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LONG PAPER

A framework for optimal techno-economic assessment of broadband access solutions and digital inclusion of rural population in global information society

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Abstract Broadband solutions, i.e., broadband technologies and services, offer users numerous benefits. However, inequalities related to the levels of broadband solutions' deployment and adoption between rural and urban areas, i.e., the digital divide, remain a consequential problem worldwide. To reduce the digital divide, the issues related to the deployment and usage of broadband solutions in rural areas are analysed in this paper. To define optimal strategies for the deployment and adoption of rural broadband solutions, the application of an extended techno-economic assessment process is considered. Therefore, an additional framework that extends the structure of standard techno-economic models is proposed, and its detailed overview is given. Within the framework, the regression analyses of factors relevant to broadband solutions deployment and adoption in rural areas are defined. The results of conducted analyses are used in the standard techno-economic modelling process. Finally, the efficiency of framework usage in techno-economic assessment process and in finding optimal broadband solutions is demonstrated for a case study rural scenario.

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1 Introduction

The development of every modern information society is based on the development of new information and communication technologies (ICTs) and services, such as broadband Internet access technologies and services. In the context of broadband Internet, the term 'broadband access' refers to access that is always on and is faster than dial-up access [1]. Moreover, the term 'broadband service' refers to Internet service requiring transmission channels capable of supporting data bit rates greater than the primary rate, which ranges from 1.5 to 2 Mbit/s [1]. Since novel information and communication services constantly require more available bandwidth, broadband solutions have become essential in fulfilling the ever-growing bandwidth needs.

Although it is difficult to measure the precise impact of broadband usage, the results of numerous case studies conducted in various countries around the world have shown that broadband usage has a significant beneficial impact on the quality of life of residential users and on the productivity of business users with respect to their locations (rural or urban) [2]. For example, the quality of life of residential users can be positively impacted by broadband services usage in cases where access to broadband services enables easier performance of everyday activities or the acquisition of new skills and knowledge. Moreover, a positive relation between the increase of broadband penetration rates and economic growth is indicated [3]. This positive relation is especially strong when a critical mass of infrastructure is present, as is noted, for instance, in [4]. Therefore, all countries aiming to become competitive in the world market encourage further deployment of broadband Internet infrastructure through their programmes. Various initiatives and strategies that foster further broadband implementation have been proposed worldwide. The aim of these strategies, including the latest adopted broadband development strategy of the European Union, i.e., the Europe 2020 Digital Agenda [5], is the delivery of sustainable economic and social benefits from the digital single market based on broadband Internet connections. However, although the overall number of broadband connections rises relatively quickly, unequal access to broadband services among different classes of the population, i.e., the 'digital divide', remains a considerable problem. Furthermore, the digital divide relates to the existing inequalities in the levels of broadband infrastructure development among different areas, such as rural and urban areas [6].

Further implementation of broadband infrastructure in all areas non-adequately covered by broadband access, comprising mostly rural areas, addresses the inequality in the levels of access to information and communication services, as well as some negative aspects of rural life that lead to the depopulation and pauperisation of rural areas. To encourage the equal deployment of broadband infrastructure in all areas of the world, the ITU's Connect 2020 Agenda [7] is proposed. The most important goals and targets of this agenda include the reduction of the existing digital divide, the uniform development of broadband access networks in all rural and urban areas, and the provision of affordable broadband services to all residents.

Considering the defined strategic goals of broadband development, the solutions used for the reduction of the existing digital divide should result in equitable access and participation of all individuals in the information society. Therefore, the possibility for enhancing the existing practices used to make digital information accessible to all should be closely examined. The proposal of optimal broadband solutions is supposed to induce further implementation and adoption of broadband technologies and services in rural areas and to improve universal access to digital information and knowledge. The techno-economic assessment process is considered relevant for finding the optimal broadband solutions since it joins the technological context with the actual business and market contexts in any given scenario.

Therefore, in this paper, the proposed solution for addressing the digital divide problem relies on the usage of the extended techno-economic assessment process, which is initially presented in [8]. Unlike the content of the paper presented in [8], which focused on an overview of the competitiveness of different broadband access solutions assessed by the extended techno-economic modelling processes, the focus of this paper is the thorough description of the proposed framework, which extends the existing techno-economic modelling process. The main contribution of this paper is a detailed overview of the proposed framework's structure and implementation. Moreover, the framework's use in the assessment of rural broadband business models is presented, and adequate strategies for further broadband deployment are proposed. Finally, to demonstrate the efficiency of the proposed framework's usage for searching for the best strategies, analyses of some case study examples are presented.

The presented strategies are listed to enable further deployment of broadband infrastructure in rural areas, to enhance broadband services and make them compatible with rural users' needs, and to enable rural users to acquire the skills necessary for broadband services usage. Finally, the availability of broadband access infrastructure and the acquisition of necessary digital skills should enable further broadband services usage, as well as the acquisition of digital knowledge in any possible formal, non-formal or informal way.

2 Broadband determinants

The interconnection among various different elements related to broadband Internet is generally referred to as the 'broadband ecosystem' [9]. The elements of a broadband ecosystem include various broadband solutions, broadband market participants, and broadband processes. Broadband solutions, comprising broadband technologies (broadband network infrastructure and equipment), as well as broadband services (broadband applications and utilities), enable the application of broadband Internet access. Accordingly, broadband solutions can be considered in view of the following processes: adoption, development, deployment (i.e., implementation), and selection of broadband technologies and services [10].

All these processes are interrelated. Hereafter, the adoption process of broadband services fosters further development of broadband technologies and services while depending on the development of these technologies and services. The deployment process of broadband technologies depends on the development of broadband technologies and services, though, at the same time it enables further development of broadband technologies and services. Both the broadband services adoption process and the broadband technologies deployment process are interrelated with the broadband solutions selection process.

The broadband adoption, development, deployment, and selection processes are influenced by numerous factors. These factors are related to the specificities of a particular area, as well as the participants and the conditions in the telecommunications market present in the area.

In broadband adoption, development, deployment, and selection processes, different broadband market participants are engaged. Participants in the telecommunications markets have different roles, related either to the formation of a broadband supply or to the formation of a broadband demand.

Therefore, the adoption process of broadband services, i.e., the demand for broadband solutions, relates to broadband adoption of the following groups of broadband users: private users (individuals or households), social groups (local communities), business users (organisations), and the public sector (local, national and international authorities).

The development process of broadband technologies and services involves the interests of the industry sector (broadband network operators, broadband content and service providers, and equipment manufacturers and vendors) and the public sector (local, national and international authorities), as well as the aims and scopes of the adopted national and international broadband development and regulatory initiatives and strategies [11]. Finally, the deployment process of broadband technologies, i.e., supply of broadband solutions, is affected by the industry, public and government sectors.

Numerous factors affect the broadband solutions' demand [12] and supply [13] sides. These are different sociological, demographic, regulatory, economic, technical, and geographical factors. Furthermore, factors affecting broadband solutions' supply and demand vary from region to region and from country to country [14]. Although all national broadband plans seem to cover all levels of information and communication technology targets, i.e., the adoption, development, deployment, and selection, the scope of the plans varies considerably in practice, particularly regarding the depth of demand-side targets.

According to [14], countries at different stages of ICT development set different priorities and scopes for their national broadband plans and strategies. While countries in a relatively early stage of ICT development, i.e., developing countries, tend to focus on infrastructure availability (by building network infrastructures) and measures to encourage Internet access take-up rates (by encouraging widespread Internet usage), countries in a more advanced stage of ICT development, i.e., developed countries, are more likely to have a greater focus on demand-side initiatives and qualitative issues.

According to the data in [15], differences in the levels of Internet usage, i.e., adoption, between developed and developing countries around the world are present. Furthermore, considering the different types of broadband Internet access solutions, different stages of ICT adoption levels among different regions around the world can also be noticed. However, positive trends in the broadband adoption processes and the increase in the overall number of Internet users are present. To further foster the adoption and deployment processes of broadband solutions, analyses of the most important factors affecting these processes are essential.

2.1 Determinants of broadband solutions deployment

Deployment processes of broadband solutions are influenced by a number of techno-economic, geo-demographic and regulatory factors. The most important ones are indicated hereafter. First, broadband infrastructure implementation costs are very important for making decisions with respect to broadband deployment [16, 17], while the population density in a considered area affects the broadband infrastructure per-user implementation costs [18, 19]. In addition, the geographical features of an area also affect broadband access deployment costs and the possibilities for broadband deployment [20]. Broadband access demand and broadband deployment costs are both affected by the specific regulatory measures [21], described in more detail in [22]. Moreover, the level of competition among operators also affects the costs of broadband deployment [23] since the increase in the total number of operators competing in the same market usually reduces broadband implementation costs [24].

2.2 Determinants of broadband solutions adoption

A large number of studies conducted so far have explored broadband adoption processes from various aspects. Several studies and analyses, such as the ones conducted in [25], indicated various socio-demographic and techno-economic factors affecting the demand for broadband services. As presented in [13], these factors include the population density, income level per capita, population age structure, the level of education, the level of computer literacy of the population, and the proportion of households equipped with a computer to the total number of households. Moreover, as also shown by numerous research studies, a higher level of education [19], a higher level of computer literacy [26], a higher income [27], and a higher portion of the young [28], as well as a higher proportion of the employed population [19] to the total population in a particular area, have a positive impact on the adoption and use of Internet technologies and services. The correlation between the percentage of broadband connections per capita and the proportion of broadband Internet users according to their employment status, education level, and age structure are examined, for instance, in [29]. A positive correlation between broadband users and the employed population (population with income), the younger population, and the better-educated population (population with a higher level of computer literacy) can be noticed [30]. In countries with the most developed digital economies, i.e., the ones that have the lowest ICT global rank index according to [31], the proportions of the employed, the young and the higher-educated population to the country's total population are the highest [31].

3 The digital divide problem

The digital divide problem relates to the strong differences in the uptake of ICT among different social classes. Additionally, the existing differences in broadband Internet adoption rates among those classes relate to residence (urban or rural), gender, age structure, education level (secondary or tertiary education), and employment status (employed or not in the labour force). In general, more broadband users are urban residents, male, younger, those with higher levels of education (population having a higher level of computer literacy) and employed (population earning income).

Moreover, the digital divide relates to the differences in ICT infrastructure development levels among different types of areas, such as the ones that exist between rural and urban areas. Also, the digital divide can be noticed among different regions and among different countries worldwide [30]. Accordingly, depending on the size of the area studied, the digital divide can be distinguished in several hierarchical levels [31]. These hierarchical levels include the local (settlements or municipalities), the national (countries), the regional (regions), and the global (world). Therefore, the digital divide analysis should be conducted in view of the existing hierarchical levels [8]. According to [32], the most important global reasons for not having broadband Internet access in households are as follows:

– Internet service is not available;
– Internet service is available but does not correspond to household needs;
– Cost of service is too high;
– Knowledge or skills needed to use the Internet are lacking.

3.1 Broadband adoption in rural areas

When analysing the broadband adoption process, areas can be classified as rural or urban. Measures of rurality of certain areas are generally classified as quantitative and qualitative. Quantitative measures of rurality are often related to the population density of a certain area and the rate of the rural population with respect to the total population of that area. The two most commonly used quantitative measures of rurality based on the total population density of a certain area are the OECD criterion and the European, i.e., the EU, criterion of rurality. While the OECD criterion of rurality classifies areas as rural if the population density is below 150 inhabitants per square kilometre, according to the EU criterion, rural areas are areas with a population density below 100 inhabitants per square kilometre. Qualitative measures of rurality are related to the residents' style and way of life.

Since broadband services bring substantial social and economic benefits to residents, they are considered valuable to rural residents as well. For example, broadband Internet access enables remote access to health care and education systems and expands the market potential for rural businesses. Moreover, broadband Internet access technologies present an effective means of delivering digital information to end users. Hence, residential and business users demand ubiquitous high-speed Internet access, and the demand for broadband technologies and services is continuously growing.

To compare broadband adoption rates in rural and urban areas, and to predict if broadband adoption rates in rural areas could reach the broadband adoption rates of urban areas, the results of the conducted broadband diffusion analyses for a chosen case study are presented in [33]. The given results show that if the present trends in broadband adoption rates continue in the future, the long-term adoption rates of broadband solutions in rural areas will never reach those in urban areas. Considering the results of the conducted analyses for a given case study, it is obvious that when aiming at the identification of appropriate strategies for increasing the broadband adoption volume in rural areas and reducing the existing digital divide, the digital divide reduction methods should be closely considered and applied.

3.2 Digital divide reduction methods

The set targets of the Connect 2020 Agenda for global telecommunication and ICT development include increased access to and use of telecommunications/ICTs, as well as bridging the digital divide and providing broadband solutions for everyone [7]. Therefore, several methods for the digital divide reduction that are closely related to the Connect 2020 Agenda targets are highlighted in this paper.

A. One method for the reduction of digital divide is based upon the target that proposes a more than 40% increase in the availability of affordable broadband solutions worldwide by 2020. This suggested method aims at encouraging further deployment of profitable and low-cost broadband solutions, i.e., an access network infrastructure [5]. Lower access costs should increase the probability for broadband access infrastructure implementation, as well as for broadband solutions usage [19]. Therefore, further deployment of broadband access infrastructure and an upgrade to the existing wired and wireless infrastructures by adding new broadband technologies are generally recommended [34]. All wired as well as all wireless access solutions can be included for the achievement of the set target [35].

B. A second method for the digital divide reduction is based upon the target that states that broadband services should not cost more than 5% of the average monthly income in developing countries by 2020. This suggested method includes the coordination of broadband service prices with the income levels of rural residents. As noted in [8], a decrease in broadband service prices correlates with an increase in the number of broadband subscriptions.

C. A third method for the digital divide reduction is based upon the target that proposes that the 90% of the rural population worldwide should be covered by broadband services by 2020. This suggested method includes the encouragement of further adoption of broadband solutions through the development of new broadband services [36]. The developed services should be adjusted to meet the requirements and needs of rural residents. In general, content suited to user preferences and needs should increase the broadband services adoption rate [37]. Such services should enable advanced communication, access to relevant digital information sources, acquisition of new knowledge through the use of online education content, teleworking, etc. Additionally, higher-quality services and faster access speeds should increase the volume of broadband services adoption [38]. Moreover, the increase in the volume of available high-quality broadband services, i.e., the ones ensuring higher access speeds, as well as greater bandwidths, generally correlates with the increase in the number of broadband subscriptions [8]. To meet the ever-increasing demands on broadband services, both the advanced techniques for increasing data throughput rates and the novel regulatory methods for the provision of the optimal usage of limited resources [39] have to be considered.

D. A fourth method for the digital divide reduction is based upon the target that proposes that equality among Internet users should be reached by 2020. This suggested method includes processes that provide equal opportunities for all users to acquire broadband services. As can be noticed from the data in [31], inequalities in the availability of broadband access presently exist among different classes with respect to location, gender, and employment status in all countries worldwide.

4 Technical and economic aspects of broadband implementation

Various broadband technologies provide broadband Internet access and services to residents. Those technologies differ greatly in their technical capabilities. However, due to the fast development of new access solutions and the uncertain conditions of rural broadband markets, pure technical superiority is not a guarantee for market success with regard to new technologies [40]. The importance of analysing different business models and technologies in the telecommunications industry is crucial for the investment policy of telecom operators [41]. As noted in [42], various social, economic, regulatory, and political issues have an important role in network rollout and broadband service offerings.

All these issues have a direct impact on the viability and cost-effectiveness of broadband access deployment projects, as presented, for example, in [8]. Moreover, a set of additional issues, such as the level of available resources, as well as the conditions of the existing infrastructure in specific locations, affects investment decisions for different types of providers [43]. Hence, to demonstrate how broadband providers can succeed in competition with these issues in the chosen areas, the techno-economic assessment of broadband network deployments is essential [44].

There are many possible theoretical models for telecommunications analyses [45]: economic models—used for analyses of telecommunication market dynamics; econometric models—used for analyses of the statistical significance of parameters for the given model; costs models—used for analyses of capital and operational costs; system dynamics models—used for analyses of the interactions among different players in the markets; business models—used for analyses and evaluation of the financial viability of investment models; and game-theoretic models—used for analyses of the interactions among market participants in cooperative or non-cooperative markets.

In comparison with other possible theoretical models for telecommunications analyses, the advantage of the techno-economic analyses is the fact that they enable the implementation of the functionalities of all other models, i.e., the estimation of the number of users from economic models, the analyses of the influence of different factors on the number of users from econometric models, the evaluation of model profitability from costs models, the analyses of real options from system dynamics models, the analyses of the financial viability of models from business models, and the implementation of game theory aspects from game-theoretic models. The importance of conducting the techno-economic assessment prior to actual implementation of the defined solutions relies on the several facts defined hereafter [46]:

- Since the techno-economic modelling process presents the theoretical modelling process, the given results do not induce any additional costs related to the actual deployment of analysed solutions prior to their optimisation;
- Unlike other theoretical models for telecommunications analyses, the techno-economic analytical models can comprise the interconnections among all relevant techno-economic, geo-demographic and regulatory factors influencing the deployment and adoption processes of analysed solutions;
- The techno-economic assessment process enables the prediction of all possible outcomes of the defined business models. In this way, techno-economics assessment enables the prediction and forecast of the most important risks related to uncertain market conditions that affect the cost-effectiveness of the considered business models;
- The techno-economic assessment enables the search for the most cost-effective business solutions since this guarantees that the operator will achieve the most benefits if the best business model is implemented;
- Since broadband access solutions differ with regard to their features, the techno-economic assessment process enables the fair comparison of different solutions with regard to the technical or other advantages and constraints of the solutions under the equal market conditions.

In general, the standard techno-economic modelling processes are based on the theoretical and methodological results of research projects [47–53] that have helped in defining the guidelines and the methodology for the techno-economic modelling processes. During the last decade, many analyses that attempted to determine the competitiveness of selected broadband technologies from the techno-economic point of view have been conducted.

The analyses conducted differ depending on the applied methods and the analysed aspects that were placed in the research focus. A number of issues and problems have been discussed and addressed, including the following. In [47–53], the specific guidelines for the implementation of techno-economic processes were defined to answer the question: *HOW should one conduct techno-economic processes to evaluate broadband deployment business models?* In [54], the prediction models of the future number of service users were analysed to answer the question: *WHAT methods should be used to model the broadband service adoption and diffusion processes?* In [55], the game theory in the techno-economic models was applied to answer the question: *WHICH of the possible broadband strategies should be chosen in a competitive market environment?* In [56], the real options in the techno-economic modelling were introduced to answer the question: *WHEN should one invest in broadband Internet access?* In [57], the main risks involved in making investments were defined to answer the question: *WHERE should one invest in broadband?* In [58], the techno-economic modelling of industrial architectures was conducted, and the roles for different actors in telecommunications markets were defined to answer the question: *WHO invests in broadband access?*

These standard techno-economic models have been defined based on the methodology and the results of research projects related to the techno-economic processes. They comprise a set of related segments that include the modelling processes of the market and services, industrial architectures, technical architectures (i.e., access network), revenues, costs, economic and financial aspects, and profitability. Since optimisation is essential in all aspects, in the technical network design and economics, sensitivity and risk analyses are often conducted to determine the most important factors affecting the technical performance and cost-effectiveness of the analysed solutions. Furthermore, real options and game theory are also essential components of the techno-economic assessment process and choosing the best business strategies.

5 A framework for extended techno-economic assessment process of rural broadband business models

5.1 The importance of the extended techno-economic assessment process for rural broadband solutions adoption and deployment

As already noted, one of the most important reasons for the presence of the digital divide is the lack of available broadband infrastructure. To encourage further implementation of broadband access network infrastructure in rural areas and to reduce the existing digital divide, it is necessary to choose cost-effective broadband access solutions [59] and to deploy the best business models for operators. In this way, the wide deployment of broadband network infrastructure should induce an increase in the total number of broadband users and reduce the existing digital divide. However, as has also been stated, despite the availability of broadband infrastructure, the availability of adequate broadband services is also essential for broadband adoption and development. Therefore, when considering the deployment of broadband solutions, it is also necessary to consider the relevance and affordability of broadband services for users.

Due to various specificities of rural areas, the introduction of broadband access in these areas needs special consideration. However, a lack of available criteria regarding key factors that influence rural broadband access implementation is present. Recent studies, referenced in the introductory sections in the paper, have analysed many different factors to gain a better understanding of the digital divide. They have shown that the technological determinants are not sufficient to explain the emergence of the digital divide.

Therefore, the analyses of broadband access implementation in rural areas should be conducted using additional criteria. These criteria have been introduced within the extended techno-economic modelling process, initially presented in [8]. This extended process consists of the standard techno-economic assessment process, in which additional analyses are included. These additional analyses can be found and are defined in the additional framework. The analyses conducted within the proposed framework produce a set of criteria that are entered into the standard techno-economic modelling process so that an extended assessment process of business models for broadband deployment can be conducted afterwards.

In [8], the main focus was the overview of the competitiveness of different broadband access solutions given as a result of the extended techno-economic assessment processes. The defined framework was not described in detail. In this paper, the focus was placed on thorough description of the proposed framework and its implementation in the standard techno-economic assessment process. The framework assists in giving an answer to the following question: *IN WHAT WAY should broadband Internet access be employed within a given rural scenario?*

5.2 Framework structure

To identify the most important factors that can be used in the interpretation of different levels of broadband adoption in cross-area patterns, econometric analyses are essential [27]. When the most important factors that affect the total number of broadband users should be determined, it is possible to use the regression analyses of the available data. If a limited set of data is available, due to the fact that the parametric regression analyses generally require smaller sample sizes than the regression analyses based on nonparametric models, parametric regression models should be used. Since the accuracy of given analysis results depends on the accuracy of the input data, an increase in the amount and variety of collected data improves the conducted assessment process. The importance of regular collection of relevant data is recognised by ITU, and recommendations regarding the data collection processes have recently been proposed [60].

In general, the total number of broadband users is assumed to depend on various technical, economic, demographic, and sociological factors and their combinations:

$$number\_of\_users = f(factors : technical, economic, demographic, sociological, and\ their\ combinations) \quad (1)$$

To identify the most important factors for broadband adoption in rural areas, all data typical for rural users should be included in the regression analyses. Aiming at reducing the digital divide, the main idea of the proposed framework, which extends the standard techno-economic assessment processes, was to include the most important factors for rural broadband adoption, defined using regression analyses, in the standard techno-economic assessment processes. The results of the extended techno-economic process should provide a more detailed evaluation of chosen broadband solutions.

Therefore, the extended process should help to identify the appropriate strategies for increasing broadband adoption volume in rural areas. To include rural users' demands in the assessment process, additional analyses had to be considered within the proposed framework, as presented in Fig. 1. The chosen analyses and the reasons for their inclusion in the extended techno-economic process, as well as the expected outcomes, are defined hereafter.

5.2.1 Analysis of geo-demographic factors

The results of this analysis are the expected annual changes in the number of residents in the given scenario (ΔPU) and the related demographic factors. The results are directly included in a scenario geo-demographics component planning process as a part of the standard techno-economic assessment process, as presented in Fig. 1. The expected changes are used to consider the impact of uncertainty on the estimated values in the given period.

5.2.2 Regression analysis and determination of the most important socio-demographic factors that affect the broadband adoption

As noted in Sect. 2.2, the broadband adoption process is influenced by various socio-demographic factors. These factors should therefore be considered within the techno-economic assessment processes to find the most influential

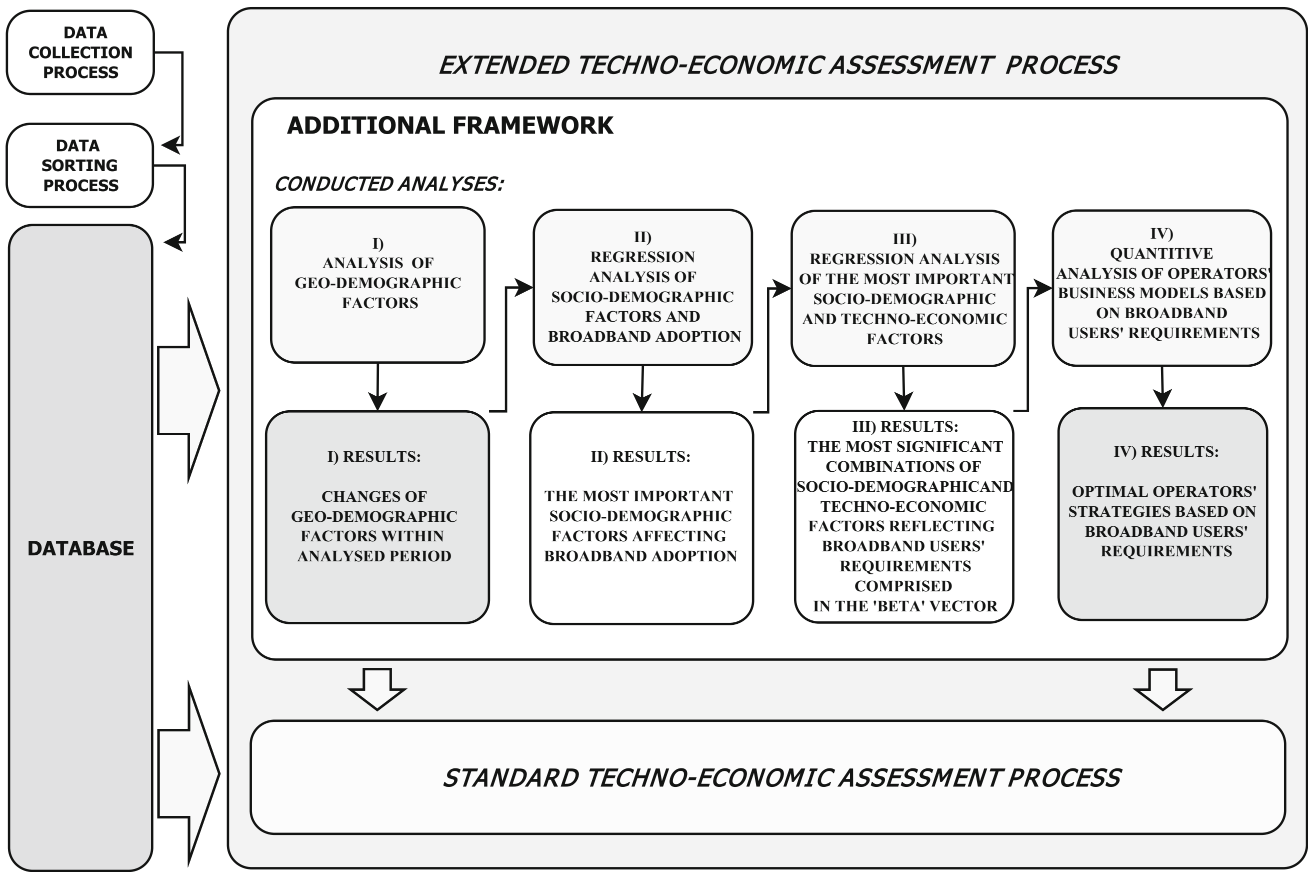

Fig. 1 Overview of analyses defined within the additional framework

factors in the given scenario. An analysis of the impact of socio-demographic factors on broadband adoption, i.e., on the total number of broadband users, should be conducted:

$$number\_of\_users = f(socio\text{-}demographic\_factors) \quad (2)$$

A large number of socio-demographic factors (for instance, age, education, income, population density, primary business sector, employment, etc., defined in Sect. 2.2) may be used to achieve a clear picture of the broadband adoption in different types of rural broadband markets. To determine the most important factors that impact the total number of users, a regression analysis of the factors should be conducted, as presented in Fig. 1. The following model can be applied:

$$\begin{aligned} \ln(number\_of\_users) &= \beta 0 \\ &+ \beta_N 1 \cdot \ln(socio\text{-}demographic\_factor\_1) \\ &+ \cdots + \beta_N n \cdot \ln(socio\text{-}demographic\_factor\_n) \end{aligned} \quad (3)$$

The aim of this analysis is to determine the most important socio-demographic factors that affect the total number of broadband users. Therefore, the factors are sorted according to the values of the coefficients β_N, from the most to the least influential ones. In addition, auto-correlated factors are omitted from the analysis.

5.2.3 Regression analysis and determination of the most important socio-demographic and techno-economic factors that describe the user requirements

As noted in Sect. 2.2, the broadband adoption process is influenced by various techno-economic factors, as well. Therefore, these factors should also be considered within the techno-economic assessment processes. The following techno-economic factors, i.e., service price, quality of service, traffic volume, and broadband access speed, have been selected for further analyses for several reasons listed hereafter:

- First, the given variables enable a fair comparison of various broadband access solutions with regard to the techno-economic advantages and constraints of the solutions under equal market conditions (i.e., within the ‘net neutrality’ principle proposed by the EU Agenda) since these variables can be included in the planning process of every possible type of access solution (fixed, mobile, wired, and wireless);

- Furthermore, once defined, these variables can be easily implemented in the access network planning and modelling processes conducted within the standard techno-economic assessment processes;
- Finally, the given variables are defined based on the parameters that are most commonly used in every broadband service's promotion process in every telecommunications market since the defined broadband service packages differ based on the available access speed, traffic volume, quality of service, and price range.

The framework is defined considering that the network planning process should be based on actual broadband demand. In this way, considering the demands on available service prices, service packages, and access speeds initially determined based on historical data, the network can be further planned for regarding actual user requirements, which, according to [57], reduces the per subscriber costs for broadband implementation. The inclusion of user requirements in the planning process is important for the encouragement of the broadband services adoption process since the estimated benefits arising from broadband usage are subjective and users are therefore prone to reject innovation that is not consistent with their norms, even in cases in which the innovation brings direct benefits to users, as noted in [61]. As noted in [57], if the users' demands on price are unknown in the pricing process, the price may frequently change throughout the observed period. However, if the maximum price is preliminarily defined, this information could be used in planning [62]. Similarly, it is possible to determine the user requirements related to the offered quality of services, as well as the broadband access speeds. Therefore, the users' demands on service prices, service quality, traffic volume, and access speed are included in the analysis, as presented in Fig. 1. The data related to user requirements should be obtained by surveying an appropriate sample of potential broadband users in rural areas. The questionnaire should be composed of questions scaling the range of importance to the potential broadband users of the defined techno-economic factors for broadband adoption. The given result values should be scaled in a range from '0' to '1' (i.e., 0–100%), where '0' denotes that the given factor is not important for future broadband adoption and '1' denotes that the given factor is very important with respect to the intentions of the surveyed users regarding broadband adoption. The given results are considered to be the techno-economic coefficients.

Furthermore, the analysis of the obtained data allows the formation of the most important links between socio-demographic and techno-economic factors (based on the suggestions given in [25]). The links between socio-demographic and techno-economic factors are important for proposing guidelines that define what should be done to promote broadband adoption in rural areas despite the unfavourable socio-demographic structure of the rural population. The values of coefficients that describe the impact of certain combinations of the most important socio-demographic factors, established in the previous step, and the techno-economic factors (e.g. age and access speed, income and service prices) should be determined:

$$\ln(number\_of\_users) = \beta 0 + \beta_K 1 \cdot \ln(combination\_of\_factors\_1) + \cdots + \beta_K N \cdot \ln(combination\_of\_factors\_N) \quad (4)$$

Regarding the analysis results, the most significant values of the coefficients β_K for the combinations involve four chosen techno-economic factors: service price, quality of service, traffic volume, and access speed (denoted hereafter as $\beta 1$, $\beta 2$, $\beta 3$ and $\beta 4$, respectively). These *beta* coefficients, comprising the vector **beta**:

$$\mathbf{beta} = [\beta 1\ \beta 2\ \beta 3\ \beta 4] \quad (5)$$

are included in the further techno-economic assessment processes of operator business models and are considered within the best strategies proposal process, as will be presented hereafter.

5.3 Integration of determined user requirements into the standard techno-economic assessment process of rural broadband business models

Unlike the results of the econometric analyses of end user data given, for example, in [25, 27, 29], the results of the analyses carried out within the framework, i.e., the determined broadband user requirements, are directly involved in the further techno-economic modelling process. The main focus of the extended techno-economic assessment process used in this paper is to meet rural users' requirements, as well as the techno-economic evaluation of rural broadband business models. The technical requirements in the preparation of the extended techno-economic model include the determination of relations between a set of demands on service capacity, access speed and coverage area, and the necessary network infrastructure. Economic demands include the relations between the demands on the service price and the achievement of cost-effective business models.

5.3.1 Quantitative analysis of operator business models based on broadband users' requirements

The main issue defined in this paper is to find a balance between the needs of users of broadband services in rural areas and the interests of network operators. Among the user requirements that are considered in the further analysis, are requirements regarding the broadband service price, service quality, traffic volume, and broadband access speed. Accordingly, the operators' interests include revenues per user, per-user costs for covering the service area, capacity costs per user, and access speed costs per user. Hence, the sets of technical (i.e., throughput, speed, and quality) and economic metrics (i.e., price) are examined. For further analysis, it is assumed that users' demands can be associated with a reduction in broadband service prices, an enhancement of service quality, an increase in traffic volume, and an increase in broadband access speeds. The impact of the techno-economic factors, i.e., service price (*C*), quality of service [which is analysed considering the service coverage area (*PP*)], traffic volume [i.e., available bandwidth (*PR*)], and broadband access speed (*BR*), on the total number of users (*BK*), is determined using regression analysis of the available data:

$$\begin{aligned} number\_of\_users &= f(techno\text{-}economic\_factors) \\ &= f(service\_price, service\_quality, \\ &\quad traffic\_volume, access\_speed) \end{aligned} \tag{6}$$

The influence of certain factors on the total number of users is estimated for the previously obtained $\beta1$, $\beta2$, $\beta3$, and $\beta4$ coefficient values:

$$\begin{aligned} number\_of\_users = {} & \beta1 \cdot price + \beta2 \cdot \text{coverage} + \beta3 \\ & \cdot bandwidth + \beta4 \cdot speed + \beta0 \end{aligned} \tag{7}$$

The expression for determining the total number of users is given by:

$$BK = \beta1 \cdot C + \beta2 \cdot PP + \beta3 \cdot PR + \beta4 \cdot BR + \beta0 \tag{8}$$

Once the *beta* coefficients and their values in the model are known, the number of users can be estimated for new values of techno-economic factors:

$$BK1 = \beta1 \cdot C2 + \beta2 \cdot PP2 + \beta3 \cdot PR2 + \beta4 \cdot BR2 + \beta0 \tag{9}$$

Furthermore, the possible changes in the values of the techno-economic factors, denoted hereafter by delta symbols (i.e., ΔC, ΔPP, ΔPR, and ΔBP), that may occur in a future period are considered. Hence, the expression for determining the impact of changes in the values of the techno-economic factors on the change in the total number of users (ΔBK) can be formulated as:

$$\begin{aligned} \Delta BK &= BK1 - BK \\ &= \beta1 \cdot \Delta C + \beta2 \cdot \Delta PP + \beta3 \cdot \Delta PR + \beta4 \cdot \Delta BR \end{aligned} \tag{10}$$

Several components of the techno-economic assessment process are directly affected by the total determined number of users and the possible changes to this number. Those components are the revenue and cost assessments, as well as the operator business models assessments.

In addition, it is assumed that the operators' interests include an increase in average revenue per user, a reduction in per-user costs for covering the service area, a reduction in the bandwidth costs per user, and a reduction in the access speed costs per user. Finally, it is assumed that a balance between user requirements and operator interests (which include the cost-effective business models) can be achieved by changing the service prices, the service coverage area, the available bandwidth per user, and the per-user access speed.

The aim of the further process is to determine the possible business models for operators based on the determined values of the *beta* coefficients when considering the impact of changes in techno-economic factors, i.e., *delta* parameters.

5.3.2 Operator business models

The operator business models defined depend on the market conditions in a particular area. For example, in the telecommunications market, in which only one operator considers whether to invest in an access network based on the profitability of the business models, the possible operator's choices may include the case in which the operator decides to invest and that in which the operator decides not to invest. Moreover, if two concurrent operators consider the investment in a given market based on the best possible business model profitability, the possible operator's choices comprise the cases in which both operators choose to invest, just one operator chooses to invest or no operator chooses to invest [63]. The process of defining the best operator business models is based on the techno-economic assessment of different models. The differences among these business models are achieved by the inclusion of different combinations of the *delta* parameters values in the techno-economic planning and modelling processes.

The *delta* parameters values define the changes in the initially defined service prices (ΔC), coverage area (ΔPP), capacity, i.e., bandwidth (ΔPR), and access speed (ΔBR). These values are standardised for the range of -1 to 1, denoting the range from a 100% reduction in value to a 100% increase in value, respectively. The different combinations of values of the *delta* parameters, which are directly included in the techno-economic planning and modelling processes, impact the final business models' profitability and are used for finding the best (i.e., the most profitable) business model, as presented in Fig. 1. The algorithm used for determining the best business model, i.e., the one resulting in the greatest net present value (NPV) using the defined combinations of *delta* parameter values, is presented below:

The determination of the beta coefficients and their values (taken from the conducted regression analyses' results)
The determination of all values of the delta parameters that will be included in the analyses
The determination of operator's costs using adequate expressions
The determination of operator's revenues using adequate expressions
The determination of operator's business model based on the defined market conditions
The determination of the total number of all possible combinations of values considering the defined operator's business models, operator's revenues and costs, and the defined values of the delta parameters
For every defined combination, the following procedure is conducted:

The determination of the vector ***CHANGES*** *which comprises the values of the listed delta parameters that define the changes of: service prices (ΔC), coverage area (ΔPP), capacity, i.e., bandwidth (ΔPR), and access speed (ΔBR)*
The conduction of the techno-economic assessment process within the techno-economics framework using the determined delta parameters values
The determination of the business models NPV and subsidy values
The determination of the classification rules based on the defined operator business models and the given delta parameters values

End
The optimal strategies decision (i.e., the classification) tree formation considering the given delta parameters values
The formation of the NPV and subsidy values histograms
The determination of the most profitable business model (i.e., the one having the greatest NPV value)
The determination of the values in vector ***CHANGES*** *which cause the most profitable business case*

The resulting *delta parameters values* that yield the most profitable business cases are listed based on the vector **CHANGES** in the following order:

$$\mathbf{CHANGES} = [\Delta C, \Delta PP, \Delta PR, \Delta BR] \tag{11}$$

5.3.3 Techno-economic assessment processes based on broadband users' requirements

The techno-economic assessment processes conducted using the standard techno-economic models can be divided into several related components. These components include, in order, the techno-economic scenario planning process as the first, the techno-economic modelling process as the second, and the cost-effectiveness evaluation process as the third. The structure of the standard techno-economic models, presented in [44], is not the exact focus of this research. However, since the techno-economic planning, modelling and evaluation processes are influenced by the determined *delta* parameters values, a short overview of the most important relations between the *delta* parameters and the listed techno-economic processes are given hereafter.

I The techno-economic planning process

For instance, in the techno-economic scenario planning process, the relations listed hereafter have been used. All these relations consider the impact of the *delta* parameters values on the initially defined values of the corresponding variables (i.e., the initially defined number of users, service price, targeted part of the coverage area, bandwidth, and access speed).

I (a) In *the scenario's geo-demographic component planning process*, the total number of users is determined based on the expected annual variation of the number of residents (ΔPU) in the given scenario

$$number\_of\_users = initial\_number\_of\_users \cdot (1 + \Delta PU) \tag{12}$$

I (b) In *the scenario's economic component planning process*, the per-user service price is determined based on the *delta* parameter value that defines the variation (ΔC) of the initially defined service price

$$per\_user\_service\_price = initial\_service\_price \cdot (1 + \Delta C) \tag{13}$$

I (c) In *the scenario's regulatory component planning process*, the coverage area is determined based on the *delta* parameter value that defines the variation (ΔPP) of initially defined target part of the coverage area:

$$coverage\_area = total\_area\_size \cdot initial\_target\_part\_of\_coverage\_area \cdot (1 + \Delta PP) \tag{14}$$

I (d) In *the scenario's technological component planning process*, the per-user bandwidth and the per-user access speed variables are determined based on the *delta* parameters values that define the variation of the per-user bandwidth (ΔPR):

$$per\_user\_bandwidth = initial\_bandwidth \cdot (1 + \Delta PR) \quad (15)$$

as well as the variation of the per-user access speed (ΔBR):

$$per\_user\_access\_speed = initial\_access\_speed \cdot (1 + \Delta BR) \quad (16)$$

II The techno-economic modelling process

Furthermore, in the techno-economic modelling process, the relations listed hereafter are used.

II (a) In *the market modelling*, as a part of the standard techno-economic assessment process, the standard models (i.e., the Logistic, Gompertz, Richards, and Bass models) for broadband adoption fitting and prediction are used. To find the most adequate adoption model among all possible standard adoption models that could be used, additional analyses have to be considered for the given scenario. As presented in [64], these analyses include the fitting and the prediction process. The most accurate model is selected and used to predict the future number of users in the given scenario; afterwards, Eq. (12) is used to consider the impact of uncertainty on the estimated values in the given period.

Although the application of standard adoption models enables adequate prediction of the broadband adoption processes, these standard adoption models do not give insight into the factors that are important for broadband adoption. Therefore, additional regression analyses have been conducted within the proposed framework to more accurately plan broadband deployment based on the defined user requirements.

The possibility of regression usage in the broadband adoption fitting process (which has been proven to be accurate, as presented by the *R-squared* statistics given in Table 2) is considered in the extended model to analyse the factors that are important for broadband adoption within the analysed time period. Although the usage of regression in the fitting process has proven to be helpful in defining the most important factors for broadband adoption and the user requirements regarding broadband solutions, further possibilities for regression usage in the prediction process of broadband adoption are included in the planned future research activities and do not affect the assessment conducted within the proposed framework.

The given results of the regression analyses are directly included in several segments of the standard techno-economic planning and modelling processes: the economic, regulatory, and technological component planning for the scenarios, i.e., the broadband services, access network, revenues and costs modelling, as is defined in Eqs. (13)–(18) and explained hereafter.

II (b) In *the services modelling,* the determined per-user service price demands defined by Eq. (13) are used;
II (c) In *the network architecture modelling,* the access network dimensioning is conducted, considering the determined coverage and capacity demands per user defined by Eqs. (14)–(16);
II (d) In *the operator revenues* (P) *modelling,* the revenues are determined considering the determined number of users (BK) and the per-user service price (C) demands, as well as their possible changes, denoted by the delta symbol:

$$\Delta P = \Delta BK \cdot \Delta C \quad (17)$$

II (e) In *the operator costs* (T) *modelling,* the capital and operational costs are determined considering the number of users, as well as the coverage and capacity demands per user. The coverage demands per user are defined within the scenario's regulatory component planning process based on the target part of the coverage area, i.e., PP, and its possible variation. The capacity demands are defined within the scenario's technological component planning process based on the per-user bandwidth, i.e., PR, and the per-user access speed, i.e., BR, and its possible variation. The changes in values are denoted by the delta symbols:

$$\Delta T = \Delta BK \cdot (\Delta PP + \Delta PR + \Delta BR) \quad (18)$$

(III) *The techno-economic assessment process*

Therefore, in the techno-economic cost-effectiveness assessment process, the impact of the given delta values on the resulting cost-effectiveness for all analysed business models can be defined. Considering the given results, the best operator business models can be chosen, i.e., the ones resulting in the greatest NPV, calculated based on the given revenue and cost values:

$$\Delta NPV = \Delta P - \Delta T \rightarrow \max. \quad (19)$$

5.4 Possible strategies for broadband implementation

As already noted in Sect. 2.1, the broadband solutions deployment process is influenced by a number of techno-economic (infrastructure implementation costs), geo-demographic (geographical features, as well as the population density) and regulatory (broadband strategies) factors. The majority of techno-economic and geo-demographic factors in rural areas are considered unfavourable for broadband solutions deployment. Considering the fact that quick changes in the demographic structure of a population are not possible and that an area's geographical features cannot be changed, the easiest way to induce further broadband solutions deployment is the application of specific regulatory measures, i.e., strategies for broadband deployment.

The results of applied extended techno-economic assessment processes should indicate the best business models and the best strategies that could be implemented in the given scenario to solve the existing digital divide problems. The proposed strategies listed in Table 1 have been defined based on the most important global reasons for the digital divide, defined in Sect. 3, i.e., the inadequate techno-economic and regulatory factors (the lack of available broadband infrastructure and inadequate broadband services), as well as the unfavourable socio-demographic structure of a population. The given strategies correlate well with the Connect 2020 Agenda targets and contribute to the achievement of the digital divide reduction goals. Although it may seem that the proposed strategies are somewhat general, they are considered as adequate and necessary solutions to the digital divide problem, as explained below.

(A) Problem: *Internet services are not available;*
Target: *More affordable broadband solutions;*
The suggested solution: *Deployment of optimised low-cost and cost-efficient broadband solutions;*

Considering the fact that the development of rural broadband offers numerous benefits to users in rural areas, there are many reasons in favour of the introduction of broadband access in rural areas, even in cases when the cost-effectiveness, i.e., NPV of broadband implementation, is not sufficient. In such cases, the necessary subsidies can be defined. Since the cost-effectiveness of the implementation of technical broadband solutions in rural areas is often not significant and relies on regulatory measures that define the adequate funding policies, the techno-economic assessment process used should enable determination of the necessary subsidies for the cost-effective business models and the creation of subsidiary implementation plans. The short-term subsidiary plans allow for adjustments to the planned subsidiary activities so that the long-term plan's targets set can be successfully achieved.

Table 1 Overview of suggested strategies for digital divide reduction

Problem	Connect 2020 Agenda target	Suggested solution	Influencing factors	Source	Metric	Suggested strategy
(A) Internet services are not available	*Broadband solutions should be* 40 *percent more affordable worldwide by* 2020	Deployment of optimised low-cost and cost-efficient broadband solutions	Regulatory and technical factors	*TECHNO-ECONOMIC ANALYSES*	NPV	Subsidisation
(B) Internet is available, but the cost of services is too high	*Broadband services should cost not more than* 5 *percent of average monthly income in developing countries by* 2020	Coordination of broadband service prices with the rural residents income levels	Economic factors	*SURVEY OUTPUTS AND RESULTS OF ANALYSES*	Service price demands	ARPU levels coordination
(C) Internet services do not correspond to users' needs	90 *percent of the rural population worldwide should be covered by broadband services by* 2020	Development and adoption of high-valued broadband services	Technical and socio-demographic factors	*CONDUCTED WITHIN FRAMEWORK*	Requirements regarding: - access speed - traffic volume - service quality	Broadband services adaptation and customisation
(D) Lack of knowledge or skills to use the Internet	*Equality among Internet users should be reached by* 2020	Digital inclusiveness considering 'broadband for all' concept	Socio-demographic factors		Digital skills levels	Promotion of Internet usage and computer literacy

(B) Problem: *Internet is available, but the cost of services is too high;*

Target: *Cheaper broadband services;*

The suggested solution: *Coordination of broadband service prices with the income levels of rural residents;*

To enable the coordination of broadband service prices, i.e., average revenue per user (ARPU), with the income levels of rural residents, analyses of key economic factors influencing broadband implementation and adoption in rural areas should be conducted within the proposed framework. The results of the conducted analyses should be directly included in the further techno-economic modelling process to yield the best business model in a given case.

(C) Problem*: Services do not correspond to users' needs;*

Target: *Higher level of usage of broadband services;*

The suggested solution: *Development and adoption of new high-valued broadband services that correspond to rural users' requirements;*

To increase the overall number of users in rural areas and to reduce the existing digital divide, rural users should be encouraged to request broadband technologies and services compatible with their needs. Hence, within the proposed framework, analyses of key technical and socio-demographic factors that affect broadband adoption of rural users should be conducted to define the actual requirements of potential end users. According to the suggestions given in [58], such process should assist in encouraging greater applicability and availability of broadband in rural areas.

(D) Problem*: Knowledge or skills needed to use the Internet are lacking;*

Target: Digital divide reduction;

The suggested solution: Digital inclusiveness considering the 'broadband for all' concept;

By the additional promotion of Internet usage and computer literacy, as well as by enhancing users' digital skills, based on the outputs of the conducted survey, further broadband adoption should be achieved, the digital divide should be reduced, and inequalities in the usage of broadband services among different socio-demographic groups of users should be accomplished.

5.5 Strategies selection process based on the determined broadband users' requirements and the conducted techno-economic assessment process

Considering the fact that the rural scenarios differ based on the existence and the level of development of broadband solutions (infrastructure and services), as well as the necessary socio-demographic structure of rural residents, not every strategy is adequate for all rural scenarios. Therefore, the appropriate analyses (the ones proposed within the given framework) should be conducted to point to the reasons for the digital divide in a certain scenario and to choose the most adequate strategy/strategies among the possible ones. Finally, considering the given results of the conducted extended techno-economic assessment process for the implementation of broadband solutions, adequate strategies for the digital divide reduction, presented in Table 1, should be suggested. The suggested strategies include:

- the subsidisation—in the cases in which the cost-effectiveness of the business model for broadband implementation is not sufficient (influenced by regulatory and technical factors);
- the provision of broadband services that offer significant socio-economic benefits to users—in the cases in which available Internet services do not correspond to user needs (influenced by technical and socio-demographic factors);
- the coordination of the proposed broadband service prices with the actual income levels of rural residents—in the cases in which the cost of Internet services is too high (influenced by economic factors);
- the promotion of computer literacy and enhancement of digital skills of rural residents—in the cases in which the results of the survey show that a lack of knowledge or skills necessary to use the Internet is present (influenced by socio-demographic factors).

Since the proposed strategies are not mutually exclusive, depending on the given analyses results, a single strategy or a combination of strategies can be proposed. For example, in the case in which the results of the conducted analyses point to the fact that the most important factor for the broadband adoption process is the offering of existing broadband services and that the available services do not correspond to users' needs (regarding their access speed, traffic volume, or service quality), the strategy should be aimed at broadband services adaptation and customisation. This should result in the development and adoption of broadband services that are considered valuable to rural users.

A possible outcome may also include the cases in which multiple strategies should be proposed. Therefore, in a case in which the results of the conducted analyses indicate that the most important factor for the broadband adoption process is the price of broadband services (related with the population economic background) and that the service price has a major impact on the cost-effectiveness of a given business model, but the given business model cannot induce positive NPV values regardless of the reduction in the revenues within the defined feasible range, the strategies should allow for the ARPU levels to be coordinated with the average users' income levels and for the necessary amount of subsidies to be determined. In this way, broadband infrastructure would be further deployed, and the price of broadband services would correspond to users' economic statuses. This should result in better possibilities for rural users to access digital sources and knowledge.

Moreover, in the case in which the results of the conducted analyses show that the lack of knowledge or skills necessary to use the Internet is the most important reason for the lower level of usage of broadband services, so that the total base of possible service users is too small to make a broadband business model cost-effective in the given scenario, the proposed strategies should include the subsidisation of broadband infrastructure deployment for the best determined business case and the additional enhancement of the population's digital skills. In this way, the availability of broadband access infrastructure and the acquisition of skills necessary for broadband services usage should enable rural residents to use broadband services and access knowledge and digital sources in formal, non-formal and informal ways.

Depending on the results of the extended techno-economic process, any other combination of the related strategies aimed at further broadband solutions adoption can be proposed. It is important to notice that the advantage of the proposed extended techno-economic assessment process is its possible application to any rural scenario of any particular size (considering different hierarchical levels, as defined in [8]). Therefore, the strategies can be defined to fit any particular local-, regional- or national-level scenarios.

6 A case study of extended techno-economic assessment process and rural broadband strategies proposal

Due to the various specificities of rural areas, the introduction of broadband access in these areas requires special consideration. In general, the cost-effectiveness of rural broadband implementation is not significant and often relies on additional public funding. Hence, to find the most adequate broadband solutions for rural areas, analyses of the most important factors for broadband adoption and deployment are proposed. Since an increased number of broadband connections in rural areas can be reached through the implementation of optimised business models, i.e., models that stimulate the introduction of cost-effective broadband solutions, the extended techno-economic modelling can be applied when considering the sustainability of the chosen business model and when choosing the optimal business strategy in a particular rural area scenario.

The extended techno-economic model, the overview of which is given in this paper, is modular. It consists of a set of related components, i.e., functions created in MATLAB. While some of these functions are common in every standard techno-economic model, several additional functions defined within the proposed framework extend the standard techno-economic models and are used for the supplementary regression analyses, as described in this paper. These analyses assist in determining the way in which investment in broadband access should be conducted in a particular rural area scenario. Therefore, within the framework, the regression analyses of different socio-demographic and techno-economic factors influencing broadband adoption in rural areas have been incorporated. Considering the rural users' requirements defined in the regression analyses conducted, it is possible to evaluate any chosen business model for rural broadband access networks deployment.

(I) *Analysis of geo-demographic factors*

For the case study, broadband diffusion analysis is conducted for the rural group of counties defined in [33]. For the analyses, new data for the period 2002–2014 are used.

(II) *Regression analysis and determination of the most important socio-demographic factors that affect broadband adoption*

The socio-demographic structure of a rural population usually differs from the structure of an urban population. According to the data presented in [33], several remarks can be given when comparing rural and urban areas. First, the population density in rural areas is below the average density. Furthermore, residents in rural areas generally have lower levels of income, i.e., the average income in those areas is lower. Additionally, in the majority of rural areas, the proportions of the younger population and the higher-educated population to the total population are lower. Finally, the proportion of the population working in the primary business sector to the total population is more significant for rural areas than for urban areas, i.e., it is typical of rural areas. Hence, to identify the main factors affecting broadband adoption, the following model, obtained from a nonlinear model, is used:

$$\ln(BK_{ix}) = \alpha + \beta_N 1 \cdot \ln(Age_{ix}) + \beta_N 2 \cdot \ln(Edu_{ix}) + \beta_N 3 \cdot \ln(Income_{ix}) + \beta_N 4 \cdot \ln(Workf_{ix}) + \beta_N 5 \cdot \ln(Prim\_\mathrm{sec}_{ix}) + \beta_N 6 \cdot \ln(Pop\_Den_{ix}) + \beta_N 7 \cdot \ln(BK\_users_{ix-1}) + \eta_i + e_{ix} \quad (20)$$

where BK_{ix} represents the number of broadband users in the county i, in the period x, Age_{ix} is the population age group, and Edu_{ix} is the portion of the population attending secondary school or faculty. $Income_{ix}$ represents the per-user income level, $Workf_{ix}$ represents the work force (i.e., the labour force), $Prim\_sec_{ix}$ represents the labour force working in the primary business sector, and Pop_Den_{ix} represents the population density. The variable η_i represents a county-fixed effect (comprising the constant term), and e_{ix} is a standard error term. Before conducting the analyses, several assumptions can be made. First, a positive complementarity between the number of young broadband users and the number of well-educated broadband users, reflected by the coefficients $\beta_N 1$ and $\beta_N 2$, respectively, may be expected since a larger number of young people and a higher level of education may imply a higher probability for broadband implementation. Furthermore, it may be assumed that $\beta_N 3$ is positive since a higher income level reflects higher purchasing power with respect to broadband services. Moreover, the effects of the portion of the population that works, $\beta_N 4$, may be positive since a higher number of working individuals may imply a higher probability for broadband implementation. Finally, it may be presumed that the portion of the workforce working in the primary business sector, $\beta_N 5$, and the population density, $\beta_N 6$, are positive as well. The given results are presented in Fig. 2.

The effects of the predictors, i.e., the demographic and the socio-economic factors, on the response, i.e., broadband adoption, for the regression model with broadband user data included are presented. The plots show how changing the factors from minimal to maximal existing values influences the broadband adoption volume, while the circles represent the magnitude of these effects. The horizontal lines represent confidence intervals for the predictions. The predictions come from changing one predictor, while the others are averaged. The averaged values in the plots show that the factor with the largest impact on broadband adoption in rural counties is the employment status of the population, followed by population education structure and income level. In contrast, the least significant factors are the portion of the population working in the primary business sector and the area population density. Finally, it can be concluded that the most frequently analysed factor in the broadband implementation analyses, population density, is not the most significant factor for broadband adoption in rural counties. The presented results show that factors with the largest impact on broadband adoption in rural counties are the employment status and income level of the population, followed by the level of education and age structure. Furthermore, several disparities between the assumed and the determined coefficient signs can be noted. In both groups, a negative relation is noted between population density and the number of broadband users. This fact can be interpreted in the context of an overall growth in the number of broadband users regardless of the negative population growth trend present today in most rural areas.

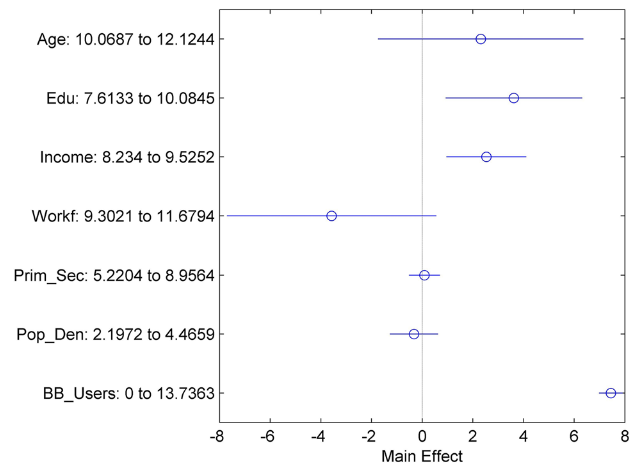

Fig. 2 The effects of the factors on broadband adoption

Similarly, a negative relation is noted between broadband adoption and the number of individuals who work since a trend of underemployment exists. In addition, an insignificant relationship between the portion of the workforce employed in the primary business sector and broadband adoption can be interpreted in the light of the fact that a lower number of individuals working in the primary business sector implies a higher number of individuals working in other business sectors and demanding broadband access more intensively.

It is important to emphasise that the auto-correlated factors are defined and omitted from further analyses. Auto-correlation sometimes exists between the broadband adoption rates and the gross domestic product since the increase of broadband adoption rates may induce further economic growth, while at the same time economic growth may enable further increase in broadband adoption rates. In the regression analyses conducted in this paper, the income level per capita, as a measure of the average income earned per person, which can be determined from the gross domestic product, is considered. However, income level and broadband adoption are not auto-correlated variables since a higher income level reflects higher purchasing power with respect to broadband services, while higher income levels do not necessary imply the presence of broadband access infrastructure or the existence of adequate broadband services. The auto-correlations between the broadband adoption rate and any other socio-demographic factor are also not significant for the same reason. The given correlations between broadband adoption and the socio-demographic factors are primarily one-way directed and are used to define the factors that are important for broadband adoption.

(III) *Regression analysis and determination of the most important socio-demographic and techno-economic factors that describe the user requirements*

For further evaluation, regression analyses are conducted based on the collected data (the previously presented actual socio-demographic data, as well as the presumed data defining the user demands on service price, service quality, access speed, and traffic volume). The results of the conducted regression analyses are expressed through the values of the β_K coefficients (i.e., $\beta 1$, $\beta 2$, $\beta 3$, and $\beta 4$), which are related to the four determined combinations of the techno-economic factors (i.e., services price—*Price*, quality of service—*QoS*, traffic volume—*Traffic*, and access speed—*Speed*, respectively), and the most influential socio-demographic factors for broadband adoption, determined in the previous step (population age—*Age*, education—*Edu*, income level—*Income* and employment—*Workf*). From the given set of all resulting *beta* factors, only the most significant factors that involve the combinations of the four techno-economic factors and the socio-demographic factors are presented in Table 2. In the analysed scenario, the most significant numeric values of the *beta* coefficients ($\beta 1$, $\beta 2$, $\beta 3$, and $\beta 4$) comprising the vector **beta** are:

$$\mathbf{beta} = [1 \quad 0.766 \quad 0.209 \quad -0.010] \tag{21}$$

According to the results given in Table 2, several remarks can be made. First, since income level is an important socio-demographic factor for broadband adoption, the service price related to income level is the most significant factor for broadband adoption. The quality of service related to education level is a significant factor for broadband adoption as well. Additionally, traffic volume related to employment status is significant for broadband adoption. Finally, access speed is the least important factor among all techno-economic factors reflecting the users' request for broadband services, as the value of the coefficient $\beta 4$ is insignificant (<0.05).

Examining these results, it is obvious that while aiming at the further encouragement of broadband adoption in rural counties and the closure of the existing digital gap, appropriate strategies for enhancing broadband adoption should be considered. In relation to the regression analysis results showing the most significant factors for broadband adoption in rural counties, the proposed strategies should include careful ARPU planning and the coordination of the proposed broadband service price levels with the actual rural residents' income levels. The given conclusions and results can be used in techno-economic modelling. In this way, the best operator strategies can be chosen, as will be shown hereafter.

(IV) *Techno-economic assessment of rural broadband business models related to the broadband users' requirements*

To find the optimal broadband access solutions for rural areas, the most important factors for broadband adoption

Table 2 Estimation of nonlinear regression model coefficients for rural broadband adoption (2002–2014)

Most important determined socio-demographic factors affecting broadband adoption	Estimated values of β_N coefficients using regression model	Most important combinations of socio-demographic and techno-economic factors that reflect users' requirements	Normalised values of β_K coefficients
ln (*Age*)	1.125	ln (*Price–Income*)	1.000
ln (*Edu*)	1.464		
ln (*Income*)	1.960	ln (*QoS–Edu*)	0.766
ln (*Workf*)	−1.506		
ln (*Prim_sec*)	0.023	ln (*Traffic–Workf*)	0.209
ln (*Pop_den*)	−0.144		
ln (*BK_users*)	0.542	ln (*Speed–Age*)	−0.010
(*Intercept term*)	(−24.79)		
Statistics:			
Number of observations	195		
R-squared	0.938		

and deployment should be analysed from the techno-economic point of view. For the techno-economic evaluation, a case study business model has to be selected.

It is important to emphasise that within the technical architectures modelling process, any fixed or mobile and any wired and wireless access network can be modelled, as already demonstrated in [8]. Additionally, the techno-economic methodology used to compare different access solutions was presented in [8].

Since the standard techno-economic process is not in the scope of this paper, details regarding the planning and modelling of broadband access networks and the related technical details are not listed. Instead, the focus is on the extension of the standard techno-economic assessment process used to determine the user requirements that should be included in the standard techno-economic assessment process. The aim is to demonstrate in which way the results given using the extended techno-economic assessment process can be used when selecting the optimal broadband deployment strategies based on the determined user requirements.

In general, in rural areas, a low level of competition among operators exists. Hence, the common scenario in which a private operator and a public operator compete in the observed market is selected. However, any other combination of the number of operators and their chosen access technologies can be modelled within certain functions of the standard techno-economic modelling process.

In general, it is possible to observe the following cases: both operators choose to invest in the broadband network, one operator chooses to invest, or none of the operators choose to invest. To determine the best strategies for the operators, the model includes game theory.

In Table 3, the possible combinations of strategies for the two operators are defined. Based on the simulation results, it is possible to find the optimal strategies for both operators. In a competitive environment, in which each of the two operators wants to choose the best strategy, the Nash equilibrium is considered. '*D*' denotes the decision to invest, while '*N*' denotes the decision not to invest. '*U*' represents the net present value that can be achieved in a particular case, and can be determined as follows:

$$UK = Revenues - Costs. \tag{22}$$

Table 3 Combinations of strategies of the two operators

Strategies		Operator 2			
		N		D	
Operator 1	N	$UK_{(1,1)}$	$UK_{(2,1)}$	$UK_{(1,3)}$	$UK_{(2,3)}$
	D	$UK_{(1,2)}$	$UK_{(2,2)}$	$UK_{(1,4)}$	$UK_{(2,4)}$

For the evaluation of further strategies, the previously determined regression analyses results based on the collected socio-demographic and techno-economic data have been considered. The obtained numeric values of coefficients ($\beta1 = 1$, $\beta2 = 0.766$, $\beta3 = 0.209$, and $\beta4 = -0.010$) comprising the vector **beta** have been used. Depending on the changes in techno-economic factors (i.e., in the *delta* parameters values), as well as on the values of coefficients that describe the impact of changes in the techno-economic factors on the number of users (i.e., in the *beta* coefficients), the revenue and cost models change. Additionally, the best business models for each operator change.

In the test scenario, the value range of the *delta* parameters is from -1 to 1. However, the value range of the *delta* parameters could be further increased beyond 100%. It is important to emphasise that for any particular scenario, the selected range of the *delta* parameters values should be defined by the operators or the regulator. The selected number of steps necessary for the evaluation of real options using Monte Carlo simulations is 1000, and the selected number of steps necessary for simulations to assess the impact of input values on the result value is 100. Within the simulation process, the techno-economic assessment process is conducted for a total of 37500 different models and 2500 different combinations.

For the previously defined algorithm used for determining the best operator business models, the three groups of simulation results are listed to determine the optimal operator business models. Additionally, the given results should be used to compare the cost-effectiveness, i.e., NPVs of the chosen optimal model with the model that induces the maximal NPV value for the given case study.

The first group of simulation results presents the created decision (i.e., classification) tree. It enables the decision-making process and helps in the selection of an optimal strategy for the two operators. For example, if both operators decide to invest in a broadband access network in the observed rural area, as indicated in Figs. 3 and 4 by the symbol '*DD*', there are multiple ways to achieve the optimal model. Hence, the operators can choose the combination of changes of the *delta* parameters values, denoted as '*d*1', '*d*2', '*d*3', and '*d*4', (denoting the changes in service price (i.e., ΔC), coverage area (i.e., ΔPP), capacity (i.e., ΔPR), and access speed (i.e., ΔBR), respectively) that are most appropriate for a specific case. The symbol '*KK*' indicates mixed strategies.

Regarding the fact that for the model assessment process in the created test scenario, the selected *delta* parameters values change in increments of 0.5 in the range of -1 to 1, where '1' represents a 100% increase in value, '0' represents no change in the initially determined value, and '-1'

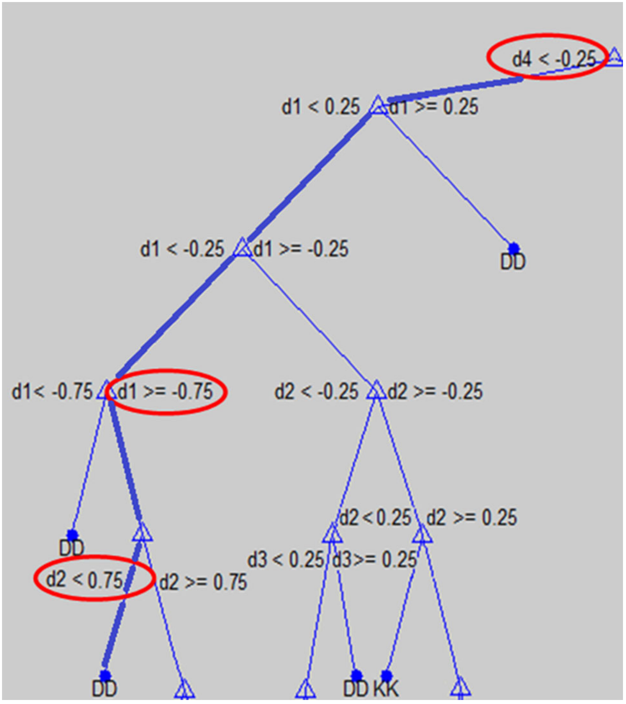

Fig. 3 Chosen strategy

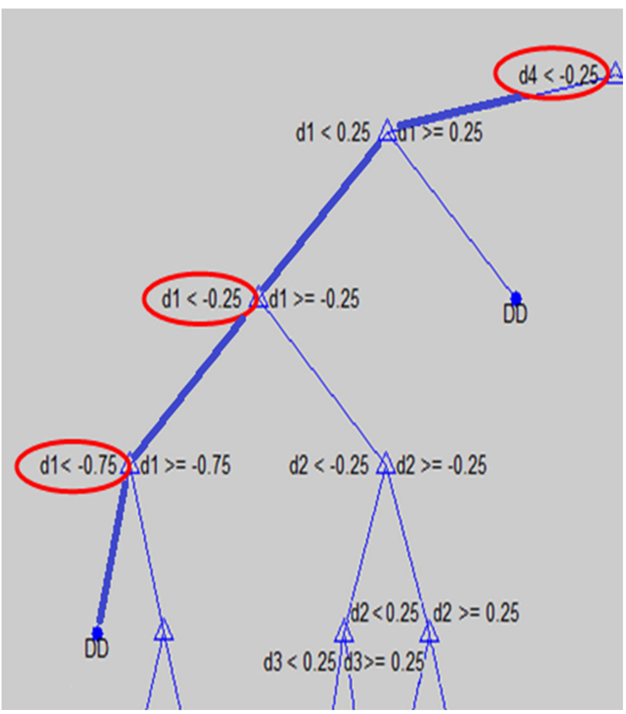

Fig. 4 Additional strategy

represents a 100% reduction in the value of a parameter, the changes of the parameter values are shown in the graph within those ranges and the changes in their values are expressed by the following values: −0.75, −0.25, 0.25, and 0.75.

There are many combinations of *delta* parameters values that result in the '*DD*' strategy, from which the operators may choose the most appropriate values for the given case. In the given case study, the relations between the range of the chosen *delta* parameters' values and the complexity of the resulting classification tree have been considered.

The defined changes in *delta* parameters values used within the simulation process result in a very large number of different outcomes, which are presented in a very complex classification tree, single parts of which are presented in Figs. 3 and 4. However, to additionally improve the accuracy of the given results, the selected *delta* parameters values could change in increments that are less than 0.5. In that case, the complexity of the resulting classification tree would additionally increase.

The main focus of this section of the paper is to select the best operator strategies with respect to the results of the conducted regression analyses. Therefore, to prove that the usage of an additional framework enables the proposition of the most appropriate operator strategy considering the defined regression results, the strategy should be defined based on the conclusions of the conducted regression analyses. In the given scenario for which the regression analysis has been conducted, the service price is the most significant factor for broadband adoption. Therefore, while aiming at further encouraging broadband adoption, the proposed strategy for the given scenario should include the coordination of the proposed broadband service price levels with the users' income levels, i.e., the minimisation of the initially defined average service price. Considering the defined changes in parameter values, the service price values can be reduced within the following intervals: 0–25, 25–75, or 75% and more.

Thus, if operators plan to significantly minimise the service price, the strategy they use should include the reduction of the service price by 75% (or even more): $d1 \geq -0.75$, as presented by the selected path in the tree in Fig. 3. In that case, to make an investment in broadband access infrastructure profitable for both operators ('*DD*'), the increase of the planned coverage area should be at least 75% ($d2 < 0.75$). Moreover, this may result in a maximum decrease of 25% of the previously planned access speed per user ($d4 < -0.25$), though this is an acceptable outcome since the access speed is the least important factor among all techno-economic factors that reflect the users' request for broadband services in the given case study, as was already proven by the regression analyses results.

However, investment in broadband access infrastructure could also be profitable for both operators ('*DD*') even if the chosen service price reduction is smaller, for example, if the reduction is in an interval between 25 and 75%, as presented in Fig. 4. Although this may also result in a maximum decrease of 25% of the initially planned access

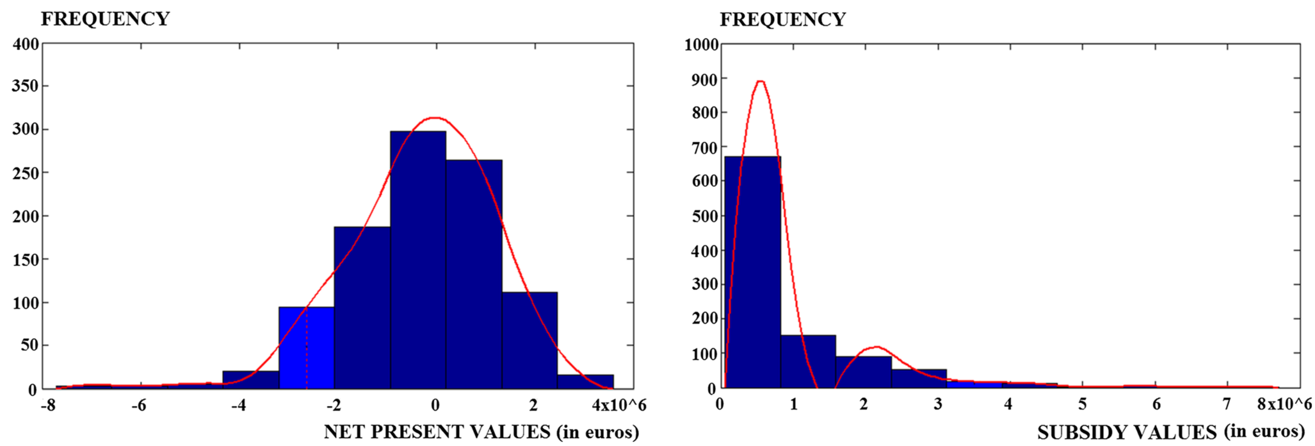

Fig. 5 Histogram of NPV values (*left*) and subsidy values (*right*)

speed per user ($d4 < -0.25$), in this case, no further network coverage expansion is necessary. However, a smaller area would be covered by broadband access in this case compared to the previous one.

The second group of simulation results presents the resulting histograms, shown in Fig. 5. These histograms display the frequencies of the predicted NPV and subsidy values for the chosen business model. The greatest value on the frequency scale, presented on the left side of the graph, is the group frequency interval that contains the largest number of predicted values. For the given case study, the most important costs associated with the deployment, operation and maintenance of the chosen broadband access solution are taken into consideration, and the cost-effectiveness of its implementation in rural areas is determined.

Moreover, a set of technical and financial results obtained using the NPV method is presented to show the effects of key factor changes on the overall costs of network deployments. The presented results include the value range of the estimated net present values for both operators and the necessary subsidies.

Finally, the third group of simulation results is presented to compare the previously chosen values of the *delta* parameters, defined with respect to the chosen optimal strategy, with the values of the *delta* parameters that induce the maximal possible NPV values. The presented results comprise the maximum possible real options value, the average subsidy value needed for the cost-effective business model, the set of the suggested *delta* parameters values defining the best operator strategies, and the ordinal number of the suggested best combination, expressed numerically as:

$$\begin{aligned} &Maximal\_real\_option\_value = 1.2104e + 007 \\ &Average\_subsidy\_value = 7.8872e + 005 \\ &\mathbf{CHANGES} = [1.0000 \; -0.5000 \; 0 \; 0] \\ &Ordinal\_number\_of\_suggested\_combination = 858. \end{aligned} \tag{23}$$

For the operator strategies defined, the *delta* parameters values proposed for the vector **CHANGES** should be used in the techno-economic planning and modelling processes to achieve the determined maximal real option value, i.e., the NPV value, numerically expressed as a result of the techno-economic process. Those values should be interpreted as the percentage changes of the defined techno-economic values, i.e., of the initial service price, initial targeted part of the coverage area, initial bandwidth and initial access speed, which are included in the techno-economic planning process. For the given scenario, in which the two network operators are considering to invest in broadband access, the determined values of the vector **CHANGES** enable operator coordination of the planning and modelling processes with the defined user demands on service price, service quality, access speed, and traffic volume. The given values of the *delta* parameters that induce the maximal NPV values should help in making decisions in the cases in which it is possible to choose more than one strategy that satisfies the user's request. In that case, the strategy that results in NPV values that are the closest to the calculated maximal NPV value should be chosen.

To conclude, several remarks related to the broadband ecosystem elements, presented in the introductory sections of the paper, should be given. To improve adoption, development, deployment, and selection processes of broadband solutions, in the given case study, the following recommendations for broadband market participants on both the broadband demand and supply sides can be proposed:

- The several studies referenced in this paper show that the unfavourable socio-economic conditions present in the majority of rural areas cause lower service adoption rates. The results of the regression analyses conducted in this paper for the chosen case study show that the income level of the population is a very important factor for broadband services adoption in rural areas. Therefore, the broadband operators or regulators should coordinate the broadband service price levels (ARPU) with rural users' income levels to encourage further broadband adoption:

- Furthermore, the several studies referenced in this paper also show that one of the most important reasons for the lack of broadband usage is the deficiency of useful *e*-services. The development of adequate services should induce further broadband adoption. Since the offered broadband services are often not adjusted to users' requirements and needs, broadband users should precisely define their requirements so that the adequate broadband solutions can be developed;
- Moreover, broadband operators continually aim at growth, where the requirements are often set to cover either the specified percentage of the geographical territory (i.e., 'geo' coverage) or the specified percentage of the population (i.e., 'pop' coverage). Rural areas offer opportunities to achieve further growth. As presented in (IV) of Sect. 6, based on the given results of the analyses conducted for the chosen case study, further growth can be achieved by deploying broadband access solutions in new coverage areas, i.e., rural areas
- Finally, as proposed in (IV) of Sect. 6, broadband market regulators should encourage business cases that are created based on the defined user requirements to avoid usage of non-adequate broadband access solutions and to determine the necessary amount of subsidies, in the case in which it is not possible to deploy cost-effective broadband solutions.

7 Conclusions

Considering the fact that broadband access is not available in the majority of rural areas worldwide, a digital divide exists between those people who have and those who do not have access to information and communication technologies and services. The results of some recently conducted studies referenced in this paper indicated that technological determinants are not sufficient to address the emergence of the digital divide. Therefore, it is important to answer the following question: *How should broadband access networks be developed in rural areas to achieve an increase in the total number of broadband users?*

The implementation of broadband access in rural areas generally presents a great challenge for operators. In rural scenarios, business cases of broadband implementation can often be interpreted as 'difficult' since the achieved profitability is often not significant. The techno-economic assessment process is considered to be relevant for finding the optimal broadband solutions. The proposal of optimal solutions could induce further implementation and adoption of broadband technologies and services in rural areas. This is the reason for the importance of the extended techno-economic modelling methodology used in this paper.

The starting point of the issues presented in this paper is the improvement of universal access to digital information sources to improve the digital skills and access to knowledge of a rural population. Within the given context, the needs and abilities of a rural population are analysed using the extended techno-economic methodology. The main focus of this paper was the detailed overview of an additional framework that upgrades the existing techno-economic models and enables the inclusion of the regression analysis-induced factors relevant for rural broadband adoption in the techno-economic assessment process. To demonstrate the efficiency of the proposed framework's usage in finding the best operator business strategies, the analyses of the case study examples were presented.

The presented strategies are proposed to enable further deployment of broadband infrastructure in rural areas, to enhance broadband services and to enable the acquisition of the skills necessary for broadband services usage. Moreover, the availability of broadband infrastructure and the acquisition of necessary digital skills should enable further broadband services usage, as well as the acquisition of digital knowledge in any formal, non-formal, or informal way.

The main advantage of the defined extended modelling methodology, in contrast to other standard techno-economic modelling methodologies that result in a plain set of estimated NPV values, is the possibility of the coordination of the investment strategies based on the best business models (the ones with the greatest values from all possible NPV values) with the actual user requirements (considering the socio-demographic and techno-economic factors) given as the input for the techno-economic modelling process.

Without this coordination, it is possible that the operators could choose the business models that include solutions that do not correspond to the user requirements. In this case, the investment risks would be higher because the users may adopt fewer services than are assumed within the techno-economic planning process, which would result in less profitable business cases.

It is important to note that although the NPV values associated with the business cases in which the best suited strategies have been chosen are generally less than the maximal NPV values that could exist in the given case, the adoption of strategies that correspond to users' requirements reduces the risk of service adoption to a much smaller extent than in the initially planned case.

As shown in the given results, few of the assessed business models turn out to be profitable. It is obvious that the majority of the presented business cases require subsidisation. Thus, an additional advantage of the proposed modelling methodology is that the given results define the best ways for achieving the maximal profitability for the considered business cases, which are created based on the defined user requirements. This is crucial to avoid unnecessary subsidisation when possible. Moreover, with the proposed methodology, it is possible to evaluate the cost-effectiveness of business models, considering the implementation of different technical broadband access solutions for different numbers of operators and their modelled strategies. Hence, this methodology can be used by both network operators and broadband market regulators to find the best deployment solutions.

The proposed extended modelling methodology can be generally applied to any scenario, but since the digital divide problem in rural areas is analysed in this paper, data typical for rural areas, as well as for rural populations, are used in the regression analyses. The fact that the rural geo-demographic features usually differ from the urban ones has been addressed to define the proposed methodology. Hence, the specificities of rural areas are examined within the extended techno-economic modelling process.

As has already been proven, the digital divide exists and should be quantified to apply appropriate methods for its reduction. However, in general, there is a lack of relevant ICT indicators. Since the accuracy of the given analyses results depends on the accuracy of the input data, an increase in the amount and variety of collected data, as well as more timely statistics, would improve the conducted assessment process. The importance of regular collection of the relevant statistical data is globally recognised, and several recommendations regarding data collection processes have recently been proposed. In the case in which input data are just demonstrative, the given outputs can be used to indicate the most likely strategies that should be used in a given scenario. The application of the results presented could be useful to both network operators and broadband market regulators when choosing the best deployment solutions and broadband deployment strategies, even in the cases where the results are only used to demonstrate the most convenient strategies for a given case study.

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References

1. The International Telecommunication Union—Telecommunication Standardization Sector (ITU-T): Vocabulary of terms for broadband aspects of ISDN. Recommendation I.113 (1997)
2. Grimes, A., Ren, C., Stevens, P.: The need for speed: impacts of Internet connectivity on firm productivity. J. Product Anal. **37**, 187–201 (2012). doi:10.1007/s11123-011-0237-z
3. Czernich, N., Falck, O., Kretschmer, T., Woessmann, L.: Broadband infrastructure and economic growth. Econ. J. **121**, 505–532 (2011). doi:10.1111/j.1468-0297.2011.02420.x
4. Koutroumpis, P.: The economic impact of broadband on growth: a simultaneous approach. Telecommun. Policy **33**(9), 471–485 (2009). doi:10.1016/j.telpol.2009.07.004
5. The European Commission: A Europe 2020 initiative: Digital Agenda for Europe. Strategy. Brussels: COM (2010) 245. https://ec.europa.eu/digital-agenda/en/digital-agenda-europe-2020-strategy. Accessed Dec 2015
6. Rose, La, et al.: Closing the rural broadband gap. Telecommun. Policy **31**(6–7), 359–373 (2007). doi:10.1016/j.telpol.2007.04.004
7. The International Telecommunication Union (ITU): Connect 2020 Agenda for Global Telecommunication/ICT Development (2014). http://www.itu.int/en/connect2020/Pages/default.aspx. Accessed Dec 2015
8. Krizanovic Cik, V., Zagar, D., Rimac-Drlje, S.: Broadband Ecosystem elements in techno-economic modelling and analysing of broadband access solutions for rural areas. J. Tech. Gaz. (2016). doi:10.17559/TV-20150508131935
9. Kim, Y., Kelly, T., Raja, S.: *Building Broadband: Strategies and Policies for the Developing World*. Global Information and Communication Technologies Department. World Bank Publications, Washington (2010)
10. Publishing, O.E.C.D.: *The Development Dimension ICTs for Development Improving Policy Coherence. Book*. OECD Publishing, Paris (2010). ISBN 9789264077409
11. Bauer, J.M.: Regulation, public policy, and investment in communications infrastructure. Telecommun. Policy **34**(1–2), 65–79 (2010). doi:10.1016/j.telpol.2009.11.011
12. Peronard, J.-P., Just, F.: User motivation for broadband: a rural Danish study. Telecommun. Policy **35**(8), 691–701 (2011). doi:10.1016/j.telpol.2011.06.008
13. Chaudhuri, A., Flamm, K.: An analysis of the determinants of broadband access. Telecommun. Policy **31**(6–7), 312–326 (2007). doi:10.1016/j.telpol.2007.05.006
14. Cullen International: Benchmarking Fifteen National Broadband Plans. Ericsson, Study (2014)
15. The International Telecommunication Union (ITU): Key ICT indicators for the ITU/BDT regions, developed and developing countries and the world. Database (2015). http://www.itu.int/en/ITU-D/Statistics. Accessed Dec 2015
16. Loo, B.P.Y., Ngan, Y.: Developing mobile telecommunications to narrow digital divide in developing countries? Some lessons from China. Telecommun. Policy, **36**(10–11), 888–900 (2012). ISSN 0308-5961

17. Prieger, J.E.: The broadband digital divide and the economic benefits of mobile broadband for rural areas. Telecommun. Policy **37**(6–7), 483–502 (2013)
18. Götz, G.: Competition, regulation, and broadband access to the internet. Telecommun. Policy **37**, 1095–1109 (2013). doi:10.1016/j.telpol.2013.03.001
19. Billon, M., Marco, R., Lera-Lopez, F.: Disparities in ICT adoption: a multidimensional approach to study the cross-country digital divide. Telecommun. Policy **33**(10–11), 596–610 (2009)
20. Kolko, J.: Broadband and local growth. J. Urban Econ. **71**(1), 100–113 (2012). doi:10.1016/j.jue.2011.07.004
21. Tselekounis, M., Varoutas, D.: Investments in next generation access infrastructures under regulatory uncertainty. Telecommun. Policy **37**, 879–892 (2013). doi:10.1016/j.telpol.2013.06.001
22. Cambini, C., Jiang, C.Y.: Broadband investment and regulation: a literature review. Telecommun. Policy **33**(10–11), 559–574 (2009). doi:10.1016/j.telpol.2009.08.007
23. Chen, Y., Savage, S.: The effects of competition on the price for cable modem internet access. Rev. Econ. Stat. **93**(1), 201–217 (2011). doi:10.1162/REST_a_00070
24. Bouckaert, J., van Dijk, T., Verboven, F.: Access regulation, competition, and broadband penetration: an international study. Telecommun. Policy **34**, 661–671 (2010). doi:10.1016/j.telpol.2010.09.001
25. Savage, S.J., Waldman, D.: Broadband internet access, awareness and use. Telecommun. Policy **29**(8), 615–633 (2005). doi:10.1016/j.telpol.2005.06.001
26. van Deursen, A.J.A.M., van Dijk, J.A.G.M.: Improving digital skills for the use of online public information and services. Gov. Inf. Q. **26**(2), 333–340 (2009)
27. Andres, L., et al.: The diffusion of the Internet: a cross-country analysis. Telecommun. Policy **34**(5–6), 323–340 (2010). doi:10.1016/j.telpol.2010.01.003
28. Abbey, R., Hyde, S.: No country for older people? age and the digital divide. J. Inf. Commun. Ethics Soc. **7**(4), 225–242 (2009)
29. Lee, S.: A cross-country analysis of ubiquitous broadband deployment: Examination of adoption factors. Ph.D. thesis, University of Florida, United States (2008). etd.fcla.edu/UF/UFE0022611/lee_s.pdf
30. The International Telecommunication Union (ITU): Yearbook of Statistics: Telecommunication/ICT Indicators—2005–2014 (2015). The 41st Edition of the Yearbook
31. Riggins, F. J., Dewan, S.L.: The Digital Divide: Current and Future Research Directions. *Journal of the Association for Information Systems*. **6**(12) (2005). http://aisel.aisnet.org/jais/vol6/iss12/13
32. The International Telecommunication Union (ITU): Measuring the information society. Report (2015). http://www.itu.int/en/ITU-D/Statistics. Accessed Dec 2015
33. Krizanovic, V., Zagar, D., Grgic, K.: Econometric Analysis of Demographic and Socio-Economic Factors Influencing Broadband Adoption in Croatian Rural Counties. In: *Proceedings of the 12th International Conference on Telecommunications (ConTEL)*, Zagreb, Croatia. IEEE (2013)
34. The European Commission: Proposal for a regulation of the European parliament and of the council on measures to reduce the cost of deploying high-speed electronic communications networks. Brussels: 2013/0080 (COD) (2013)
35. Lemstra, W., Melody, W.H. (eds.): *The Dynamics of Broadband Markets in Europe: Realizing the 2020 Digital Agenda*. Cambridge University Press, Cambridge (2014)
36. Prieger, J.E., Hu, W.-M.: The broadband digital divide and the nexus of race, competition, and quality. Inf. Econ. Policy **20**(2), 150–167 (2008). doi:10.1016/j.infoecopol.2008.01.001
37. Orviska, M., Hudson, J.: Dividing or uniting Europe? internet usage in the EU. Inf. Econ. Policy **21**(4), 279–290 (2009)
38. Savage, S.J., Waldman, D.M.: Ability, location and household demand for Internet bandwidth. Int. J. Ind. Organ. **27**(2), 166–174 (2009)
39. Lucic, D., Caric, A., Lovrek, I.: Standardisation and regulatory context of machine-to-machine communication. In: *Proceedings of the 13th International Conference on Telecommunications (ConTel)*, Graz, Austria. IEEE (2015)
40. Verdegem, P., Marez, L.D.: Rethinking determinants of ICT acceptance: towards an integrated and comprehensive overview. Technovation **31**(8), 411–423 (2011). doi:10.1016/j.technovation.2011.02.004
41. Harno, J., Katsianis, D., Smura, T., Eskedal, T.G., Venturin, R., Pohjola, O.P., Kumar, K.R.R., Varoutas, D.: Alternatives for mobile operators in the competitive 3G and beyond business. Telecommun. Syst. **41**(2), 77–95 (2009). doi:10.1007/s11235-009-9150-4
42. Grubesic, T.: The Geodemographic Correlates of Broadband Access and Availability in the United States: a Longitudinal Analysis. Telemat. Inform. **21**(4), 335–358 (2004). doi:10.1016/j.tele.2004.02.003
43. Wood, L.E.: Rural broadband: the provider matters. Telecommun. Syst. **32**(5), 326–339 (2008). doi:10.1016/j.telpol.2007.08.004
44. Verbrugge, S., et al.: Practical steps in techno-economic evaluation of network deployment planning. In: *Proceedings of the 13th International Telecommunications Network Strategy and Planning Symposium*. Budapest. IEEE (2008)
45. Sigurdsson, H. M. (2007). Techno-Economics of Residential Broadband Deployment: Multimedia Services in Residential Broadband Networks. Ph.D. thesis, Technical University of Denmark
46. Kantor, M., Wajda, K., Lannoo, B., Casier, K., Verbrugge, S., Pickavet, M., Wosinska, L., Chen, J., Mitcsenkov, A.: General framework for techno-economic analysis of next generation access networks. In: *Proceedings of the 12th International Conference on Transparent Optical Networks (ICTON)*. Poland. IEEE (2010)
47. Website of the European FP3-RACE 2 project: Tool for Introduction Scenario and Techno-economic Evaluation of Access Network (TITAN). (1992–1995). http://cordis.europa.eu/project/rcn/14533_en.html. Accessed Dec 2015
48. Website of the European FP3-RACE 2 project: Information and Techno-Economics in RACE Two (INTERACT). (1992–1995). http://cordis.europa.eu/project/rcn/14538_en.html. Accessed Dec 2015
49. Website of the European FP4-ACTS project: Optimised architectures for multimedia networks and services (OPTIMUM). (1996–1998). http://cordis.europa.eu/project/rcn/35037_en.html. Accessed Dec 2015
50. Website of the European FP4-ACTS project: Techno-economic results from ACTS (TERA). (1994–1998). http://cordis.europa.eu/project/rcn/46606_en.html. Accessed Dec 2015
51. Website of the European FP5-IST project: Techno-economics of IP optimised networks and services (TONIC). (2001–2002). http://cordis.europa.eu/project/rcn/53630_en.html. Accessed Dec 2015
52. Website of the European Celtic project: Techno-economics of integrated communication systems and services (ECOSYS). (2004–2007). http://www.optcomm.di.uoa.gr/ecosys/. Accessed Dec 2015
53. Website of the European FP6-IST project: Multi service access everywhere (MUSE). (2004–2006). http://cordis.europa.eu/project/rcn/99178_en.html. Accessed Dec 2015
54. Sokele, M.: Analytical Method for Forecasting of Telecomm. Service Life-cycle Quantitative Factors. Ph.D. thesis, Faculty of Electrical Engineering and Computing, Croatia (2009)

55. Katsianis, D.: Telecommunications Networks Planning and Evaluation with Techno-Economic Criteria. Ph.D. thesis, University of Athens, Greece (2009). http://cgi.di.uoa.gr/~phdsbook/files/katsianis.pdf
56. Riihimäki, V.: Managing Uncertainties in Broadband Investments - Case Studies of Real Options for Rural Area Access Networks. Ph.D. thesis, Helsinki University of Technology, Finland (2010)
57. Laaksonen, P.: Critical factors of high-speed broadband investments in rural areas from perspective of operators. Master thesis. Helsinki University of Technology, Finland (2011). http://lib.tkk.fi/Dipl/2011/urn100543.pdf
58. Smura, T.: Techno-economic Modelling of wireless network and industry architectures. Ph.D. thesis, Aalto University, Finland (2012). http://lib.tkk.fi/Diss/2012/isbn9789526045252/isbn9789526045252.pdf
59. Kelly, T., Rossotto, C.M.: *Broadband Strategies Handbook*. The World Bank, Washington (2012)
60. The International Telecommunication Union (ITU). The 13th World Telecommunication/ICT indicators Symposium. Conclusions and recommendations (2015). http://www.itu.int/en/ITU-D/Statistics. Accessed Dec 2015
61. Kwak, N., Skoric, M.M., Williams, A.E., Poor, N.D.: To broadband or not to broadband: the relationship between high-speed internet and knowledge and participation. J. Broadcast. Electron. Media **48**(3), 421–445 (2004)
62. Trinh, T.A., Gyarmati, L., Sallai, G.: Understanding the impact of loyal user behaviour on Internet access pricing: a game-theoretic framework. Telecommun. Syst. **48**(1), 43–61 (2010). doi:10.1007/s11235-010-9333-z
63. Riff, A.: Game-theoretic Analysis of Deployment Schemes for Mobile Network Offloading. Master thesis, Aalto University, Finland (2011)
64. Krizanovic Cik, V., Zagar, D., Kordic, K.: Comparison of models for prediction and forecast of broadband services adoption. In: *Proceedings of the 39th International Conference on Telecommunications and Signal Processing (TSP)*, Wien, Austria. IEEE (2016)