limitations of state-of-the-art approaches in the respective fields. Finally, the selected methods will be discussed and future avenues will be presented, towards the implementation of the methodology.

II. Literature Review

A. Modelling the Interactions and Movement of Pedestrians and Vehicles

In general, capturing and modelling the behaviour of vehicles and pedestrians is very challenging activity, because of the data acquisition methods and validation. There is a number of software packages developed by commercial vendors or research organisations, but most of them implement one of the two. Additional interfaces are available, but these are bespoke developments and cannot be generalised.

In an urban network, the interactions between cars and pedestrians are simulated by using a cellular automata model, as presented in [11]. A prototype, called Simulation Agents et Modélisation Urbaine (SAMU), was developed as a hybrid model that combines principles from cellular automata and agent-based modelling, where cars and pedestrians are represented as agents that operate (and interact locally) on an active grid. A set of rules in traffic, including accidents, are simulated so as to assess the impact of traffic management on the network structure and infrastructure on safety by varying the number of lanes. The accident risk is calculated as a function of the vehicles' density, in the form of a quadratic formula. By varying the vehicular density, the probability of accident per crossing in the whole urban network is calculated. However, this work remains at a prototype level and any interaction mechanisms are not obvious, which would impede the integration of additional principles such as network simulation.

A commercial software package that simulates pedestrians, called Legion, provides a bespoke interface to another commercial software package that simulates vehicles travelling in lanes [12]. However, this provides very limited interfacing capability and comes at high costs for the proof-of-concept phases of the design, but it could be beneficial for validation and cross-validation purposes.

The solution approach to a hybrid instance of the vehicle routing problem where the vehicles vary in many different aspects was presented in [13]. An in-house code is linked to a genetic algorithm to perform the routing optimisation, where it was demonstrated that traditional approaches are not fit-for-purpose. Three approaches were presented that varied the objective functions and optimisation modelling, so as to demonstrate the effectiveness of the method if deployed in an urban environment. However, this is a prototype solution and higher fidelity modelling approaches (i.e., vehicle microsimulation) would be required in order to be used in the urban design process, which should also consider pedestrian dynamics and other principles.

As the impact of big data is highly appreciated towards better understanding an societal needs, the Big Project was launched, so as to address economic and social fields [14]. Among the other projects, the mobile phone pilot is going to acquire population densities, flows and tourism statistics, so as to reflect the travel and mobility patterns, which are going to compared against historical data and demographics. This could be used as the source to create origin-destination matrices and a synthetic population in an urban environment. Naturally, the volume of data will give rise to big data processing techniques and infrastructure, so as to effectively analyse the data and make more informed decisions, so as to effectively manage public assets and optimise the traffic.

B. Investigating the fundamentals of V2X Communication

This category mainly comprises of the following types of communication: vehicle-to-vehicle(V2V), vehicle-to-infrastructure(V2I) and vehicle-to-pedestrian(V2P).

A number of different architectural approaches towards the design of a smart city were presented in [15]. Implementing architectures and platforms is the vital, so as to mitigate the increased urbanisation, which is further complemented by implementing appropriate interfaces. Among others approaches, the Architectural Layers (AL) and Service Oriented Architecture (SOA) are suggested to support the development of smart cites or components of thereof. The Internet of Things (IoT) is an emerging architecture, as it is closely related to the vast number of sensors deployed in a smart city. Regarding technical requirements, data stream and process, data collection and interoperability are of paramount importance, which should be considered along with security requirements.

Coupling together microsimulation software packages and network traffic simulation is a very promising research direction, as described in [3], which also contributes to the VANET research. Two open-source packages, one from each category, have been coupled, under the framework called veins, so as to enhance the driving behaviour. The implemented bidirectional interface allows to conveniently evaluate communication protocols at higher levels of precision. The framework relies on the existence of the underlying packages. It is also possible to integrate CO2 emissions models. Although, this is a very comprehensive and widely used approach, it is again a bespoke coupling that cannot easily generalise to other packages, to enable different levels of simulation fidelity.

The improvement of a VANET protocol for use in an urban environment was presented in [16]. Consequently, this offers two important advantages; the routing data increase in accuracy and the efficiency of the routing protocol is enhanced at the intersections by predicting the vehicle motion. A number of open-source software packages that perform network simulation and vehicle microsimulation were combined to create network traffic and realistically model driving behaviour. The next hop is determined by using a vector, which is combined with previous features to improve the accuracy of the introduced algorithm that achieves better packet delivery ratio and routing overhead. A similar approach was also demonstrated in [17] to support complex urban traffic environment. In order take into account the traffic load and geographic information, a new strategy for VANETS was introduced, so as to more effectively relay packets along the road in an urban environment. Compared to another state-of-the-art strategy, the new one improves the packet delivery ratio and average packet end-to-end delay. The new strategy was proven to be flexible enough for dense and heavily load environments. Although these two works did not consider pedestrian dynamics, it is considered as important contribution to this research, as the initial building block in terms of an implementation to bridge the aforementioned gap.

Another approach, which is based on existing solutions is presented in [18], [19], where the High Level Architecture (HLA) [20]–[22] is employed as an intermediate interfacing mechanism. The main benefits of the standard is that it favours the reuse of existing models and interoperability across diverse platforms. It is a mechanism based on the publish-subscribe design pattern, where a number of individual simulations can collaboratively run by publishing and subscribing generated information and events either by the same simulator or another one. This information is exchanged via a service bus, call Run Time Interface (RTI) that connects all the simulations and manages the traffic.

A feasibility study was conducted in [23] to demonstrate the effectiveness of 802.11p WAVE protocol, by carrying out simulations and experimental trials, with the potential to model vehicle-to-vehicle communication at large scale. Regarding the former, an in-house vehicle simulator by Ohio State University was linked to network simulator 3 (ns3) to model the line-of-sight (LOS) and non-LOS, which satisfactorily meet the needs of complicated urban environment.

In order to improve the road safety, the concept of V2P has been studied in [24]. By using the existing infrastructure, wireless communication that is based on 3G and LTE protocols of smartphones is a promising direction. From the vehicle's side, either driver's smartphone or vehicle's dedicated systems can be used. Because the power source is identified as a weakness, energy-saving modes are employed in risk-free situations that automatically changes mode, as necessary. In the proposed solution, cloud-based infrastructure will process data (i.e., speed, location and direction), so as to detect collisions. Through this study, it was demonstrated that using cellular technology for higher market penetration. A number of energy-saving profiles were also calculated and illustrated. As this is a prototype work, only three smart phones were considered. In addition, pedestrian and vehicle dynamics were not covered.

A similar application was presented in [25], where this time Wi-Fi was selected for wireless communications. By conducting field trials, it was demonstrated that Wi-Fi is a viable alternative at frequency rates higher than 1Hz. More importantly, during field trials, the weather condition could severely affect the accuracy and, hence consequently, the safety.

While investigating a future concept, where electrical vehicles are expected to be deployed at a large scale, the supporting infrastructure is going to be design by using big data from multiple sources, as described in [26]. More specifically, the driving patterns in an Italian Province were studied for over a month and projections suggest a paradigm shift from conventional vehicles to battery electric vehicles. The market penetration could reach up to 57% and several charging point will be required. By applying appropriate routing schemes and a V2I strategy, the demand for energy could be effectively controlled and points of interest (i.e, charging stations) were suggested. Additional strategies were also investigated, where the electric vehicles could return energy back to the grid, to cover/mitigate any peak periods. Ultimately, the use of big data aims to suggest sustainable policy changes and an alternative urban design. Nevertheless, only big data techniques were used by using a commercial software package (i.e., MATLAB), without any modelling of vehicle or pedestrian dynamics.

C. *Optimisation and Decision Making in Intelligent Mobility*

The combination of a MOO genetic algorithm with fuzzy logic was demonstrated in a real-world application in [27], where a road corridor in the streets of London was simulated and optimised. The microsimulation of vehicles was carried out by using VISSIM. The delays and stops of vehicles were adjusted by employing the traffic control system called SCOOT, which alters the duration of the stages of the cycle. The aim was to optimise public transport, pedestrian flows and road traffic. However, by design, using genetic algorithms is not a sustainable solution when the problem scales, as the size of the problem and any constraints could trap the optimiser.

During the design of a network, the minimisation of emissions and travel time were presented in [28]. Two problem instances were optimised; one single- and one multi-objective, for time and time and emissions, respectively. It was demonstrated that the considered objectives are actually conflicting. A number of solutions were generated by the optimisation method, where it is suggested to employ MOO in large problem instances (e.g. a city network). As mentioned above, the use of genetic algorithm is appropriate only when the size of the problem is small.

A series of simulations with multiple populations of vehicles per hour were run to optimise the traffic singals in [29]. A genetic optimiser was linked to an in-house vehicle microsimulator based on cellular automata, and deployed on a custom computer cluster. Four different types of objective functions were used: the number of vehicles, mean travel time, rate of time of occupancy over state of occupancy and global mean speed, but only one of them was optimised each time. A similar case is also described in [30], [31], where a genetic algorithm was combined with a simulation package accelerated by Graphics Processing Units (GPUs), so as to optimise the number of vehicles exiting a road network within a give time interval. A small road network that comprises of 4 signalled intersections was considered in a quadratic optimisation problem. Apart from the limitation of genetic algorithms mentioned above, these studies optimised a single objective only, which cannot reveal any trade off among conflicting objectives.

The optimisation of traffic signal timings in urban and rural environments was discussed in [32]. A genetic algorithm was coupled to VISSIM, where 4 basic signal timing parameters and transit priority settings are evaluated. This approach had outperformed other competitive solutions of commercial optimisation algorithms that were coupled with commercial micro simulators. However, this is a computational intensive task and very specific to the underlying vehicle microsimulator.

A real-world application of a platform for transport decision making is described in [33]. By using anonymous monitoring of mobile cellular networks, a new real-time urban monitoring system was developed and deployed in Rome. The received feeds by a number of sensing systems is expected to assist in understanding and accordingly managing/optimising urban dynamics. The status of vehicular traffic and movements of pedestrians and foreigners were registered in maps to reflect their behaviour, so as to construct layers of maps so as to realise the needs for data to assist citizens and offer additional services. This could feed into urban-planning activities and tourist management, so as to extract deeper knowledge about the urban dynamics, while provide high levels of information to enable much more informed decisions. However, this is mainly for monitoring purposes and cannot suggest solutions for design, but it can be used for assessment and validation purposes.

III. Conclusion

Because of the scarcity of research work, selected state-of-the-art methods in intelligent mobility and telecommunications were presented above. To the best of the authors' knowledge there is not any study, where an urban environment that includes vehicles, pedestrians and telecommunications has been integrated into a simulation, so as to discover and suggest optimum solutions to the design of the urban environment. There are solutions that attempt to combine two of the above, but this relies on bespoke interfaces developed to support commercial software packages. One level above, such simulations were not linked to any optimisation methods. Because of the diversity of available solutions, the approach from [18], [19] is selected, as it has the potential to carry out large-scale modelling at scale and can transparently integrate a number of principles.

Future steps will include the experimental development of a prototype junction in an urban environment at simulation level by using all the above methods. This will be converted into a black-box simulation, where parameters that characterise the road traffic, mobility and telecommunication network operation would be specified by an external system. Consequently, this simulation should be calibrated (by using real-world data), verified and validated against real-world data, so as to produce repeatable results that could be used to extract additional knowledge of the simulated system. It is important to mention that validating dynamics and adaptive systems is a relatively new field, where the validation methods/approaches have not been widely established, which leaves more room for improvement and innovation. Then, this will be linked to MOO algorithms, so as to minimise the emissions produced of selected use cases along with operational performance indicators (e.g., average travel time per agent). Thereafter, the optimum solutions revealed, will be ranked by using MCDM algorithms, so as to rank the solutions based on authors' experience, with intention to provide to community of intelligent mobility the means to specify their desired parameters.

Acknowledgment

The authors would like to thank the anonymous reviewers for their feedback and advice.

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