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MCDA/M in Telecommunication Networks - challenges and trends

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Abstract: The extremely rapid evolution of new telecommunication technologies and services and its interaction with a complex socio-economic environment, justifies the increasing interest in applying multi-criteria evaluation approaches in a wide variety of decision making processes involved in network planning and design. After a brief overview of critical evolutions in telecommunication network technologies and services, an outline analysis of issues and difficulties concerning the applications of multi-criteria decision aiding/making (MCDA/M) in telecommunication network planning and design, is described. Also highlights on more relevant or recent contributions of this type, in network design and planning models, including strategical and policy issues, will be presented. Finally, an analysis and outline discussion of current and future research trends and challenges concerning the use of multi-criteria approaches in these areas, is put forward.

Keywords: multi-criteria decision aiding/making; telecommunication networks, network design; telecommunication policies.

1 Motivation

Telecommunication networks and technologies, as well as the services they support, have been and continue in a process of extremely rapid evolution. These trends, fostered by an exponential increase in offered traffic and a substantial demand for better and more advanced services, constitute a process of the greatest importance, not only in terms of technological advances, but also regarding their quite significant impacts on the economy, having in mind the large investments involved, moreover on the society as a whole. The evolution of these networks gives rise to a great variety of complex and multifaceted problems, typically involving multiple dimensions, often of conflicting nature. This means that the interaction between the complex socio-economic environment of nowadays societies and the extremely fast evolution of new telecommunication networks, clearly justify the interest in using multi-criteria evaluation in decision making and analysis processes concerned with multiple activities of network planning and design. These factors, and the past research experience of the authors in some of these areas, laid the motivation for the topic of the present work, where we will seek to analyze and discuss trends and challenges of MCDA/M in relation to telecommunication network evolutions. A state of art review on applications of MCDA/M to telecommunication network planning and design, was presented in [Clímaco *et al.*, 2016], where papers up to 2012 were analyzed.

This work is organized as follows. In the next section we will present an outline of the more relevant evolutions of telecommunication network technologies and services**,** emphasizing more recent and foreseeable developments. Also in this section, an outline of major multi-criteria approaches and methods, all relevant in the addressed application areas, will be put forward. In section 3 we highlight more recent or relevant works, using multi-criteria models, published in the context of routing methods, planning and design of telecommunication networks, including strategical and policy issues.

Finally, a discussion of future trends in these areas will be outlined, seeking to emphasize possible challenges concerning applications of MCDA/M to new technological platforms and services, as well as correlated methodological issues and challenges.

2. Telecommunication Networks and Multi-criteria Analysis

2.1 Evolutions of Telecommunication Networks - Brief Overview

For a better understanding of the implications of network technologies evolutions in the emergence of a significant number of new sets of problems of network planning and design, many of which may involve multiple criteria, we present a very short overview of major trends and factors concerning such evolutions.

In historical terms, we can say that the most relevant telecommunication network evolutions have been centered around two major modes of information transfer: circuit switching (typical of classical telephone networks) and packet switching (typical of Internet). An historical milestone was the development of the TCP/IP (Transmission Control Protocol/Internet Protocol) suite, that enabled the very rapid expansion of the Internet in the 1980s, strongly accelerated in the 1990s through the release by the European Laboratory CERN (European Organization for Nuclear Research), in 1993, of basic Web technologies. Concerning the classical telephone networks, they rapidly evolved from the 1980s into ISDNs (Integrated Services Digital Networks) enabling the convergence of different types of services and to broadband ISDNs (B-ISDNs), as a response to the rapid expansion of the demand for new data services and to more bandwidth "greedy" services. These latter networks were based on the ATM (Asynchronous Transfer Mode) technology, which was rapidly abandoned after 2000, as a consequence of the emergence of cost effective multiservice Internet based technologies, supporting the implementation of connection oriented services and advanced QoS (Quality of Service) routing and network management mechanisms. In this context we could refer to IntServ (Integrated Services), and DiffServ (Differentiated Services) technologies.

In recent years MPLS (Multiprotocol Label Switching) and GMPLS (Generalized MPLS), based on optical networks, have emerged, as more advanced base technologies for use in IP networks. In MPLS [Awduche *et al.,* 2001], label switched paths are established, enabling traffic flows to be carried while ensuring various QoS requirements. Note that a fundamental reason for the success of Internet based technologies, as basic communication transfer platforms, is the fact that they enable a high percentage of the capabilities of an "ideal network", in terms of supported services, at a significantly low relative cost, as shown in [Handley, 2006]. These evolutions were supported, at the level of the transport infrastructure (transmission networks) by the development, especially in the last decade, of more advanced optical networks capable of making the most of the large bandwidths associated with the extremely low wavelengths that may be carried by optical fibers. This trend led to the deployment of WDM (Wavelength Division Multiplexing) and DWDM (Dense WDM) networks, the latter using tens of wavelengths on each fiber, enabling extremely large information rate transfers and an enormous traffic carrying capability with flexibility, provided by the introduction of wavelength conversion in the optical switches.

As for the transmission technologies (or 'carrier technologies') based on optical fibers, the existing SONET/SDH (Synchronous Optical Network/Synchronous Digital Hierarchy) systems gave rise to new carrier technologies, such as Carrier Ethernet [Reid *et al.* 2008] and MPLS-TP (Transport Profile) [Niven-Jenkins *et al.,* 2009], as cost-effective and functionally advanced alternatives. A major recent trend in transport technology evolution for optical networks is OTN (Optical Transport Network) originally designed (see [ITU, 2009]), as the base transport system for SDH and subsequently extended for supporting IP (Internet Protocol) and Ethernet. It has a multiplexing hierarchy from 1.25 to 100 Gb/s, capable of coping with very large bandwidths, and providing advanced capabilities in terms of operations, administration, maintenance and provisioning at wavelength level. The interplay between these technologies in the different functional layers of telecommunication networks, enables the use of various network architectures such as IP/MPLS over WDM or IP-over-OTN-over-WDM, the latter being expected to reduce the needed router capacities and power consumption, also enabling a more efficient utilization of bandwidth, as a result of the advanced capabilities of the OTN switches. Another area where there have been extremely rapid evolutions concerns wireless networks, driven by the exponential increase in the demand for mobile data services, namely Internet access, since early 2000, where the annual increase rates were 60-80% – *apud* [El-Sayed & Jaffe, 2002]. The rapid evolution of 3G (third generation) to 4G networks provided, in many countries, mobile broadband access to different mobile devices, in a comprehensive and reliable IP-based network. These technologies enabled a quick shift from traditional telephone services, predominant in earlier technologies, to data services. Note that 4G (fourth generation) networks are interoperable with existing wireless standards, enable significant improvements in QoS performance and provides an extensive range of services, including applications like HD (High Definition) broadcast, video calls and mobile TV, as well as a multitude of applications for entertainment, business, social networking, education, etc. For instance, according to a CISCO report [Cisco, 2017] 4G traffic accounted for 69% of global mobile traffic in 2016, although 4G connections represented only 26 percent of mobile connections in 2016. According to [Tran *et al*, 2017] it is expected that mobile data traffic will continue to double every year in the near future. Another major factor driving the developments in wireless networks is the expected increase in mobile video traffic; according to the Cisco report [Cisco, 2016] this traffic already represented 55 percent of the total video traffic, and there are estimates of an annual growth rate of more than 60 percent [Tang *et al.,* 2017]. For example, at present, it is estimated in [CTIA, 2017] that 7 per cent of US consumers watch mobile videos daily. Other important aspect should be mentioned, concerning new types of service demand, namely the great impact on telecommunication networks of the unprecedented evolution of cloud computing. This trend generates significant amounts of traffic flows of new type, namely dynamic 'anycast' flows (i.e. from one origin to one of many possible destinations), and poses new challenges to the design of transport networks, as analyzed in [Contreras *et al.,* 2012].

The factors discussed above, pave the way and justify the necessity for the next step in wireless technology evolution, the 5G (5th generation) networks [Monserrat *et al*., 2014]. This is expected to provide important quantitative and qualitative advancements regarding increased bandwidth access (enabling new and/or better QoS data streaming services, including broadband services) and transmission latency (enabling more stringent requirements for real-time services). This will answer to the technical challenges raised by the fact that mobile users are subject (unlike users in wired networks) to time-varying, significantly heterogeneous transmission channel conditions and variable availability of network resources. Note that ITU-R (International Telecommunication Union-Radio Communication Sector) and the Next Generation Mobile Network Forum have proposed ambitious objectives for 5G networks, such as access bit rates up to 10 Gb/s. The implementation of 5G will also require the need for coordination among various domains of telecommunication networks, namely involving wired networks, radio access, distributed processing and service related functions.

The mentioned expected evolutions in wired and wireless networks are also fostered by the development of the IoT (Internet of Things) in which a plethora of devices are equipped with electronic systems, sensors and software, enabling to exchange data through the Internet. According to [Ali *et al*, 2015] it is forecasted more than 28 billion machine type devices connected to the Internet by 2021, surpassing the number of expected human-centric connections. The IoT involves multiple, interrelated technologies, and its use includes a multitude of applications, from remote smart home control, intelligent transportation systems, grid automation, remote health care to industrial automation (see e.g. [Zanella *et al.,* 2014]). The convergence of IoT and cloud computing technologies is also a developing trend, having in mind the limited resources of IoT devices and the fact that cloud servers can be used for data processing and storage. According to some authors, [Perera *et al.,* 2014]] the technological and industrial-economic impacts of IoT make that it may be considered as one of the main forces behind a fourth industrial revolution. There is a significant number of issues, risks and design challenges raised by IoT technologies, namely of technical, economic, social, cultural, privacy and security-juridical nature, having in mind the massive impact that these technologies, involving both human centered and machine to machine centered interconnections, may have in a near future.

A new technological paradigm that is expected to have a decisive impact in overcoming important limitations in the working and management of current network structures is Software Defined Networking (SDN). The basic concept behind SDN is the separation between the network control logic and the underlying devices that actually implement the forwarding of traffic flows, achieved by direct control of various types of hardware through common management interfaces [Gallis *et al.,* 2013]. The introduction of SDN has quickly moved from small-scale data center/campus networks to large-scale carrier networks and is also being developed for application to 5G wireless networks [Rostami *et al.,* 2017]. This may be viewed as a major development in a wider trend directed to the 'softwarization' of key network functions, based on the separation of the control plane functionalities from the data transport plane. This has major implications in terms of service provisioning flexibility and technical efficiency of networks, thence enabling a reduction in investment and operational costs.

Finally, it should be stressed the increasing relevance of multidimensional QoS/QoE (QoE-Quality of Experience i.e. the multiplicity of performance measures as perceived by the end users, e.g. service availability or communication latency, in a given service) issues in relation to the technological platforms. The QoS/QoE objectives/requirements are defined and have to be analyzed in the context of multi-service Internet based technological platforms and involve the assessment of multidimensional QoS parameters and of the associated network control and traffic management mechanisms. These issues have important reflexes in the type and nature of many new problems of network planning and design, e.g. concerning routing methods, the choice of alternative network architectures or the evaluation of alternative policies involving socio-economic factors. These issues as well as the main functional features of the networks, increasingly involving heterogeneous, interoperable technical platforms, increase the complexity and reinforce the multidimensional nature of many planning and design problems and of the associated decision analysis problems. The multidimensional nature of the aspects to be evaluated and the often conflicting nature of the criteria that should be included in the decision models associated with various instances and problems of the planning and design processes, make it interesting and potentially advantageous, in many situations, the development of MCDA/M approaches in this broad area.

2.2 Multi-criteria Models - Brief Overview

It seems clear that decision processes associated with telecommunication networks take place in a more and more increasingly complex environment characterized by a very fast pace of technological evolution combined with significant improvements in offered services. This trend is interrelated with drastic transformation of market workings and societal expectations. These key aspects of telecommunication networks evolution often involve multiple and potentially conflicting criteria. This is undoubtedly an area where various decisions of socio-economic nature have to be made but where, at the same time, the technological issues are of critical importance as pointed out by [Nurminen, 2003] : "(...) The network engineering process starts with a set of requirements or planning goals. Typical requirements deal with issues like functionality, cost, reliability, maintainability, and expandability. Often there are case specific additional requirements such as location of the maintenance personnel, access to the sites, company policies, etc. In practice the requirements are often obscure. (...)". This author, who collaborated with Nokia in the development of network planning and design models, makes it clear the limitations of single criterion approaches. Nevertheless, he put in evidence the difficulties in the tuning of the parameters involved in mathematical programming models. He also draw attention to the fact that this issue is more difficult to tackle in multiple objective formulations, once the procedures of preference aggregation by the decision maker(s), (DM(s)), require, in general, the specification parameters, for example, the determination of some sort of "weights", objective function thresholds, etc. However, this difficulty does not imply less interest in the development of multi-criteria approaches in this area, although it must be seriously taken into account. In fact multi-criteria models address different concerns of the decision process in an explicit manner, enabling the DM (or DMs) to grasp the possibly conflicting nature of the considered criteria, so that he/she may tackle the compromises that have to be made in order to obtain 'satisfactory' solutions. Of course these difficulties are extensive to multi-attribute models.

When different and conflicting criteria are at stake, the concept of optimal solution is replaced by the concept of non-dominated (also known as Pareto optimal or efficient) solutions set. This includes only feasible solutions for which no improvement in any criterion is possible without worsening at least one of the remaining criteria. In general, we can say that multi-criteria choice approaches seek to obtain one or more non-dominated (or at least approximately non-dominated), solution(s) considered as satisfactory by the DM(s). Note that choosing the method that is used for aggregating the DM preferences is also multi-criteria in nature. Beyond the difficulty previously mentioned, concerning the specification of parameters in the developed models, we should access whether there is the possibility of using interactive procedures, especially taking into account the required speeds of calculation, for a given application. This means that an interactive procedure cannot be used if the calculations, in an interaction, are too slow, with respect to the envisaged application. Furthermore, in various telecommunication network decision problems (for example, in many routing methods), no more than a few seconds (sometimes much less) can be accepted for finding a final solution to be implemented. These are cases in which interactive procedures cannot be used in practice. All these factors, including cognitive as well as technical aspects, are at stake, so that, in many cases, the quality of the selected solutions may be compromised.

Of course it is important to address, in a wider perspective, which multi-criteria model is more adequate to each case. In the above paragraph we referred mostly to mathematical programming models, that may be linear, non-linear and additionally, may have, or not, a specific structure. In contrast, there is other type of models, here designated as multi-attribute decision models, that also have been subject to significant developments, also including applications in telecommunication issues. While in multi-criteria mathematical programming models it is assumed that the set of feasible solutions/alternatives is defined implicitly through the constraints, in multi-attribute models a small and discrete set of alternatives is specified explicitly. The alternatives in this set are then analyzed with respect to multiple criteria (or attributes). Note that in this type of models it is possible to carry out a more detailed evaluation of the alternatives, considering a bigger consistent family of criteria, and this can be done without implying a computational explosion. Nevertheless, in many situations of network design and planning (namely in typical routing and facility capacity calculations) this implies a reductive point of view, which may not be realistic, because it does not enable a proper exploration of the decision space. As illustrated later on, in the highlights of some studies in this area, in some specific problems, the complementary utilization of both types of approaches can be advantageous.

Regarding multi-attribute models, in the so-called American School a multi-attribute utility function (based on multi-attribute utility theory) that may be linear or non-linear (depending on the problem) is constructed [Keeney & Raiffa, 1993]. In the case of the Analytical Hierarchy Process (AHP), this can be viewed as a particular branch of the American School, that involves the identification of a hierarchy of interrelated decision levels [Saaty, 1980], [Saaty, 1994a], [Saaty, 1994b]. An alternative methodology is the so-called French School, the basic principle of which is the introduction of partial orders, that is outranking relations are involved. This means that no more complete comparability of alternatives and transitivity relations are obtained. In conclusion, these methods are less demanding than the former, concerning the fixation of parameters, but, on the other hand, in general, they do not allow a complete ranking of alternatives, hence not guaranteeing the principle of optimality, that is, neither transitivity nor full comparability are verified. Therefore their results are less conclusive with respect to the aggregation of the preferences of the DM.

As the most relevant example of the French School approaches, we can mention the ELECTRE family of methods [Roy & Bouyssou, 1993], [Figueira *et al.,* 2016]. Depending on the problem, the purpose is the selection of the most preferred alternative, the classification or the ranking of alternatives.

More recently, mathematical programming and multi-attribute approaches basing the preference aggregation in inductive rules, have been developed. Namely, the approaches rooted in an adaptation of the rough sets concepts must be emphasized [Slowinski *et al.,* 2012].

Concerning the approaches dedicated to multi-criteria mathematical programming models, attention should be paid to the dimension of the real problems we are dealing with and, many times, as noted above, there is the necessity of a rapid execution. We would like to note that, in many situations, the mathematical programming models to be used have a network structure and, in some of these cases, there are very efficient specific exact algorithms for solving even big instances. This is the case for models involving multi-criteria shortest path problems (see e.g. [Clímaco & Pascoal, 2012]).

However, in most of the situations this is not the case. Therefore, it is often necessary to use heuristics and metaheuristics for resolving these models in acceptable computational times, namely when on-line (and specially real time), calculation methods are to be implemented. In particular, the development and application of multi-objective evolutionary algorithms is remarkable and, as we will show in our summary of some papers, these methods have also been applied to some problems of telecom planning and design.

Furthermore, another key issue has to do with the treatment of the uncertainties in various instances of the models. In particular, in many models, the uncertainty associated with traffic flows offered to the network is of great importance. The representation of this this uncertainty is a task with two major aspects: the use of adequate stochastic models (often mere approximations) for the traffic flows, in the context of the model, and the determination of estimates of the statistical parameters of the stochastic sub-models. Uncertainties and/or imprecisions inherent to other quantities involved in the multi-criteria model, that may be of different natures, for instance data collection or modelling of preference aggregation (see [Bouyssou, 1990]) are also relevant issues in this regard.

Remember that multi-criteria approaches enable, in these conditions, the identification of the set of criteria associated with the stable part of the DMs' preferences, so that a further aggregation of their preferences, is left for further analysis. So, in many cases, the output of the multi-criteria analysis is not a solution but a set of satisfactory solutions, in the context of the used model.

Thence, an *a posteriori,* more detailed analysis of those solutions (namely, having in mind characteristics which were not initially included in the model), is advisable.

In the next section of this text, an outline of more relevant works using multi-criteria models, published in the context of planning and design of telecommunication networks, as well as in the context of socio-economic implications of telecommunications evolution, including strategical issues, is presented.

3. Highlights of Applications of MCDA/M

In this section we will present highlights on recent applications of MCDA/M telecommunication network planning and design problems including strategic planning and policy issues. For a better understanding and facilitation of the analysis of the problematic areas where there has been a cross-fertilization between MCDA/M and telecommunication networks we will consider three areas of decision support and optimization issues, each corresponding to a sub-section. The first area is focused on highlights of recent routing models, an area where there has been a great increase in contributions using various types of multi-criteria based models. The second area refers to network planning and design issues and papers that present multi-criteria modelling approaches dealing with socio-economic evolutions associated with specific telecommunication network problems and the third area includes strategic planning and telecommunication policy evaluation problems. It should be strengthened that there is no sharp frontier between these areas, noting, for example, that network design includes implicitly or explicitly some routing sub-model and that most models of network planning and design involve, either directly or implicitly, economic and/or social aspects.

3.1 Routing models

In the general context of planning and design processes, routing is a key network functionality that may be considered as an integral part of the network operational planning decision process. It is strongly related to other planning activities, namely network structure design (that includes topological design and equipment capacity calculation) and traffic network management (a top level network functionality aiming at a dynamic global optimization of traffic flows throughout the network, having in mind information on the currently available resources and offered traffic). Routing models are essentially concerned with the calculation and selection of a path or set of paths from an originating node to one (several) terminating node(s) (considering that the network representation is a connected graph the arcs of which have a limited transmission capacity), seeking to optimize certain objective(s) and satisfy certain technical/economic constraint(s). Routing solutions have a strong impact on network performance, namely in terms of traffic carried and resulting QoS levels and cost/revenues of the network operator(s).

An important class of routing methods, other than the most common *point to point (or unicast) routing*, involves the calculation of several paths simultaneously, between two nodes or between two sets of originating/terminating nodes. These methods correspond to a class of routing problems designated, in general, as *multi-path routing* problems. A specific type in this class (which may be designated as point-to-point multipath routing) refers to routing models with reliability requirements/objectives, or resilient routing, in which an active path and a back-up path (which will be used in the event of failure in the active path), have to be computed for each pair of origin-destination nodes. Another type is *multicast routing* in which a set of paths has to be calculated from the originating node to a set of destination nodes – point-to-multipoint routing. This is the type of routing for the distributional services supplied by a certain service provider or interconnecting two sub-sets of network nodes, a multipoint-to-multipoint routing model, for example in teleconferencing services in Internet. Assuming all the nodes have to be interconnected, the multicast routing problem is designated as *broadcast routing*, and is usually formulated as a spanning tree problem. If the set of destination nodes is a proper sub-set of the set of network nodes, the corresponding multicast routing problem is typically formulated as a Steiner tree problem, where the destination nodes and the originating node are the terminal nodes.

Routing problems may have different natures and often a multiplicity of formulations, depending on fundamental aspects, namely: the mode of information transfer, the type of service(s) associated with the routed connection demands (for example a telephone call, a video-service, a data stream transfer, a wavelength assignment), the considered level of representation of the network (typically, at least two levels may be considered: the physical or transmission network and the logical or functional network) on which the routing problem is formulated, and main features of the routing paradigm (for example, whether it is static or time varying according to traffic fluctuations or network conditions, in a given time scale). The network technical entities that actually implement, at a lower level of functional network representation, the routing function, are the routing protocols, critically interrelated with the network technological features.

The rapid technological evolution in the late nineties, associated with the increase in the demand for new communication services, mainly Internet based services, implied the necessity of developing multiservice networks capable of dealing multiple, heterogeneous QoS metrics. As noted above, in these networks different classes of services are specified (in the context of given technological platforms) which have different requirements of QoS. The performance of these networks is naturally a function of the degree to which such requirements are achieved and is also expressed in terms of global network measures such as mean traffic carried, blocking probability or average delay. This led to a routing paradigm in telecommunication networks designated as QoS routing. This type of routing methods involves the calculation and selection of chain(s) of network resources along one or multiple feasible paths from origin to destination, satisfying given QoS requirements. These requirements are dependent on traffic features associated with service classes, so that the associated QoS routing algorithms need to consider distinct metrics [Lee *et al.,* 1995]. These routing models typically seek to optimize some metric(s) such as delay, cost, number of edges of a path or loss probability, while the other metrics are treated as constraints. In this context the path calculation problem is typically formulated as a shortest path problem with a single objective function which is either a single metric or a function of different metrics while QoS requirements are included as constraints, that is, it leads to a constrained optimal path problem.

This type of models (usually designated, in the telecommunication literature, as constrained QoS routing), may be considered, as proposed in [Clímaco *et al.,* 2016] as a *first tentative of MCDA/M modelling*. This is justified by the well known principle that a possible approach in multi-criteria model analysis is the transformation of the initially considered objective functions into constraints, excepting one objective function which is optimized. The solution obtained with this procedure is (in adequate conditions) necessarily a non-dominated solution for the original multi-criteria model; moreover, it is possible to obtain different non-dominated solutions by varying the value of the second member of the constraints (see [Steuer, 1986]). This posture, concerning the characterization of approaches which are explicitly multi-criteria, was also adopted in [Wierzbicki & Burakowski, 2011]. These authors proposed a conceptual framework for the development of explicitly multi-criteria modelling approaches, in the context of QoS routing in IP networks

Therefore, in the present highlights of papers, we will refer only to recent contributions on models which are *more explicitly multi-criteria*. Moreover, we think there are significant advantages in approaching many routing problems in modern telecommunication networks, through explicitly multi-criteria formulations. This type of modeling approach to such problems is potentially advantageous although we cannot ignore that, in many instances of routing design, the solution to be implemented, in a given technological context, has to be calculated in a short time, that may range from a small fraction of a second (typically up to tens of ms) to a few seconds. In these cases, as noted above, there is no possibility of using interactive resolution methods, thence leading to the necessity of developing automated path calculation and selection procedures. Nevertheless, there are many situations in which this limitation does not apply, namely in static routing methods, in transport networks where transmission paths are maintained for relatively large time periods or in various types of dynamic routing methods, where the input parameters of the routing algorithm are estimated in advance (for example, considering node-to-node traffic intensities or current link bandwidth occupations, in different time periods), cases in which an interactive procedure could be used to select the routes (for every node pair) to be memorized in routing tables assigned to every router, to be up-dated only after many minutes, when new transmission route(s) have to be calculated. This means that there are many routing models, considering multiple criteria, some of which will be illustrated next, where it is possible the conciliation of automatic path calculation procedures with some flexibility in the form of preference aggregation. For this reason and the possibility of using interactive procedures, in various routing problems (not involving real-time/short-time routing decisions), adequate multi-criteria approaches enable the grasping of the compromises among different and conflicting criteria, also taking into account various QoS requirements. Moreover, such approaches enable a consistent comparison among distinct routing possibilities, in the context of a certain routing principle.

In our highlights of recent contributions, illustrative of the application of MCDA/M, we will consider 'clusters' of routing problems of different types (in italic) and, for each type, a classification acronym for each reference, dedicated to the papers outlined in this work, according to the MCDA/M approach/method used in the modeling and/or resolution method.

Having this in mind, we consider a tentative classification of the used multi-criteria models and resolution methods, according to the following types and corresponding acronyms: i) simple weight additive models, (SWAM – namely models where there is an *a priori,* direct or indirect, specification by the DMs of weights assigned to the each criteria; ii) multi-criteria network flow programming (MNFP); iii) multi-criteria shortest path models (solved with exact algorithms) (MCSP); iv) multi-objetive integer linear programming based formulations (MILP); v) multi-objective nonlinear programming based formulations (MONLP); vi) multi-criteria minimal spanning tree models (solved by exact algorithms) (MMST); vii) multi-criteria heuristics (MH); viii) multi-criteria metaheuristics (MMH); ix) outranking methods: (ELECTRE) and (PROMETHEE) methods; x) Analytic Hierarchy Process and extensions (AHP-E); xi) multi-attribute utility theory based methods (MAUT). Note that under the classification MH we may find quite different techniques, from heuristics based on simple empirical enumeration rules of generation of feasible solutions, with elimination of the dominated ones, to dedicated heuristics, seeking to explore properties of the problem, often based on exact sub-algorithms for generating candidate solutions. Also under the classification MMH we may find quite different procedures, from simulated annealing to evolutionary algorithms of various types.

We will begin by considering some *multi-criteria routing models for Internet*.

The paper [Girão-Silva *et al*.(2012)] (MH) describes a dedicated heuristic, using a Pareto archive, for solving a complex hierarchical multi-objective routing model in MPLS networks with two service classes, formulated as a multi-objective network-wide optimization model (characterized by the fact that the objective functions of the route optimization problem depend explicitly on all traffic flows in the network), with stochastic objective functions, including fairness objectives; the developed heuristic is ultimately based on a bi-criteria shortest path sub-algorithm, using as path metrics implied costs and blocking probabilities.

The paper [Girão-Silva *et al*.(2015)] (MNFP) presents a multi-objective routing model for MPLS networks, considering multiple service types and traffic splitting, using a network-flow approach; the routing problem is formulated as a multi-objective mixed-integer program where the considered objective functions are the bandwidth routing cost and the load cost in the network links, with a constraint on the maximal splitting of the service bandwidth demand; two different exact methods are developed for obtaining non-dominated solutions, one based on the classical constraint method and another based on a modified constraint method [Messac *et al.,* 2003].

In [Girão-Silva *et al*., 2017] (MILP) the authors propose a multi-objective resilient routing model for MPLS networks with multiple services and path protection, where the considered objectives are route cost and load cost; the routing problem is formulated as a bi-objective integer program, in the context of a network-wide optimization approach using a link-path formulation; an exact method based on the classical constraint method for solving multi-objective problems, is used for obtaining all non-dominated solutions, given the set of feasible node disjoint path pairs.

The paper [Bhat & Rouskas, 2016] (MH) describes a new type of *routing model assuming marketplaces* of dynamically supplied 'path services', that considers as objectives, to be optimized, cost and expected delay and includes various QoS requirements; users are supposed to choose from a set of 'path services', offered by multiple competing network providers, which are feasible for given time intervals; the authors propose a dynamic programming heuristic for solving the associated multi-criteria constrained shortest path formulation, for certain time windows.

[Aissanou & Petrowski, 2013] (MAUT) propose a MCDA/M model for route selection by an autonomous system, in a dynamic data routing network, considering, as criteria to be optimized, packet delay and loss rate; the model uses a set of nested 'quality boxes' in the criteria space, for defining an utility function; a learning heuristic procedure is proposed to configure the boxes, based on subjective quality assessments provided by users, considering an application to *wireless ad-hoc networks*.

[Thaalbi *et al.,* 2013] (based on AHP-E) propose a multi-attribute model for route selection in a multipath dynamic routing process in mobile ad-hoc networks, the criteria being delay, jitter, packet loss rate and data rate, considering multiple service classes; the multi-attribute decision procedure used for selecting 'best quality routes', was proposed in [Savitha & Chandrasekar, 2011] and is based on AHP.

Wireless sensor networks (WSNs) - composed of sensor nodes that are installed with the objective of gathering real time information, of certain type, in a given area, so that the associated data are forwarded to a special node, the sink node - is an area where multi-criteria routing models have been recently proposed. Most proposals aim at the introduction of 'fast' heuristic procedures of path calculation in the routing protocols, taking into account several criteria to be optimized. [Sahli *et al.,* 2012] (SWAM) describe a generic routing framework concerning the criteria to be addressed and discuss a form of additive aggregation based on technical features of the used routing protocol.

[Bhunia *et al.* 2014] (SWAM) present a multi-criteria routing model for WSNs, considering as objectives residual energy of a node, frequency count of packet transmission via a node, value of frequency count of packet transmission via a node, number of hops counted from the sink node; a heuristic routing procedure based on additive aggregation of criteria, using various weight sets, empirically evaluated in terms of the resulting packet loss ratio, is proposed. The same type of modeling approach is presented in [Das *et al.,* 2015] (SWAM) but considering a heuristic based on a weight product calculation (with weights assigned to each criterion) where the weights are chosen by a 'weight rating' method.

Also [Suh *et al.* 2015] (SWAM) describe a multi-criteria routing procedure for WSNs, considering distance, queue length, and residual energy of each node; the model uses a concept of 'virtual potential field-based energy' routing and a weighted normalized decision matrix for choosing the next node to be selected in the path.

In a model, shown in [Rehena *et al.*, 2017] (MH)), the two criteria, in WSN routing with partitioned sink nodes, are the distance of the node from the sink and the remaining energy of a node; a heuristic procedure is used, based on the calculation a decision matrix the elements of which are obtained from an utility function, involving those criteria, the value of which is associated with the choice of the next node to be selected in the path. Note that almost all these routing models for WSNs use a ´step-by-step´ path calculation heuristic, where the next node in the path is chosen through a multi-attribute model based on the construction of a performance matrix at each step of the procedure.

In [Bueno & Oliveira, 2014] (MMH) a multicast routing model is formulated as a multi-objective Steiner tree optimization problem; the objective functions are the tree cost, mean end-to-end delay to the destination nodes, maximum end-to-end delay, number of arcs and maximum link utilization; a metaheuristic, based on the Strength Pareto Evolutionary Algorithm [Zitzler *et al*., 2002] is used as resolution procedure, and three variants of the heuristic are tested.

A bi-criteria *resilient routing model* (MCSP) for transport networks is described in [Gomes *et al.,* 2012] seeking the calculating of a bi-criteria active path (in terms of minimal load cost and hop count) with a maximally disjoint protection path; an exact resolution method is described, which is based on a k-shortest path algorithm, applied to the convex combination of the two objective functions, hence enabling to obtain all supported and unsupported non-dominated solutions. [Gouveia *et al.,* 2016] (MILP) present a multipath problem, in the context a general resilient point-to-point routing model, by considering a lexicographic optimization formulation; the aim of the formulation is to minimize the number of service (or active) paths with the worst number of hops, such that each connection demand is routed through a set of node disjoint service and backup paths, all with a bound on the number of arcs; integer linear programming formulations are specified and tested for obtaining exact solutions.

The paper [Gomes *et al.,* 2016] (MH) proposes a lexicographic approach to the point-to-point resilient routing problem in GMPLS networks; the model involves the calculation of pairs of paths seeking to minimize, lexicographically, the number of common nodes, the number of common arcs, the number of common SRLGs (Shared Risk Link Groups, i.e. sets of arcs which share a common risk) and the path pair cost; two heuristics for solving the problem are developed and its performance evaluated with reference test networks.

The reference [Craveirinha *et al.* 2013] (MMST) describes a bi-criteria minimal spanning tree routing model for broadcasting messages or defining *overlay networks* over a MPLS network; the considered objective functions are the total load balancing cost and an average upper delay bound on the arcs of the spanning tree. An exact algorithm is used for the calculation of all supported non-dominated solutions and one of such solutions is selected by a method based on the approach in [Gomes da Silva & Clímaco, 2007]. In [Craveirinha, *et al.,* 2016] (MMST) a bi-criteria optimization model for constructing resilient overlay or broadcast networks, based on spanning trees, over WDM optical networks, is presented; the objective functions are the minimization of the total number of different SRLGs of the tree (hence seeking to maximize reliability) and the minimization of the total bandwidth usage cost; the formulated problem is solved by an exact algorithm which is an extension of the minimal cost/minimal label algorithm in [Clímaco *et al.*, 2010], enabling the whole set of non-dominated solutions to be calculated; methods for selecting a final tree structure, in various practical decision environments, are put forward.

In [Esteves & Craveirinha, 2013] (MONLP) a stochastic bi-criteria problem, for calculation of the *allocation of servers* in a multidimensional Erlang loss system, considering a max-min criterion of equity in the blocking probabilities and the maximization of the total traffic carried by the system, is formulated. An exact algorithm for traveling on the Pareto frontier, in the objective function space, based on a Newton-Raphson method, is also described.

3.2 Network planning and design

Network planning and design designates a vast area of activities, dealing with short and medium term network problems, that are focused on the location, interconnection lay-out and dimensioning of transmission systems (cables, optical fibers, radio and satellite links) and other facilities such as switching units, traffic concentrators, routers or mobile stations. Operational planning usually refers to short term network design, often encompassing network management, maintenance and related activities. As for strategic planning, it deals with the development, analysis and evaluation of scenarios of qualitative and quantitative network expansion, focused on medium/long term periods, taking into account the traffic growth, the demand for new services, the introduction of new technologies and economic objectives. It must be remarked that the frontiers between medium and long term planning is often blurred. At the highest level, strategic planning also concerns, explicitly, telecommunication government policy and socio-economic issues. Note that this type of strategic decision problems involves a multiplicity of factors some of which cannot be directly represented by an economic indicator.

Many network planning and design models seek to express different aspects of the associated optimization problems, involving, in reality, multiple requirements and often conflicting objectives, in terms of economic measures, in order to encompass those aspects in a unique objective function. These models lack, in most cases, to capture explicitly the various and possibly conflicting aspects arising in evaluating network design solutions and network expansion policies. That is why MCDA/M models, by enabling an explicit consideration of technological, economic, and social aspects, allow the DMs (Decision Makers) to tackle the conflicting nature of the objectives and analyze the trade-offs that have to be made, having in mind to choose a satisfactory solution.

Only in specific problems of network planning and design there have been recent proposals of multi-criteria modelling. Here we present highlights of some recent and significant papers in these areas. The same system of classification of papers, according to the MCDA/M methods used in the resolution approach, described in the previous sub-section, is used.

The paper [Bezruk *et al.,* 2012] (SWAM), describes a generic multi-criteria system-optimization approach for network design, seeking to obtain Pareto optimal variants of the network design solution; the approach is applied to the design of a *cellular wireless network* and the resolution method, after generating a set of permissible variants of the system, obtains non-dominated solutions based on the optimization of a convex combination of the objective functions, the form of which is determined with the use of some additional information obtained from a decision maker.

Concerning the design of wireless networks, [Statnikov, *et al.* 2013] (MH) describe a multi-criteria optimization model of cellular networks with seven quality of transmission related parameters and two variables per cell (transmitter power and electrical tilt); the authors use the 'Parameter Space Investigation (PSI) method' in [Statnikov & Statnikov, 2011] for obtaining non-dominated solutions, through an interactive search.

A problem of design of transmission systems and the *optimization of bandwidth allocation* is described in [Gonzalez *et al.,* 2016] (MMH) by formulating a multi-objective optimization model for fractional frequency reuse in mobile wireless networks, considering as criteria to be optimized: system average bandwidth capacity, cell edge bandwidth performance, and energy consumption; an evolutionary metaheuristic is used for obtaining an approximation to the Pareto front of the formulated problem.

The paper [Shi *et al.,* 2014] (AHP-E) describes a multi-attribute model for application of *countermeasures against malicious attacks* to nodes of mobile ad hoc networks (MANETs), for e.g. in military, emergency or mining operations, using a cluster-based strategy; the AHP methodology is used to choose 'cluster head' nodes which are supposed to implement the countermeasures, by weighting the three selected technical criteria.

A multi-attribute model for *global performance evaluation* of IP based networks (under different traffic loads or for comparison of networks with the same traffic), is proposed in [Chen *et al.,* 2014] (ELECTRE); from a network performance matrix, with tens of QoS parameters measured in different time periods, a maximizing deviation method based on ELECTRE principles [Chen & Hung, 2009] is used to determine the attribute weights; this leads directly to a ranking of network alternatives, based on the resulting values of an additive value function.

The social penetration of communication technologies and services and the consequent socio-economic implications justify why they are nowadays in the agenda of various areas of science, philosophy and politics. In fact, their present relevance is remarkable and the future trends have still, in many aspects, non-expectable dimensions.

It is clear that the associated analysis and decision problems are multidimensional and it seems that multi-criteria models can be very helpful tools for decision aiding in this domain. However, as these issues are relatively new, evolving very fast and requiring also very rapid options, the number of studies involving multi-criteria tools is still very limited.

Next we make an outline of some relevant or more recent works dealing with these issues, while drawing attention to the used multi-criteria approaches. In the section dedicated to future trends we will try to foresee auspicious future trends concerning applications of MCDA/M.

The use of multi-attribute models in telecommunications planning, as far as we know, has been mainly proposed for application in models studying interactions between telecommunication evolution and socio-economic issues, as analyzed next. As we shall see, although different multi-attribute methods have been used, in most cases AHP was the chosen method. Moreover, in some cases, mathematical programming approaches have also been proposed.

The references to the studies, reported hereafter, was done taking into account the type of problems in network planning and design, involving socio-economic aspects, addressed in the papers and the type of multi-criteria analysis method used by the authors. Note that the strategical issues are dealt with in sub-section 3.3.

The paper [Mohanty & Dabade, 2015] (MAUT) presents a real case study focusing on *supplier selection* to an Indian telecom service provider, using a AHP technique.

In [Wojewnik & Szapiro, 2010] (MH) a model for *pricing of telecommunication services* is proposed; a heuristic procedure for interactive multi-criteria optimization involving fuzzy coefficients, is presented.

The authors in [Uygun *et al.,* 2015] (AHP-E) describe a MCDA/M model for evaluation and selection of an outsourcing provider for a telecommunication company, using a fuzzy multi-criteria approach (ANP-Analytic Network Process). Note that ANP is a generalization of the AHP methodology, in which hierarchies are substituted by networks that enable the modelling of feedback loops.

In [Abourezq & Idrissi, 2015] (ELECTRE) a multi-criteria model for searching and *selecting cloud computing services*, including criteria to be optimized, such as price, the bandwidth etc. and multiple QoS constraints, is presented; an outranking method, ELECTRE IS [Figueira *et al.,* 2016], is used for solution selection.

In [Adebiyi *et al.,* 2015] (AHP-E) the authors describe a model of analysis of the *behavior of subscribers* concerning retention to a given operator and apply it in the Nigerian mobile telecommunication networks; AHP is applied.

[Pereira & Bianchini, 2013] (AHP-E) present a multi-attribute model for analyzing the major factors that determine the dissatisfaction of clients of mobile network operators in Brazil; a AHP method is developed for ranking of those factors, having in mind to reduce the number of complaints.

In [Bentes *et al.,* 2012] (AHP-E), a multi-attribute model for organizational performance evaluation of a Brazilian telecom company is presented; the MCDA/M model combines the BSC (Balanced Scorecard) method, in [Kaplan & Norton, 1996], with AHP for the ranking of performances of functional units of the company.

3.3 Strategic Planning and Policy Issues

In this sub-section we refer to studies that may be considered as focusing on strategic planning and telecommunication policy issues.

The study in [Keeney, 2001] (MAUT) addresses the issues concerning the construction of a value model dedicated to decision processes in *telecommunication company management*; the author pays particular attention to the structuring of objectives, taking into account both qualitative and quantitative aspects and considering the use of multi-attribute utility functions

[Colson *et al*, 2006] (PROMETHÉE) compare the performance, in a determined period, of telecom operators in four Maghreb countries. They propose the use of a DEA (Data Envelopment Analysis) tool and a well know MCDA method, i.e. the PROMETHÉE II, in order to rank the countries. The study is done for three sub-periods between 1992 and 2001. The authors consider the service technical-economic performance and the operators performance..

[Grzegorek & Wierzbicki, 2012] present an interesting use of multi-criteria evaluation/ranking tools in the study of the social penetration of information society technologies, in the framework of supporting regional policy. Of course, the scope of the study includes the communication technologies penetration but it has a broader scope. The authors make an overview of the available indexes and, emphasizing that an aggregation is always necessary to obtain a ranking, saying that the use of classical additive aggregation is very subjective. That is the reason why they propose a so called “objective ranking” procedure. Instead of eliciting weights from the decision actors, they just use statistical parameters in order to enable the aggregation. Note, as it is admitted by the authors, that the method is not fully objective, because it depends on the options made for those calculations.

The paper [Mfupe *et al.,* 2017] (PROMETHÉE) presents a modelling approach for formulating a regulatory framework to govern the spectrum utilization by wireless networks that are based on the Dynamic Spectrum Access (DSA) technique; for the evaluation of the DSA management policies of regulatory authorities, a multi-attribute analysis model with eleven criteria, including socio-economic objectives, is presented and tackled with a PROMETHÉE method in [Brans & Mareschal, 2005].

Finally, we consider two papers not applying explicitly MCDA/M methods, but based on some multi-criteria concepts.

The first one, by [Desruelle & Stancik, 2014], makes a descriptive comparison of the six principal world players in manufacturing and in services creation, concerning information and communication technologies; the authors consider Value Added, Business Expenditures in R&D (BERD), BERD intensity and labor productivity.

The second one [Torsen *et al*., 2015] is an interesting paper regarding indices for accessing nation 'telecommunications development'; the work justifies why and how they propose a new composite metric, aggregating 11 diversified indicators.

4 Future Trends

Next, we will present an outline of foreseeable research trends and topics in some areas of network planning and design, including topics where it seems likely that more opportunities and challenges for MCDA/M may arise. For facilitating the presentation and help in systematizing the research topics, these trends will be organized in three parts: routing models, network planning and design and models studying interactions between telecommunication evolution and socio-economic issues and finally, strategic planning and policy issues.

4.1 Routing models

We will discuss future trends concerning routing models, around topic clusters, separated by hyphens, with the application feature, common to topics in each cluster, indicated in italic.

- As a first topic we would like to note that OR-based (Operations Research based) models, in network planning and design, usually consider a network representation through a capacitated graph and a matrix of node to node offered demand, or, if we wish to have a complete representation of traffic flows (of a stochastic nature) and of routing methods, a more general representation, through a 'teletraffic network', composed of several mathematical and other logical entities (see e.g. [Craveirinha *et al.*, 2008] and [Clímaco *et al.,* 2016]), should be used. Nevertheless, the nature of real telecommunication networks is even more complex, since they are organized, from a functional, operational and management/control point of view, in several interrelated layers, leading to the necessity of considering them as *multilayer networks*. An Internet network, for example, even in a limited national area, has at least three layers, namely the physical infrastructure (or physical layer, including coaxial cables, optical fiber cables and microwave links), the router topology layer (corresponding to the logical layer) and above this, the third layer, where application level and social network flows can be represented (see e.g. in US Sprint service provider [KU, 2012]). This problematic also raises difficult modelling issues, as far as routing and network design models are concerned, having in mind the very great complexity of these structures and the interrelations between the various layers. An useful tool, in this respect, is multilevel graphs [Çetinkaya *et al.,* 2013], a mathematical representation of these networks, consisting of various graphs, one for each layer, corresponding to a level of the graph, such that the set of all nodes in a higher level is a subset of the set of all nodes in the immediately lower level, and the nodes which are not connected in a lower level are equally not connected in the higher level. These aspects should be taken into account in OR-based models in general and in multi-criteria models in particular. Furthermore, we think, as noted in [Rak *et al.,* 2015], that multi-criteria routing approaches are potentially advantageous in the context of multilayer networks and pose interesting challenges. In fact, beyond the intrinsic advantages of multi-criteria routing approaches, already discussed in section 3.1, and concerning resilient routing with protection, the development of such multi-criteria routing models could enable a consistent treatment of the trade-offs between various metrics associated with different routing and protection options in each layer, in different failures scenarios. This would require to tackle the difficult issue of decomposition of the routing optimization model. In fact, the non-dominated solutions of the routing optimization problem formulated for the physical transport network (lower level, for example a OTN optical network) would correspond to pairs of light-paths, such that each light-path may correspond to different possible paths, in the following layer (for example MPLS-TP). The routing optimization model would also be multi-criteria in this layer, so that a complex problem decomposition is at stake. Note that a first approach to a multi-criteria routing optimization framework for MPLS networks, with a hierarchical structure, based on a three level hierarchy of objective functions, focused on global network objectives, service objectives and micro-flow QoS objectives, was earlier proposed in [Craveirinha et al, 2008]. However, a second kind of hierarchical modelling approach, suitable for multilayer networks, would involve a hierarchy of the routing optimization formulation, i.e. concerning the application of classical optimization methods (see e.g. [Findeisen *et al.,* 1980]) to multi-level routing, as suggested in [Wierzbicki & Burakowski, 2011]. This involves, in single-criterion approaches, the decomposition of routing problems into routing sub-problems, concerning different domains, and then the composition of solutions of these sub-problems to seek global optimality. The adaptation (in the first case, noting that it is already a hierarchical multi-criteria approach) and/or extension, in terms of multi-criteria optimization (in the second case) of these two types of modelling approaches, to the specific nature of multilayer networks, are challenging methodological issues that, in our opinion, deserve future investigation.

- Also *cellular mobile wireless, ad-hoc wireless and heterogeneous networks* (these are networks where an end-to-end connection may use different technological platforms and has to transverse several networks or routing domains with distinct technical features) are application environments that have and will be subject to significant evolutions which are and will be posing new, specific routing problems, where there are clearly new opportunities and challenges for the development of multi-criteria routing models in the near future. This is expected having in mind: the technical specificities of each network structure; the increasingly more complex nature of some of the routing problems (also reflecting the more complex nature of the network structures, specially in the case of heterogeneous networks); the multidimensional characteristics, often conflicting, of the metrics and features that, desirably, are to be explicitly included in the routing models.

- Concerning *modelling aspects for the new technological platforms*, this will require, as far as routing models are concerned, the specification of adequate criteria, involving technical and often socio-economic aspects, as illustrated in some of the references in section 3.1. We also should mention the trend for including, in network planning and design approaches, power consumption as a relevant criterion, not only by economic considerations but, foremost, having in mind the already significant environmental impacts of energy consumption by telecommunication networks and ICT (Information and Communication Technologies) structures in general. This concern also applies to routing models by considering the so-called 'energy-aware routing methods', as illustrated in [Wiatr *et al.,* 2012] where a heuristic routing method for WDM networks is presented, that shows that there is a conflict between power consumption minimization and blocking probability. This is a specific area where adequate multi-criteria routing models should be developed, namely by extending previous models which did not included this criterion, capable of exploring the trade-offs between power consumption and standard QoS/QoE objectives.

- We also should refer to issues that continue to be relevant, as a research topic, in the context of *QoS routing models which are explicitly multi-criteria,* having in mind the application of existing or of new multi-criteria routing methods dedicated to the new network technological platforms, and, in particular, to heterogeneous or multilayer networks. A first issue to be addressed, in a given application environment, is the obtainment of better trade-offs in terms of exactness of the solution and computational efficiency. Note that many unicast routing models (without protection) of this type, are formulated as multi-criteria shortest path models. This issue is particularly relevant in situations for which there is no feasible optimal solution and the algorithm takes excessive time to detect such condition or to search for non-dominated solutions in all areas of the objective function space of more interest (in terms of some system of preferences) or if the memory requirements are a practical constraint. This is often the case for networks of large dimension/connectivity and this type of limitations is critically related to the so called 'scalability' of the routing method, that is the range of network dimensions or routing domains where the devised routing model can be applied. This is a critical concern which appears when we discuss a possible protocol implementation associated with a given multi-criteria algorithm.

Regarding the complexity of exact algorithms, in our view, these should be the first type of approach, the applicability of which should be evaluated, in this particular sub-area of routing problems. We would like to remind that, although classical NP-completeness analysis is naturally relevant, this is a worst-case analysis and, in many cases of application to routing methods, it may not be the decisive factor for choosing a resolution procedure. In fact, as noted in [Kuipers & Mieghem 2005] worst-case complexity and execution times can be quite different in different cases of application. We think this is relevant, not only in 'classical' QoS routing algorithms but also in some multi-criteria routing methods, as the ones using exact multi-criteria shortest path formulations, tackled with efficient algorithms, compatible with the required computational times, examples of which were referred to in section 3.1. Similar considerations apply to some multicast routing models based on bi-criteria spanning tree algorithms, as illustrated in [Craveirinha *et al.,* 2013].

- Increasingly important as research themes, in relation to the new technological platforms and services, are routing methods that require the calculation of several paths simultaneously, i.e. *multipath routing models*. In particular, multicast routing involves the calculation of a set of paths from an originating node to multiple destination nodes, constituting a sub-set of the total node set, which involve the calculation of "minimum" (single criterion or multi-criteria) Steiner trees. Of course these are research topics where new problems and challenges can be foreseen, taking into account, on the one hand the great complexity of the associated combinatorial problems, on the other hand the increasing multiplicity (and often the increasing structural complexity, as noted above) of new technological platforms, network architectures and service requirements. Topics of this kind would be, for example, the development of multi-criteria routing models for 'anycast' flows associated with cloud computing, above referred to (see [Contreras *et al.,* 2012]), or specific multicast routing methods, e.g. for MPLS networks, where it is imposed that solutions include specific intermediate nodes, difficult problems which involve the obtainment of Steiner trees with special constraints. Note that related single-criterion unicast problems, (intended for applications to resilient routing with path protection) concerning the calculation of shortest node disjoint path pairs visiting specific nodes, was recently addressed, through efficient heuristics, in [Gomes *et al.,* 2017] and [Martins *et al.,* 2017].

- Another methodological trend is the development of *heuristics and metaheuristics* dedicated to the resolution of multi-criteria routing models in IP-based networks and multilayer networks, an area that is expected to continue growing in a near future. This has to do with various factors, now briefly revisited. Firstly, in spite of many classic NP-complete QoS routing problems having exact resolution methods, these may become intractable in networks of greater dimension and/or connectivity. This difficulty also may arise in many other cases, for example in models based on minimal spanning trees, where for larger dimensions of the networks, exact algorithms may become computationally too costly or even intractable. Secondly, in several cases, the introduction of new constraints may significantly complicate the base formulations. Thirdly there are many other routing optimization problems that are NP-hard in the strong sense, for which there are no exact resolution methods with execution times compatible with the applications. This is specially relevant in dynamic routing with very short routing update periods and in real-time routing. Another factor is the confluence, in some routing models, of one or several 'complicating factors' in the sense described by [Jones *et al*., 2002]: very large number of variables (in particular in integer and mixed- integer formulations), non-linear objective functions/constraints, the explicit consideration of stochastic sub-models in the problem formulation and non-standard utility functions, as in many multi-criteria approaches (see e.g. in [Craveirinha et al., 2008]). These factors, articulated with the quite rapid increase in computing power as well as the advances in metaheuristic techniques and their availability in the Internet, have promoted the increasing importance of these approaches in the solution of many routing models, as noted in section 3. Nevertheless, we also would like to remark (as a result of our own analysis of various papers) that, in some cases, authors decide to use *a priori* heuristics or metaheuristics, ignoring the existence of exact approaches that could be applied to most of the practical configurations of the problem they are addressing.

- Finally, concerning the necessity of *evaluation and comparison of the performance* of routing models for a given network setting, we would like to remark that this is inherently a multi-criteria problem. In fact, multiple network performance metrics related to QoS and economic metrics (expected costs or revenues) should be included in such evaluation, whether a DM (typically a network engineer or a network manager) is seeking a preliminary evaluation or a final selection of a routing method. This is true whatever the types of routing methods, single-criterion, classical QoS or multi-criterion flow-oriented routing methods, whenever more than one technical solution is available for a given network application. This is clearly, from an OR point of view, a problem involving classifying, ranking or selecting decision alternatives, according to multiple criteria/attributes, often conflicting and incommensurate, where the alternatives are in a small number and explicitly known, *a priori*. Note that this is particularly relevant for flow oriented optimization routing approaches, taking into account their inherent limitations, as analyzed in [Craveirinha et. al., 2008] and to single-criterion network-wide optimization routing methods. Take also note that the comparison of routing methods, in the vast literature in this area, has been based on empirical pair-wise comparison between methods. Naturally, it is adequate to tackle this issue by adequate multi-attribute decision analysis methods. A first, preliminary paper, addressing this issue, is [Clímaco *et al.,* 2015]] where it is proposed the application of the VIP (Variable Interdependent Parameter) methodology in [Dias & Clímaco, 2000] for a multi-attribute selection of flow-oriented routing methods, considering nine network performance attributes and taking into account the imprecise information associated with the relative importance of different network performance features. Also the treatment of this issue in a cooperative group decision setting, is a research topic that should be addressed, taking into account that this type of decisions, in reality, may involve more than one DM, for example two experts in network design with different technical opinions, in specific aspects of the network metrics, and a network manager.

4.2 Network planning and design

Regarding these two, quite interrelated areas, the following general topics can be explored:

- The study and development of new types of models, (concerning new planning and design problems, associated with the new technological platforms) as well as associated with different decision processes.
- The development of new variants of the types of models presented in the above outline of papers, taking into account the implications on the planning processes of the very fast technological evolution and its interaction with the turbulent transformations of the socio-economic environment involving rapid market changes. Telecommunication applications with strong socio-economic implications deserve further investment in multi-criteria modelling, in order to enable a more

realistic evaluation of their impacts. For instance, operational planning problems, vendor selection, e-commerce and e-learning problems, etc.

It is expectable that, in the future, some other problems in this area will be prone to treatment in a multi-criteria framework, especially having in mind the very rapid and multifaceted technological evolutions previously identified (in their major aspects) and their interactions with complex and fast changing economic and social trends. This trend is particular relevant to the new technological platforms, namely OTNs, 5G mobile wireless networks and IoT.

Examples of such research challenges concern cell partitioning modes and frequency allocation problems, involved in the very complex planning and design process of mobile cellular networks. A third example in this area has to do with the design models of cooperative video streaming, in which various network resources are to be pooled effectively by mobile video users, in different application scenarios (see e.g. [Tang *et al,* 2017]), involving the optimization of various technical and economic factors.

Concerning the *modernization planning* of the access networks, the generalized introduction of broadband services (requiring optical fiber directly to the customer premises) this is a type of problem in which different technological architectures can be used, so that a preliminary level of decision analysis for evaluating the alternatives, seems worth considering. This level of analysis might be concerned with the evaluation, under different performance criteria (for example, measuring up-grade cost, operator revenue, response to estimated demand and user satisfaction in different technical instances) of various technologies and associated architectures available to the operator in a given market scenario, so the use of multiple-criteria models is clearly advantageous.

Concerning design issues of *wireless networks* the reference [Bourjolly *et al.*, 2001] presents an overview of the application of OR-based decision support tools in this area. In particular the authors draw attention to the fact that cell partitioning (a decision process that has in mind to enable using several times the available frequencies hence increasing the network capacity) addresses two conflicting issues, namely covered area and capacity (involving, in essence, a choice between a smaller number of larger cells versus a larger number of smaller cells). As for the frequency allocation problem, it involves the assignment of a certain number of radio frequencies to each cell, according to some “optimality” criteria and satisfying various technical constraints. In this type of problem several objective functions can be considered, as discussed by those authors (namely the number of frequencies used, the frequency span and two types of signal interference, all to be minimized). Nowadays these models of wireless network design should also consider technical-economic and even environmental related objectives, in particular power consumption, as illustrated in some references in section 3.2. It will also be expected that new and complex problems of transmission design involving, in particular, the lay-out of mobile stations and the design of the associated antenna arrays, with multiple technical and economic objectives/constraints have been and will be fostered by the rapid expansion of mobile networks, WSNs and ad-hoc wireless networks. Also the possibility of choosing one or more different *suppliers of wireless communication services* of various sorts, in these different types of networks, to be evaluated under multiple technical and economic instances, is an issue more and more topical nowadays. The evaluation of the *behavior of the subscribers* in face of the performance of the network operators and service suppliers is also a topical issue where, again, technical and socio-economic criteria are at stake. The use of MCDA/M in this area, and in particular multiple-attribute decision analysis models, some recent examples of which were referred to in section 3, is clearly another relevant recent trend.

A recent contribution in this context is [Stocker & Whalley, 2017] where it is proposed a multi-criteria model for the analysis of the broadband consumer experience, assuming that "speed isn't everything". Following these authors: "consumer experience may be affected by the increasingly complex nature of the value chain that provides online goods and services. In other words, faster broadband speeds do not necessarily result in an enhanced consumer experience". In fact, quality in Internet, contrarily to common preconceptions, is only improved by increasing the speed until a certain level, depending on the case. In fact, it's value can be represented by a U function. The overall quality involves "the perceived 'aggregate quality' that consumers experience when using a particular service of the Internet". This is evaluated through the 'Quality of Experience' (QoE) which integrates the technical quality of service, QoS (this includes various quality of transmission and availability metrics), as we have seen before, but it goes beyond the network/service performance characteristics, integrating also multiple aspects of the quality of the interaction with the network/service, as perceived by users, for instance, technical equipment available to the user, maintenance and billing, as well as the consumer preferences… . In conclusion, the authors show that the QoE evaluation is a difficult multi-criteria problem, by discussing in some detail the dimensions under evaluation.

Of course, the next step is trying to use multi-criteria models to study this problem, being advised that it involves many imprecisions and uncertainties. It combines technical and economic criteria with very subjective ones.

These are areas where multiple-criteria models, in particular multiple-criteria location and capacity optimization problems (concerning, for example the lay-out of mobile stations and the design of transmission systems, in separate or in combination) and multi-attribute decision models (for example concerning the evaluation and choice of specific service suppliers, in various network and market environments) constitute attractive/advantageous approaches. This is clearly the case, having in mind the tendency for the increased offer in specialized wireless services, in a competitive basis, leading to a true 'market of operators and services', an area where the development of multi-attribute approaches is clearly a very important trend. Furthermore several of the more complex of these decision problems, in particular those involving several, interrelated levels of decision/optimization, pose clear modelling and methodological challenges.

Heterogeneous networks, involving the interlacing of various technologies, namely concerning wired and wireless sections, is also an area in which the application of multi-criteria approaches has drawn increasing attention. A key problem in the design of such networks is the choice of a combination of transmission and signaling systems, seeking to achieve multiple objectives/requirements of QoS and of economic nature, some of which may be conflicting, a decision problem that clearly may be modelled as a multi-attribute decision model. This is naturally an area where the application of MCDA/M approaches should be investigated and where various decision problems should be tackled.

The design issues posed by *multilayered networks,* mentioned in the previous sub-section are multifaceted and usually involve multiple criteria. A primary issue is the analysis and comparison of different arquitectures. For example, when planning the development of optical fiber based IP networks, various arquitectures can be used, namely: IP/MPLS over WDM, IP-over-OTN-over-WDM or MPLS-TP combined with OTN. Each of these configurations has specific technical features which may constitute an advantage or limitation concerning different capabilities, in particular with respect to wavelength switching, router capacities, power consumption, direct supporting of packet transport services, efficient bandwidth utilization and resilience features; also the economic features concerning capital expenditure (CAPEX), operational expenditure (OPEX) are different, as well as the cost features of different equipments to be used in such settings. The evaluation and choice of architectures of multilayered networks, under various service demand and market scenarios, is clearly a topic where multi-attribute analysis methods should be tested. The complex structures of these networks have naturally an impact in the OR formulations in general and in multiple-criteria formulations of the design problems, in particular. Concerning the design problems, besides the interest in considering multiple-criteria routing models, an issue previously addressed, the design of reliable telecommunication structures is a complex and challenging issue where multiple-criteria approaches should be tested. The factors involved, namely resiliency objectives (i.e. the ability of the network to maintain an acceptable levels of QoS in the event of failures, namely equipment or software failures, or abnormal working conditions, for example unexpected overloads in parts of the network) and the economic evaluation of the network functioning in nominal and in failure conditions (typically aiming at the minimization of both CAPEX and OPEX) in multiple and uncertain scenarios, clearly open challenging fields for the development of MCDA/M approaches, from multiple-criteria shortest paths applications to multiple-objective network flow-programming or multi-attribute decision analysis methods. An overview of research trends in the design of reliable telecommunication networks, that can help in a better understanding of these issues, can be seen in [Rak *et al.,* 2015].

Finally, we would like to emphasize the importance of modelling the uncertainty, in most of the problematic areas discussed so far, which requires particular attention in the future. In fact, the sources of uncertainty are multiple and of different natures.

4.3 Strategic Planning and Policy Issues

In this sub-section we summarize the challenges raised by very exciting strategical issues involving political, economic, social and technological challenges. Hopefully, multi-criteria decision support systems will help in the clarification of options and consequences concerning very difficult socio-technic-economic-political decisions.

A first class of problems is related to strategic telecommunication planning in countries/regions. Some papers on this issue were outlined in the previous section, however they are mostly academic works. The real impact of these studies implies, in our view, several requisites: feeding the models with more and more accurate data; the involvement of the decision makers in the process in order they can understand the advantages of using these tools; and the building of adequate/dedicate multi-criteria decision support systems. For instance, taking into account the difficulties associated with the use of many well-known methods in this context, the authors, following their recent experience, believe in the use of flexible learning oriented (open exchange) interactive tools, seeming to cope better with this type of problems. Furthermore, reinforcing the previous remarks, we believe that the following issues should be considered carefully: the involvement of several stakeholders/actors (cooperating and/or negotiating) in this area; the desirable public participation in situations where public and private spheres and the evolution of their borders are important issues; and the inevitability of coping with great uncertainties.

Secondly, structural implications of telecommunication networks evolutions, in economy (growth/inequality of income distribution, employment issues…), in society (media evolution, new services…), and in governance (e-government, cybersecurity), also advise the use of multi-criteria evaluation. Although we do not know works tackling this issue and making explicit use of multi-criteria methods/decision support systems, the potential advantages of their use can be foreseen in some papers we will refer to. Next, a short outline of trends and challenges in this area, is put forward.

As it is pointed by [Jorgenson & Vu, 2016], "A comprehensive ICT policy framework can be developed along seven dimensions: (i) connectivity and access; (ii); usage (iii) legal and regulatory framework; (iv) production and trade; (v) skills and human resources; (vi) cybersecurity; and (vii) new applications. So, of course, ICT policy is a multi-dimensional effort involving very conflicting issues. In our opinion, this justifies a strong effort to build adequate multi-criteria models in order to clarify the options of policy makers in order to minimize the dangers and potentiate their positive consequences, trying to improve and clarify the inevitable interactions among technological, economic and political forces. On the one hand, new ICT's and, in particular, communication connectivity and new communication services, in general, potentiate growth increasing, but, on the other hand, income distribution is creating very large inequalities, i.e. a so called 'digital divide'. [Ogunsola, 2005] discusses this issue, using the enlightening concept of "digital slavery"… . [Bauer, 2014], [Bauer, 2017], introduce, in a very clear manner, the strong connections between: technological change (wireless communication and new services; fusion of computing and connectivity, changing the dynamics of competition; fully algorithmicized platform markets; machine learning, AI (Artificial Inteligence); robotics, Internet of Things, etc.) and productivity, as well as the creation of new relations between location of production and workforce. As it is recognized in [Bauer, 2014]: "neither the theory of platform markets nor the ecosystem approach has yet resulted in a set of practical guidelines that could be implemented without further work by the regulatory agencies". As in many other periods of the history of mankind, the very rapid progress of science and technology opens incredible possibilities for improving human life in multiple spheres, but also generates dangers and challenges. However, the present situation is peculiar, because the new ICT technologies potentiated the globalization of the world activities. In these circumstances, although a bright future is theoretically possible, we believe that if the present trend of capitalism is not changed very fast, by regulations and other policies, in the near future we may be faced with a very destructive crisis. The speed of technological changes is incredible, and the present "rules of the game" (in particular, the short term objective of maximizing the profits of company share-holders) are leading to very large and always increasing income inequalities. Regarding the employment trends the present situation is also unsustainable. In [Bauer, 2017] it is concluded that: "these developments have contributed to wage polarization, the growth of high-paying and unskilled low-payment jobs, while the number of jobs requiring a middle level of education and paying middle wages is shrinking". We recognize this is the major trend in the developed world, although the exclusion is remarkable even in this part of the world. Two digital divides are being created, one inside the rich countries and a second one between these countries and the majority of the world, still underdeveloped. Of course, the defenders of the present "rules of the game" say that never humanity had so good conditions in the past, even the poor, and that, in long term, if everything is deregulated the markets will correct the distortions. The second statement is just a belief impossible to be supported scientifically… (empirically and/or rationally…). Furthermore, as Keynes told [Keynes, 1923], in the long term, we are all dead, so short and medium term expectations are essential for present generations. On the other hand, the first statement is true. However, it is neither fair nor adequate the direct comparison of ways of living in different stages of evolution of the human societies.

Fortunately, the globalization enables the poor people of the south being informed on the state of living in the different parts of the world. It is our conviction that, in our own interest, "rules of the game" should be changed through regulation and other policies. Otherwise, sooner or later, big social tensions and fragmentations will lead to disastrous convulsions…

As it is recognized by [Bauer, 2017]: "...whether the inequality-increasing or inequality-decreasing forces dominate, depends on economic, technological, and institutional context in which they unfold as well as on the presence of mitigating policy measures".

Moreover, in [Jorgenson & Vu, 2016] it is suggested that "Priority should be given to e-government, e-business and internet enabled services". Recognizing their great potential increasing productivity, enabling a better resource allocation, improving quality of life of citizens, etc., we must not forget the associated dangers. Besides some of the aspects above referred to, cyber security and privacy intrusion issues, must be emphasized, specially in relation to the widespread of cloud computing and the expected exponential growth of the IoT, concerns which should also be taken into account in multi-criteria approaches focusing on some strategic modernization planning problems.

In all these situations we believe that interactive multi-criteria decision support systems, in many cases rooted in learning oriented tools, can be useful, more than for decision aiding support, to help the clarification of decision options and respective consequences for the involved actors, including the intervention of citizens individually or organized. This is a huge challenge. In fact, such tools do not exist yet….

As we have seen above in this work, mathematical programming and multi-attribute models have been used, depending on the cases. In some situations, we believe in the complimentary use of both types of approaches. Mathematical programming approaches can be useful to evaluate, in a first step, the feasible alternatives, usually in big number, using a restrict number of criteria and satisfying some other restrictions, in order to make the most of their computational usefulness. This first step would enable the reduction of the scope of the search, helping in the identification of a limited number of alternatives requiring deeper evaluation which would be done in the second stage. In this step, multi-attribute models provide a deeper analysis of the problem under study by evaluating a small number of alternatives, in a more detailed/extensive family of criteria.

Thirdly, we outline the challenges and future trends regarding the strategic planning issues concerning the assignment and allocation of the broadband spectrum. Once more, there are strong conflictual challenges, namely opposing efficiency and equity issues. First of all, it must be remarked we are living a transition from an administrative assignment of bands to a new deregulation based on auctions.

In [Minervini, 2014] different strategies and tactics for deregulation of the spectrum use, are discussed. The author concludes that “a gradual approach is preferable if it offers options to deal with uncertainty better, by acting on reform sequencing to reduce uncertainty and to maximize expected payoff”. This is a first point where multi-criteria models are potentially useful. [Cave & Nichols, 2017] observe that “as demand for mobile communications grew, spectrum in additional bands was auctioned, operators built up portfolios, and their market share diverges. The old system of assigning to the highest bidders a chosen number of licences of equal and predetermined size in a single band gave way to multi-band auctions in which the auction process itself determined the size of the award by each operator”. These authors consider that multiple-objectives – efficiency and equity objectives - should be attained. In the future, it is foreseeable the use of multi-criteria models in order to clarify the auction design, combining equity and efficiency objectives.

Nevertheless, we believe that, in this area, a strong regulatory and supervisory intervention, namely by national or supra-national authorities, should be preserved. Such intervention should have in mind, on the one hand, the inherent public nature of the radio-frequency spectrum (a natural physical resource, unlike other transmission media), on the other hand, the need to guarantee technical coordination and, foremost, a balanced working of such specific 'market', avoiding explicit or tacit monopolistic situations.

Finally, we refer to two papers dealing with important issues, in this area, where the introduction of multi-criteria analysis may also be justified. The first deals with the problem of the externalities associated with broadband frequency assignment. [Cave & Pratt, 2016] deal with the important issue of taking into account externalities when spectrum is assigned and allocated to broadcasting and mobile communications. Planning the broadband use implies the evaluation of public values of alternative uses, involving social, economic, financial and political issues. Of course, taking into account externalities can make the difference, however in many situations neither the firms nor the users have market direct relations and so monetizing their values is not easy. In these circumstances one should discuss how to measure and valuing externalities, as tackled in [Cave & Pratt, 2016]. The second issue is related to the spectrum sharing potentialities and risks. [Cui *et al* 2017] discuss the multidimensional issue of compromising between the efficiency, flexibility and some QoS advantages of sharing spectrum, with the associated risks. Of course, the use of multi-criteria models incorporating uncertainties and risks, is clearly useful in this context.

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