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Methods and models for the redesign of home care services enabled by the introduction of assistive technologies

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Abstract

The pace of technological progress in healthcare has accelerated significantly in recent years. However, the limited financial resources of healthcare systems are forcing decision-makers to focus only on the most beneficial innovations. It has become essential for decision-makers to select and fund only those technological breakthroughs that offer significant benefits to all stakeholders in relation to the costs associated with their adoption. Health Technology Assessment (HTA) has emerged as a valuable tool to inform these decisions. When a technology is new to a health system, there may not be adequate empirical evidence regarding the impact of its introduction. In such instances, the assessment must deal with this lack of evidence, and it is referred to as Early HTA. Both HTA and Early HTA analyses assess the benefits against the costs of alternative ways of employing a technology. When considering technologies that could result in significant changes in a healthcare delivery processes, these alternatives may not be immediately evident at the outset of the assessment.

This thesis proposes a novel methodological approach to address Early HTA problems when there is a lack of a clear definition of alternatives at the beginning of the analysis. Such an approach involves the use of Multi-Criteria Decision Analysis (MCDA) to compare alternative modes of service delivery that are generated within the MCDA process itself. The approach was tested and applied to the real case of the social cooperative *Pane e Rose*, a member of the *Umana Persone* network, which needed to comprehend whether and how to redesign its home care services by introducing a new telepresence robot. Ten service stakeholders were involved in 7 rounds of meetings spread over 5 months. The process led to the identification of up to 19 criteria against which alternative service delivery modes could be evaluated. The MACBETH approach was selected to determine the optimal solution agreed upon by all the stakeholders involved. The preferred alternative involves using the robot for monitoring and social support services, increasing the frequency of operator intervention, and enabling both the patient and the informal caregiver to actively use the device.

Alongside the identification of the most promising way of employing the telepresence robot, this thesis also addresses operational scheduling problems. Specifically, given a set of potential patients in need of home care and a limited set of operators, this study addresses the problem of optimally choosing the patients to be served, selecting which of them are to be assisted through the telepresence robot, defining the order in which the patients are to be seen and the operator to perform the visit. To this end, a novel adaptation of the Home Health Care Routing and Scheduling Problem (HHCRSP) is proposed. The optimization model has been formulated, implemented, and successfully applied on small-sized instances. While the preliminary results are promising, additional development is necessary to apply the model to larger-scale instances.

Sommario

Negli ultimi anni, l'accelerato sviluppo tecnologico nel settore sanitario e le limitate risorse finanziarie disponibili per l'adozione di nuove tecnologie, hanno spinto i vari decisori a selezionare, tra le innovazioni più promettenti, quelle in grado di generare benefici sufficienti a superare i costi legati al loro impiego. L' Health Technology Assessment (HTA) si è dimostrato un efficace strumento a supporto di tali decisioni. In contesti in cui non si hanno evidenze empiriche dell'impatto dell'introduzione di una tecnologia, tale analisi viene denominata Early HTA. Sia le analisi HTA che le Early HTA confrontano modalità alternative di impiego di una tecnologia sulla base dei benefici ottenibili e dei corrispondenti costi. L'adozione di tecnologie innovative può determinare un cambiamento radicale all'interno di un processo di erogazione di servizi sanitari, e in tali circostanze le modalità alternative di impiego potrebbero non essere chiare all'inizio dell'analisi.

Questa tesi propone un nuovo approccio metodologico per far fronte a problemi di Early HTA in cui, all'inizio dell'analisi, non vi sia una chiara definizione delle alternative da confrontare. Tale approccio implica l'applicazione della Multi-Criteria Decision Analysis (MCDA), al fine di confrontare modalità di erogazione dei servizi generate all'interno del processo MCDA stesso. L'approccio è stato testato e applicato al caso reale di *Pane e Rose*, cooperativa sociale membro della rete di *Umana Persone*, la quale mira a riprogettare i propri servizi di assistenza domiciliare, a fronte dell'introduzione di un nuovo robot di telepresenza. A tal fine sono stati coinvolti 10 stakeholders in 7 incontri svoltisi nell'arco di 5 mesi. Il processo ha portato all'identificazione di 19 criteri attraverso i quali valutare le modalità alternative di erogazione, per poi convergere, utilizzando la metodologia MACBETH, all' individuazione della soluzione ritenuta la migliore dagli stakeholders coinvolti. Tale soluzione prevede l'impiego del robot nei servizi di monitoraggio e supporto alla vita di relazione, andando ad incrementare la frequenza di intervento degli operatori e consentendo ai caregiver informali e ai pazienti di utilizzare attivamente il dispositivo.

Oltre all'identificazione del modo più promettente di impiegare il robot di telepresenza, questa tesi affronta anche problemi di pianificazione operativa. In particolare, dato un insieme di potenziali pazienti che necessitano di assistenza domiciliare e un insieme limitato di operatori, questo studio fa fronte al problema di scegliere in modo ottimale i pazienti da servire, selezionare quali di essi assistere attraverso il robot di telepresenza, stabilire l'ordine in cui i pazienti devono essere visitati e l'operatore che deve eseguire la visita. A tal fine, viene proposto un nuovo adattamento dell'Home Health Care Routing and Scheduling Problem (HHCRSP). Tale modello di ottimizzazione è stato formulato, implementato e applicato con successo su istanze di dimensioni limitate. Sebbene i risultati preliminari siano promettenti, sono necessari ulteriori sviluppi per applicare il modello a istanze di dimensioni maggiori.

Index

List of Tables

List of Figures

1 Introduction

In recent years, there has been a significant acceleration in the technological progress within the healthcare sector. However, due to the constrained financial resources of healthcare systems, decision-makers are compelled to concentrate solely on the most propitious innovations. It has become fundamental for decision-makers to select and finance only those technological breakthroughs that demonstrate considerable benefits for all stakeholders in relation to the costs associated with their adoption. Health Technology Assessment (HTA) is a structured analysis of a health technology, a set of related technologies, or a technology-related issue that is performed to support a decision-making process and provide input to a policy decision. HTA has demonstrated its efficacy in aiding healthcare-related decisions on technology introduction, allowing the assessment of new solutions at a conceptual, investigational, established, or even obsolete stage. Early HTA analyses refer to the evaluation of solutions in their early stages of development. Dealing with such solutions often involves a lack of solid empirical evidence regarding the impact of technology introduction, thereby introducing significant uncertainty in the decision-making process. HTA and Early HTA analyses may be performed through different methodological approaches, but their aim is always to compare the benefits and costs of alternative technologies or methods of their implementation. In cases where technologies are being evaluated during their early development stages or when their use in a particular operational context is unclear, it may be necessary to rely on hypotheses and assumptions to carry out the analysis. If the hypotheses to be introduced are significant, the analysis could lead to limited or unhelpful results.

The first part of this thesis proposes a novel methodological approach for addressing Early HTA problems when a clear definition of alternatives is lacking at the beginning of the analysis. Such an approach involves the use of Multi-Criteria Decision Analysis (MCDA). To face the problem of the lack of a clear definition of alternatives, these are generated within the MCDA process, based on the identification of key value aspects, involving experts, and using practical tools to facilitate discussions. The approach was tested and applied to the decision problem of *Pane e Rose*, a social cooperative member of the *Umana Persone* network. The goal of the assessment was to support the cooperative in understanding whether and how to redesign its home care services with the introduction of a new telepresence robot. This involved the identification of the possible service delivery modes enabled by the introduction of the device and then assessing the benefits brought by the new solutions to all parties involved. The process brought to the involvement of 10 experts and the holding of 7 rounds of meetings within 5 months. The analysis guided the identification of three service delivery modes enabled by robot introduction for the private market and two for the public sector. The MCDA, applied through the MACBETH approach, was performed only for the public context, where the new modes identified were compared between them and with the traditional one based on 19 criteria. The process led to the calculation of the overall value score of the selected alternatives as a combination of relative scores and weights, generated through qualitative assessments. The process supported the identification of the best alternative, and the new modes exhibited notably greater value compared to the traditional one, although with higher costs. The preferred alternative entails using the robot for monitoring and social support services, increasing the frequency of operator intervention, and enabling both the patient and the informal caregiver to actively use the device. The results also highlighted the strong influence of operational decisions, particularly regarding patient selection for remote care, on the profitability of investments. The evaluation's results were deemed fundamental in guiding future decision-making and in supporting potential negotiations with the public contracting authority. Furthermore, the assessment of the method with participants and a group of researchers validated our approach as methodologically robust when the modes of technology introduction in services are unclear.

The second part of this thesis is dedicated to operational issues related to the introduction of the telepresence robot within the home care services delivered by social cooperatives. A novel adaptation of the classical Home Health Care Routing and Scheduling Problem (HHCRSP) is presented, to incorporate the use of telepresence robots. Notably, there is a lack of prior studies addressing the HHCRSP with the possibility of tasks being performed through telepresence devices. Firstly, the nominal version of the model was formulated, and then adapted to the introduction of the device. The model proposed is designed to address the planning of home care interventions, considering that some tasks may be carried out remotely by operators. The model allows to identify the optimal set of patients for remote care and to accordingly schedule all services. While we implemented and tested the proposed model on small-sized instances, challenges arose with larger ones. Preliminary results demonstrated the model's ability to successfully identify the optimal set of patients for remote care and to optimize home care service schedules. To apply the model to real-world problems, further work is needed to enhance its tractability. The computational efficiency of the model may be increased addressing these limitations e.g., through the introduction of valid inequalities or metaheuristics. The model, with further developments, may support the cooperatives in the early phases of technology introduction and relieve the dispatching resources from the burden of scheduling activities when dealing with a significant number of patients.

This work is organized as follows: Section 2 introduces the context of the problem; Section 3 reports a literature review of both Early HTA and HHCRSP problems and Section 4 presents the methods followed. Section 5 gathers details of the performed Early HTA and Section 6 presents the formulation of the optimization models together with preliminary results. Section 7 is dedicated to conclusions, and finally Section 8 reports limitations and future research.

2 Context

2.1 *Umana Persone* and social cooperatives

The analysis presented in this work was developed as a complementation of the curricular internship that took place from April to July 2023 at *UP Umana Persone Impresa Sociale R&S*.

UP Umana Persone Impresa Sociale R&S (*UP*) is a network of social cooperatives, operational since 2016. *UP* is a Third Sector organization and is registered in the National Research Registry.

It currently consists of 10 member cooperatives in the Tuscany region. The members of the network are social cooperatives involved in social, assistive, and educational activities.

The network activity is focused on seven different areas of research including digitalization and assistive technologies, finance for social entrepreneurship, organizational development, offer innovation, and professional training.

The internship activity was developed in the digitalization and assistive technologies area. The focus of the activity, and the results expected by the organization revolved around examining current organizational frameworks for home care services delivered by social cooperatives and assessing the implications of incorporating assistive technologies within these services.

The network selected one of the 10 cooperatives as a case study for this analysis, in particular, the cooperative *Pane e Rose* based in Prato (PO, Italy) was chosen, but the analysis and the results obtained were required to be generalizable to all cooperatives.

2.2 Home care services in social cooperatives

The central activity at *Pane e Rose* is the delivery of home care services for three main categories of patients:

- Disabled (minors or adults),
- Elderly not-self-sufficient,
- Self-sufficient (minors, adults, elderly, or people with mental distress),

Patients can be private or public:

- Private patients**,** directly, or through an informal caregiver, contact the cooperative without intermediaries and purchase an access package for home care services. The access package includes a specific number of visits that are defined based on the patient's needs.

- With public patients, it is generally the informal caregiver that requires the drafting of an operational care plan to the regional sanitary system. The social worker, based on the patient's specific situation, formulates a care plan, and addresses it to the social cooperative that will decide whether to accept the project or not. In this context the cooperative receives payment for the delivered services by the regional sanitary system. The patient pays a ticket based on their *ISEE* (Equivalent Economic Situation Indicator).

The home care services offered by the cooperatives are classified into two categories, *Personal care and external relationships* (Category *A*), and *Environmental care* (Category *B*):

- Category *A* services (*Personal care and external relationships*):
  1. Simple and complex lifting,
  2. Simple and complex bed positioning,
  3. Simple and complex bathing,
  4. Personal hygiene,
  5. Meal preparation and serving,
  6. Personal and home condition monitoring services,
  7. Support services for social life,
  8. Hygienic and healthcare services.

- Category *B* services (*Environmental care*):
  9. Household hygiene,
  10. Grocery shopping and errand handling.

The human resources, generally referred to as *operators*, assigned to these services are of three main categories:

- Health and social worker *(OSS, Operatore Socio-Sanitario),*
- Primary caregiver *(AdB, Assistente di Base*),
- Non-qualified operator.

The first two are typically dedicated to Category *A* activities, while non-qualified operators can only be assigned to Category *B* activities.

2.3 The *PHArA-ON* Project and assistive technologies

Since 2020 *Pane e Rose* and other cooperatives of the *UP* network have been involved in the *PHArA-ON* project as facilitators.

PHArA-ON (Pilots for Healthy and Active Aging)[1] is a project funded by the European Union's Horizon 2020 program. The project aims to improve the quality of life of Europe's elderly population. The project involves 41 partners from 12 European countries (Italy, Spain, Portugal, Netherlands, Slovenia, Croatia, Germany, France, UK, Belgium, Austria, and Estonia) and has a duration of 48 months (from December 2019 to November 2023). *PHArA-ON*'s partners include large, medium, and small enterprises, research organizations, universities, health authorities, public and private healthcare providers, social organizations, healthcare institutes, and standardization bodies.

Within the project, different assistive technologies have been tested in 6 pilots in 5 countries: Italy (Tuscany-Puglia), Spain (Murcia and Andalusia), the Netherlands (Twente), Slovenia (Isola), and Portugal (Coimbra- Amadora).

Assistive technologies are generally products, equipment, and systems that enhance learning, working and daily living for persons with disabilities and the elderly[2].

The objective of the Italian pilot is to propose personalized integrated care for frail older adults, and to do so it works on two sites: Tuscany Region and Puglia Region.

The challenges of the Italian Pilot sites are:

1. Positively impact the behavior and the approach of the elderly to friendly technological devices,
2. Assess the health status and its progress over time,
3. Promote social cohesion,
4. Define a specific personalized care plan based on the patient's needs,
5. Support operators towards more efficient and personalized care services.

Among the technologies used in the pilot activities, in the second half of 2021, the Italian pilots tested a multi-platform social network called *SENTAB* to boost socialization among older adults and operators. The monitoring dashboard *Discovery* supported operators in monitoring the health status of selected pilot participants. The most recent activity of the Italian pilot is a 6-month case study to assess the telepresence robot *Ohmni Robot,* for supporting operators and informal caregivers in monitoring and social support services [43].

Between the different assistive technologies that the network has been evaluating through different projects (*PHArA-ON*, *CloudIA*, etc.) the robot for telepresence was selected as the subject of this analysis. In particular, the *Ohmni Robot* was chosen as the technology of interest.

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[1] https://www.pharaon.eu/

[2] https://www.atia.org/home/at-resources/what-is-at/

Ohmni Robot (*Ohmnilab Robotics*, CA, USA)[3] is a commercial telepresence robot designed for practical remote communication and interaction. The robot is equipped with a camera and microphone system, enabling patients to remotely control its movement and interact with others from a remote location. The device is equipped with a charging station where the robot is placed when not in use. Patients can access and control the robot through a web-based interface. This interface allows for easy navigation and communication, making it accessible to patients with basic technical knowledge. *Ohmni Robot* features basic autonomous navigation capabilities, allowing it to move forward, backwards, and rotate. It can traverse flat surfaces and avoid obstacles within its limited range of motion. It also incorporates standard security measures, such as data encryption, to protect patient's information during remote sessions.

Concerning its application in home care services, it can be installed at the patient's home and be remotely controlled by the operator to move into the environment and interact with the patient. The person who remotely uses the robot can activate a video call without the need for the reached person to answer. This feature is very important in the context of home care services: patients in care may have difficulties in answering the call, and this allows both operators and informal caregivers to be able to monitor the assisted when needed. To face privacy concerns, the robot normally stays in its charging station with the camera facing the wall, and when the call is activated, the operator firstly asks the patients if they are available and only after receiving confirmation, turns the device towards them.

Figure 1 - Ohmni Robot (Ohmnilab Robotics, CA, USA)

[3] https://ohmnilabs.com/products/ohmni-telepresence-robot/

2.4 Telepresence Robot introduction in home care services

Most of the social services delivered by cooperatives are physical acts on patients' bodies or patients' homes, but two categories of services potentially don't require operators' physical presence: Personal and home condition monitoring services (6) and Support services for social life (7).

These kinds of services are often dedicated to elderly, disabled or non-self-sufficient patients who typically live alone and need to be checked on daily or need company for some moments during the day.

The goals of these kinds of interventions are:

- Monitor the patient's personal conditions,
- Monitor the patient's living conditions,
- Provide social support to patients,
- Check if the patient has taken their medication,
- Check if the patient has eaten, etc.

The results of field trials within the *PHArA-ON* project showed how these services could be successfully delivered remotely by operators through the support of the telepresence device.

In particular, L. Fiorini *et al*. [46] investigated the expectations of social operators toward assistive technologies before and during the COVID-19 emergency, and as a result of their analysis, it emerged that social professionals see great potential in the use of this kind of technologies before and during the COVID-19 emergency. Particularly, after the COVID-19 emergency, they slightly increased their positive view about the use of assistive technologies in their work.

Moreover, in their most recent work, L. Fiorini *et al*. [44] carried out a 6-month case study where the O*hmni Robot* was tested in terms of acceptability and usability and compared it to another assistive technology. The study considered both older adults, operators, and informal caregivers' points of view. The analysis pointed out that, at the end of the trial, operators believed that the older adults felt more secure, independent and in contact with loved ones. The operators felt that the older adults did not need their physical presence to interact with the technology and that their job was helped by having more contact with their assisted.

These studies focused their attention mainly on testing acceptability, usability and expectations related to assistive technologies, but as remarked by L.Fiorini *et al*. [46], some of the social workers included in one of their analyses agreed that "one of the limitations of the use of technology in social assistance services was the lack of an organizational infrastructure (at a cooperative level) that would facilitate the introduction of this technology".

UP is now, as a matter of fact, interested in understanding how the telepresence device could be introduced in the current service delivery process for monitoring and social support services and in assessing the overall value that the new service delivery modes could bring to all stakeholders.

3 Literature review

To give a clear description of the methods presented in this work, a literature review is presented regarding both Early Health Technology Assessment (Section 3.1) and Home Health Care Routing and Scheduling Problem (Section 3.2).

In particular, Section 3.1.1 provides an introduction to HTA and to the most widespread HTA methods. Secondly, Section 3.1.2 briefly describes the assessments at the early stages. Then, Section 3.1.3 focuses on the group of HTA methods selected for the present work: Multi-Criteria Decision Analysis.

Lastly, Section 3.2 provides details on the classical HHCRSP problem pointing out the main constraints and objectives.

3.1 Early Health Technology Assessment

3.1.1 Methods for Health Technology Assessment

HTA is defined as an interdisciplinary process for synthesizing information regarding medical, social, economic, and ethical issues related to the introduction of a new health technology [70].

It is a structured analysis of a health technology, a set of related technologies, or a technology-related issue that is performed to support the decision-making process and provide input to a policy decision.

Technology assessment (TA) arose in the mid-1960s from a discussion about the critical role of technology in modern society and its potential consequences. Since its early years, HTA has been driven by the diffusion of technologies that have raised social, ethical, legal, and political concerns such as contraceptives, organ transplantation, life-sustaining technologies, etc. [52]

As Goodman C.S. [52] points out, there are three basic orientations to HTA:

- *Technology-oriented* assessments are intended to evaluate the characteristics or impacts of specific technologies,
- *Problem-oriented* assessments focus on solutions or strategies for managing a particular problem for which alternative or complementary technologies might be used,
- *Project-oriented* assessments focus on the use of a technology in a specific institution, program, or other designated project.

Generally, HTA involves the investigation of many properties, impacts or attributes of health technologies or applications such as technical properties, safety, efficacy, effectiveness, economic impacts, and social, legal, and ethical aspects.

Health Technology Assessments aim to provide decision-makers with useful evidence about which solution should be preferred among the available alternatives (named comparators). The selection of the preferred alternative is based on a comparison of consequences and costs. Consequences include all aspects that are affected by the adoption of a specific solution. These consequences may be positive (benefits) or rather unexpected issues. They can be related not only to the direct user of the technology, but may have an impact on other stakeholders (the healthcare system, the patient's family, specialists delivering the care through the technology, etc.)

As for costs, assessments must consider all resources associated with a specific healthcare solution. The resources might be provided by the healthcare system, the patients or their families, or other organizations (non-profit, social enterprises, etc.)

Over the years many methods have been developed for assessing healthcare technologies, the most widespread ones are listed below:

- **Cost Minimization Analysis (CMA)**: this approach is widely used when dealing with different alternatives that imply similar consequences and when the analysis is focused on selecting the alternative that minimizes resource utilization. As an example, Boucher M. *et al*. [20] compared the cost of contemporary outpatient and historical inpatient management of proximal lower limb deep vein thrombosis (DVT) in adults through a CMA.

- **Cost Effectiveness Analysis (CEA):** this method allows to compare solutions with different consequences and different costs. When the alternatives have different consequences, the most used approach to measure them is through primary endpoints (e.g., reduction in mortality or number of life-years gained). An example of this application can be found in the study developed by Lall R. *et al*. [71]. They carried out a cost-effectiveness analysis of high-frequency oscillatory ventilation against conventional artificial ventilation for adults with acute respiratory distress syndrome.

- **Cost-Utility Analysis (CUA)**: in this case, consequences are measured as a combination of primary endpoints through an outcome measure such as Quality-Adjusted Life Years (QALYs). An example of the application of this approach can be found in the work of Jarungsuccess S. *et al*. [62], who compared new oral anticoagulants for nonvalvular atrial Fibrillation patients, with other existing solutions in terms of QALYs and costs.

- **Cost Benefit Analysis (CBA)**: this approach measures consequences in terms of saved costs or value generated, using currency as a unit of measure. This allows a direct comparison, in monetary terms, between benefits and costs. To assign a monetary term to benefits the most used approach is the measurement of patients' Willingness-To-Pay (WTP). Keller E. *et al*. [67] used CBA to assess value-for-money of publicly funded *in vitro* fertilization (IVF) treatment. IVF treatment outcomes were monetized using taxpayers' willingness-to-pay values derived from a discrete choice experiment.

- **Multi-criteria Decision Analysis (MCDA):** Multi-Criteria Decision Analysis (MCDA) has emerged as a likely alternative or supplementary approach to traditional economic evaluation techniques with the prospects of addressing some of their limitations in health related issues[2].

MCDA is a collection of approaches that support decision-making by taking explicit account of multiple criteria. A criterion is a factor or dimension that is relevant for assessing and comparing different alternatives in a decision-making process. This approach is intended to guide decision-makers through the process of agreeing on what factors are relevant to a decision, measuring the performance of options against these criteria, and understanding the trade-offs between values that may be conflicting [81]. An example of MCDA application in HTA can be found in a work developed by Brixner D. *et al*. [22]. The work structures a Multi-Criteria Decision Analysis for evaluating Off-Patient Pharmaceuticals (OPPs) in emerging markets. The criteria considered for the analysis include product, manufacturer, service, and economic aspects. A more detailed discussion about MCDA will follow in this section.

Generally, solutions can be assessed at a conceptual stage, investigational, established or even obsolete. When assessing solutions that are at the early stages of development, the analysis is referred to as Early HTA.

3.1.2 Health Technology Assessment at the early stages

Over the last two decades, there has been an increasing interest in using HTA in the early stages of technology development. This kind of approach is referred to as Early Health Technology Assessment (Early HTA) and consists of a strategic analysis of the medical context and the competition, evaluation of the economic impact of medical devices and early assessment of clinical effectiveness of the medical devices under development, all with the aim to reduce uncertainty in the developmental stage of a solution [77].

The focus of this kind of analysis is often on the "economic viability" of new solutions: it is deemed to allow companies to stop further development if findings suggest that the solution is unlikely to achieve cost-effectiveness.

As Grutters J. *et. al* [53] point out, the assessment can be carried out at different development phases of the innovation:

- *Idea screening*: the innovation is not yet being developed, but only consists of an innovative idea,
- *Concept development:* a first version of the innovation is being developed,
- *Pre-market:* a product is available, for example for clinical research, but the innovation is not yet on the market,
- *Market access*: the innovation has entered the market and is used in clinical practice.

Bouttell J. *et al*. [21] refer to analyses performed at the early stages as DF-HTA, Development-Focused HTA, to distinguish it from Use-Focused HTA. The main features that distinguish the two types of HTA are:

- Firstly, early in the development process, evidence specific to the solution may be limited and rapidly evolving. However, in use-focused HTA, evidence will be available and established.

- Secondly, DF-HTA may be used to inform a wide range of decisions concerning whether to continue investing in the development of a solution and will require estimates of the acceptable price, expected revenues, and comparative effectiveness of a solution. In contrast, use-focused HTA will be used to inform essentially binary decisions about whether a solution should be used in a specific clinical context.

From a literature review, Grutters J. *et al*. [54] classified Early HTA methods into 4 classes based on the specific goal for early assessment:

- Methods for exploring the nature and magnitude of the problem for which the technology under development should serve as a resolution,

- Methods for estimating the nature and magnitude of the (societal) value that may be expected to be associated with the use of the technology under development,

- Methods for identifying the set of conditions that need to be met for the potential value of a technology under development to materialize,

- Methods to help develop and design the type of research that is needed to demonstrate whether the expected value is borne out in practice.

To perform an HTA it is necessary to have a clear definition of the alternatives to be evaluated: for example, Fermont J.M., *et al*. [42] provided an updated list of medical innovations, categorizing them according to their impact and novelty, providing a ranking according to the perceived health benefit by Dutch clinical and health technology experts, and drawing conclusions for health technology policy making at a macro-level.

Another example may be found in the work of Mishra V. *et al.* [72] where a MCDA is performed for a different level of telemedicine (TM) intervention in the management of diabetes. The study performs HTA for three-level of TM interventions: in-person care, hybrid care and pure telecare, where the alternatives are clearly defined at the beginning of the analysis.

In situations where technologies under assessment are in the early stages of development or where the ways of using the technology in a specific operational context are not clear, it may be necessary to introduce significant hypotheses and assumptions to perform the analysis.

For the decision problem considered in the present study, where a definition of alternatives was lacking, the introduction of significant hypotheses and assumptions would have led to unsignificant results for the decision-makers. It was therefore necessary to go beyond the traditional Early HTA approaches and include the generation of the alternatives within the process.

As far as our research goes, we were unable to locate any examples of studies that have carried out Early Health Technology Assessments where the definition of alternatives was incorporated as a part of the process.

3.1.3 Multi-Criteria Decision Analysis

Devlin N.J. and Sussex J. [39] define Multi-Criteria Decision Analysis (MCDA) as a set of methods and approaches to aid decision making, where decisions are based on more than one criterion, which make explicit the impact of all the criteria applied and the relative importance attached to them.

As Marsh K. *et al*. [80] concluded in their recent work, decision-makers show a positive attitude towards MCDA's potential to improve decision-making in healthcare. Coherently, A. Angelis and P. Kanavos [3] point out that there are three main reasons why MCDA could provide a useful alternative to economic evaluation-based HTA processes:

- The first relates to the possibility to include a comprehensive set of value aspects that go beyond what economic evaluation methods currently capture,

- The second relates to the assignment of quantitative weights across the different evaluation criteria. This allows to incorporate explicitly the relative importance of various value dimensions improving the transparency of the preference elicitation process,

- The third is stakeholder participation and the possibility to include all relevant stakeholders in the value-assessment process. This is both insightful and politically correct, increasing the legitimacy of decision processes, as all stakeholder views are accounted for transparently.

There are many examples of MCDA methods in literature, and most of them share a similar basic structure.

As Muhlbacher A. *et al*. [86] point out, the steps of MCDA can be summarized in:

- Definition of the decision problem: the first step in the MCDA process is to define the main objective to unambiguously determine the decision object. MCDA usually addresses three types of decision problems: choice problems, ranking problems or sorting problems.

- Determination of alternatives: the second step is to determine the different alternatives for the decision problem. In the context of HTA, the alternatives can involve different medical devices or pharmaceuticals or care programs etc.

- Establishing the decision criteria: the third step is to define the decision criteria in the form of measurable attributes. Attributes can be both subjective and objective.

- Measurement of target achievement levels: in this step, all defined criteria are measured specific to the related alternatives.

- Scoring the target achievement levels: the scoring method is a measure for the multidimensional evaluation of alternatives. The purpose of scoring is to make the target achievement comparable for different target criteria.

- Weighting of target criteria: weighting allows to express the extent to which the criteria are relevant in the assessment; many methods can be applied at this stage, such as AHP, DCEs, best-worst scaling, etc.

- Aggregation of measurement results: scores and weights are combined to create a value index. The details of this step may differ according to the type of aggregation model used. Overall, the individual criteria scores and their respective weights are combined to produce weighted scores and are summed to arrive at an overall value score for each option.

- Support decision making: the results of MCDA can be a quantitative overall score or merely a structured deliberation of data. In cases of dealing with a choice problem, MCDA should result in the identification of the best alternative or a reduced set of alternatives. When the decision problem is a ranking problem, MCDA should produce a rank ordering of the alternatives. When the underlying problem is a sorting problem, then MCDA should yield an assignment of alternatives to predefined ordered categories of merit.

As pointed out by Devlin N.J. and Sussex J. [39], MCDA approaches can be classified broadly into three categories: value measurement models, outranking models, and goal, aspiration, or reference-level models.

In value measurement models the degree to which one decision option is preferred over another is represented by constructing and comparing numerical scores (overall value). The scores are developed for each individual criterion initially and aggregated into higher-level value. Some examples of value measurement models are AHP (Analytical Hierarchical Process), weighted sum method, SMART approach (Simple Multi-Attribute Rating Technique), MACBETH approach (Measuring Attractiveness by a Category-Based Evaluation Technique) etc.

In outranking models, the alternatives are compared pairwise, initially in terms of each criterion, to assert the extent of preference for one over the other for that criterion. The preference information across all criteria is aggregated to establish the strength of evidence favoring the selection of one alternative over another. Some examples of outranking models are the ELECTRE approach (Elimination and Choice Expressing Reality), PROMETHEE-GAIA (preference ranking organization method for enrichment evaluations) etc.

Goal, aspiration, or reference-level models involve the derivation of the alternative that is closest to achieving the predefined desirable levels of achievement for each criterion. Examples of this kind of models are Goal Programming, Heuristics and Meta-Heuristics.

Finally, stakeholder involvement is fundamental in MCDA: choices and results must be constantly shared with stakeholders to obtain significant results. As Marsh K. *et al*. [79] point out, when implementing MCDA to support healthcare decisions, it is fundamental to constantly report, justify, and validate the results of each step. Validation with decision-makers is especially critical given the subjective nature of many inputs of the MCDA.

Many examples can be found in literature of MCDA application in HTA: Baeten S.A. *et al*. [4] evaluated different breast cancer interventions through MCDA to rank them based on their overall attractiveness. Cho K. *et al*. [30] applied MCDA to the selection of the most attractive medical product among 88 evaluated products. Hilgerink M. *et al*. [56] applied MCDA through the AHP method to assess the potential clinical value of different scenarios incorporating Photoacoustic imaging for breast cancer imaging. As a last example, Hummel J. *et al*. [57] used MCDA to predict the health economic performance of the non-fusion surgical treatment for idiopathic scoliosis comparing it with standard treatment.

For this study, a value measurement model was selected, in particular, the MACBETH approach was chosen for its main advantages compared to other methods:

- The MACBETH approach employs categorical scales that enable decision-makers to express their judgements more intuitively compared to numerical scales,
- The criteria to be considered can be structured in a hierarchic form that can help in creating a more detailed set of criteria and in evaluating decision components. The hierarchic structure supports capturing the complexity of the decision problem,
- The MACBETH approach allows to consider possible uncertainties in the various steps of the process through robustness analysis,
- The approach facilitates the identification of eventual inconsistencies in judgements, that can be successively discussed with decision-makers,
- The sensitivity of the model can be assessed and discussed with decision-makers to understand how minor variations in the elements of the model may change the result.

3.2 Home Care Routing and Scheduling Problem

The second part of this work was dedicated to the formulation and implementation of an optimization model to support decisions of device assignment and scheduling of home care services, considering the introduction of a telepresence robot. Firstly, the nominal form of the model was formulated and implemented, and then new variables and constraints were introduced to deal with the introduction of the device.

In this section, a brief overview of the traditional Home Health Care Routing and Scheduling Problem (HHCRSP) will be given.

The most crucial objective of Home Health Care (HHC) is to ensure people who need medical attention and daily care to receive high-standard home services. According to patients' needs, nurses, physicians, doctors, and operators visit patients' homes periodically and provide services [38]. The HHC covers a wide range of services, which may involve medical care such as occupational and physical therapy, speech therapy, nursing, and activities of social support [16].

As pointed out by B. Bashir *et al*. [15] HHC problems can deal with many different issues, such as:

- Dimensioning the resources,
- Modeling of system,
- Resource allocation,
- Districting problem (i.e., the problem of partitioning a territory into districts),
- Cost-saving study (cost comparison of Home Care),
- Routing Problem for health Care Personnel and Medicines,
- Planning and Scheduling of nurses and doctors,
- Assignment of human resources to patients,
- Workload balance among healthcare personnel and satisfaction of their preferences,
- Efficient use of Technological support in the Home Care service delivery.

One of the main organizational issues is the scheduling and routing of health care personnel; in Operations Research it is referred to as Home Health Care Routing and Scheduling Problem (HHCRSP), which is an extension of the Vehicle Routing Problem (VRP).

As pointed out by M. Di Mascolo *et al.* [40], in an HHCRSP, a set of patients is considered, spread over a given territory, who need care, for different durations, and require specific qualifications, at their homes. Such care is provided by care workers, with different skills and availabilities. A time window, corresponding to the patient availability, and a number, corresponding to the visit duration, are assigned to each patient. Weights can be assigned to each arc linking two patients. These weights classically correspond to the distance between two patients or the travel cost.

Usually, care workers start travelling from the HHC agency, using diverse means of transportation and return there at the end of their working period. However, in some situations, they can start traveling from their homes, or from the first patient of the day to the last one. The HHCRSP consists in deciding which care worker visits which patient, at what time, while respecting a set of various constraints and optimizing some criteria (such as cost or quality of service), over a given horizon.

As remarked by Benzati E. *et al*. [18] there are many complexity factors that operations management must deal with in this type of care structures, such as:

- Diversity of services proposed: patients may have different needs in terms of types and frequencies of care, and their social and psychological conditions. This implies that the care delivery process cannot be standardized,

- Diversity of resources involved in the care delivery process: based on patients' needs, different types and number of human and material resources may be required, and it is necessary to coordinate all these resources,

- Uncertainty sources: in this context there may be many sources of uncertainty. First, uncertainty in demand which is related to the number of patients who need care, the level of care required by each patient and the time this demand would arise. Second, the uncertainty of travel time, duration of the visits, and the evolution of patients' needs. Third, the uncertainty of the material and/or human resources availability,

- Necessity to guarantee a satisfactory service quality level: it is important to consider the definition of the market strategy by specifying the standard of the service offered, the performance objectives of the structure and resource dimensioning.

Cissè M. *et al*. [32] group the constraints of this kind of problem into categories and sub-categories:

1) Constraints related to the HHC organization:

- **Temporal constraints:** such as the planning horizon, that is typically considered to be one day or one week; and the frequency of routing decision, that refers to how often the routing decision is repeated within the planning horizon.

- **Assignment constraints:** the assignment constraints of an HHC service organization are mainly related to the continuity of care. According to quality standards adopted by HHC providers, services to patients can be provided under full, partial or no continuity of care.

- **Geographic constraints**: the provider can decide to cluster the operators in districts according to the territory, skills, or requirements of patients.

2) **Constraints related to patients:**

   - **Temporal constraints:** these constraints consider the nature and frequency of visits required by the patient, and time windows for starting service which can be soft or hard. In addition, visits assigned to a given operator may have a temporal dependency. Dependencies can exist among the routes of different care workers or among the services provided by a care worker within the same route. In the first case (dependency among routes), visits may require more than one operator at the same time to provide synchronized or shared services. In the second case (dependency within routes), a certain visit must be conducted before another because clinical precedence relationships among services exist.

   - **Assignment constraints:** patient's preferences may be taken into account when assigning operators.

   - **Geographic constraints:** the type of network is an important feature of the HHCRSP. Depending on the context (rural or metropolitan) and where patient homes are scattered in the region, the travelling times of operators can be significant.

3) **Constraints related to operators:**

   - **Temporal constraints:** the capacity of an operator refers to the time frame in which they may work, according to the type of contract. The operator can be a full-time, half-time, or externally subcontracted employee of the HHC provider.

   - **Assignment constraints:** the most important assignment constraint regards operator qualification. Operator workload balance is also an often-faced issue.

   - **Geographic constraints**: these constraints are mainly related to the starting and ending point of each operator's route, that can be a depot, or the operator's home.

With respect to the objective function, Di Mascolo M. *et al*. [40] identified two main categories of goals:

1) **Cost optimization:** minimize travel time/cost/distance, minimize overload costs, minimize waiting times, etc.

2) **Optimization of quality of service and well-being at work:** minimize time window violations, maximize patient preferences, maximize continuity of care, balance workload, etc.

Literature examples of HHCRSP can be found in the work of Carello G. *et al*. [25] who propose a set of mathematical models for the nurse-to-patient assignment problem in home care under continuity of care, inspired to multi-criteria optimization, to investigate the effect of each stakeholder's goal on the others and their interactions.

Cappanera P. *et al*. [24] propose an integrated approach that jointly addresses the assignment of operators to patients, the scheduling of the visits and the determination of the operator tours.

Decerle J. *et al*. [36] address the multi-objective home health care problem with the aim of ensuring the applicability of the planning considering the minimization of the total working time of the operators, while maximizing the quality of service and minimizing the maximal working time difference among nurses and auxiliary nurses.

Nikzad E. *et al*. [88] propose a two-stage stochastic integer model to consider simultaneously decisions on districting, staff dimensioning, resource assignment, scheduling, and routing.

As a last example, Savaşer S. *et al.* [98] focus on the delivery of mobile healthcare services in rural areas, where doctors visit remote villages which do not have a healthcare facility nearby.

To the best of our knowledge, there are no examples of studies dealing with the problem of HHCRSP that include the possibility of performing tasks through a telepresence device, that allow to identify the optimal set of patients to serve remotely and consequently schedule services.

Nevertheless, a similar problem faced in literature may be found in the work of Taiwo E. *et al.* [102]. They face the problem of appointment scheduling for physician–nurse teams in the presence of patient choice and no-shows. They propose a novel model that accounts for patient choices, on the day of the appointment, in a system with two provider types (nurses and physicians). In this work, the element of decision is between two different types of human resources.

The following section presents the methods applied for both problems faced.

4 Methods

In this section an overview of the methods applied for the faced problems will be given. Firstly, the steps for Early HTA will be shortly described, and then, the process for the formulation of the optimization models will be summarized.

4.1 Early HTA using MACBETH approach

In this work, an Early Health Technology Assessment was performed applying Multi-Criteria Decision Analysis through the MACBETH approach for the evaluation of alternatives having multiple criteria and conflicting objectives. The possible alternatives investigated represented the current service delivery mode and the ones enabled by the introduction of a telepresence robot (*Ohmni Robot*) in monitoring and social support services delivered by social cooperatives for public patients. The definition of the alternative service delivery modes was part of the investigation since a structured mode was lacking. 10 participants were involved in the process, and 7 rounds of meetings were necessary for the assessment. All meetings were conducted online.

The following table shows, for each participant, their reference organization, their role in the organization, their involvement in projects regarding the telepresence robot (e.g., *PHArA-ON*) and their participation in the seven meetings:

Participant	Organization	Role	Involvement in projects	0	1	2	3	4	5	6
1	1	Project Manager	Yes	X	X	X		X	X	X
2	1	Project manager, Coordinator of home care services	No			X			X	
3	1	Specialist center manager	Yes		X	X		X	X	X
4	2	Social worker	No				X			X
5	2	Ageing psychologist	Yes		X	X	X	X		X
6	3	Psychologist	Yes	X			X	X		X
7	4	Psychologist, Home Care services manager	Yes		X	X	X	X	X	X
8	5	Geriatric educator	Yes		X	X				X
9	6	Researcher - Industrial Bioengineering	Yes		X	X			X	
10	6	Research Assistant - Industrial Bioengineering	Yes		X	X				

Table 1 - Participants and meetings

The analysis was structured in the following main phases:

1. Structuring the problem,
2. Structuring the model,
3. Evaluation of alternatives,
4. Testing the requisiteness of the model.

Each of these main phases was divided in different steps:

1. **Structuring the problem**

   Understanding of the context and information gathering
   This phase was developed during the three-month internship at *UP Umana Persone Impresa Sociale R&S*, in particular, the *Pane e Rose* cooperative was taken as a case study. Through expert interviews, document consultation and data collecting, it was possible to understand the current work organization of home care services, with particular attention to the work carried out by coordinators. Coordinators are responsible for the organization of home care services and are in direct contact with patients and their families. Particular attention was also paid to the current and past projects regarding the introduction of assistive technologies in which *Umana Persone* was involved, and to the studies developed by the Department of Industrial Bioengineering of the *Università degli Studi di Firenze.*

   Definition of the decision problem and HTA method selection
   This phase was focused on determining the goal of the analysis and the expected results. To do so, a kick-off meeting was conducted to define the focus of the analysis, determine the best approach to be followed, and identify participants to be involved.

2. **Structuring the model**

   Criteria identification – Literature review
   For the identification of the criteria to be considered, firstly a literature review was conducted to identify the main topics considered in scientific papers when dealing with similar technologies. A first set of value aspects was created.

   Areas of concern, screening and evaluation criteria
   The 1st meeting with participants was organized to discuss areas of concern, identify screening criteria, select the relevant stakeholders and the effects that technology introduction could have on each one of them. As a support for this phase, mind maps were used to discuss and generate value aspects.

Value aspects relevance evaluation
The 2nd meeting was held to assess the relevance of each of the identified value aspects. To do so a questionnaire was completed by participants expressing their judgement on the relevance of each criterion. During the meeting, some of the selected criteria were unanimously excluded.

Structuring the alternatives
Based on the information gathered from the previous meetings, a specific tool, the so-called Strategy Table[4], was employed to outline the necessary building blocks and their options for structuring the new service delivery modes. The Strategy Table was validated and then used during the 3rd meeting to build the new service delivery modes as combinations of the elements of the table. This led to the definition of three new service delivery modes enabled by the introduction of the telepresence robot in the private context, and two for the public one. The alternatives were successively formulated using the Business Model Canvas and shared with participants. The following steps were only applied to the context of public patients, since for private patients, decision-makers agreed on limiting the analysis to alternatives definition.

Descriptors of impact construction and validation
A first formulation of the impact descriptors was created, and then discussed and validated during the 3rd meeting with participants.

Value functions and weights
For the assessment of the attractiveness of improvements and weights of each criterion, two questionnaires were shared with participants. The answers to the questionnaires were gathered and processed, and the 4th meeting was scheduled to validate the results and determine the value functions of criteria and their relative weights. The second part of the meeting was dedicated to the determination of weights for each macro-category of criteria in the value tree. This led to the calculation of the overall weight of each criterion.

3. **Evaluation of alternatives**

Target patient identification and impact appraisal
The first step of this phase was to identify the category of patients to consider for the analysis, in particular, two different categories of patients were distinguished. Based on the category, different alternatives were considered. To assess the overall value of each option, an assessment of their performance level on each criterion was performed. To do so, in the 5th meeting participants were asked to discuss for each option, their

[4] https://www.structureddecisionmaking.org/tools_trashed/toolsstrategytables/

performance in each criterion selecting from the levels defined in the descriptors. The software generated the scores coherently with the value functions.

Calculation of the overall value and cost of alternatives
Weights and performance scores were combined in an additive model to obtain an overall score of performance. The overall value of each option was determined and associated with the coherent category of patients. The cost of each option was also calculated in the form of annual differential cost. In addition, the Net Present Value of the investments was evaluated, with a sensitivity analysis on the parameters that have a strong influence on the profitability of the investment.

4. **Testing the requisiteness of the model**

   Sensitivity and robustness analyses
   A sensitivity analysis on weights was performed to identify elements whose weight variation led to a change in the best option. Weight variations required to obtain a different best options were all not plausible or justifiable, hence no discussion with participants was carried out. A robustness analysis was performed using ordinal, MACBETH, and cardinal information. Only one criterion was worth discussing with participants during the last meeting.

   Model validation and method assessment
   The results were presented during the last meeting, and participants were questioned about their coherence and compliance with their expectations. The methodological approach was then assessed in terms of usefulness, requisiteness, adequacy, robustness, and ease of use asking for feedback from participants. Finally, an assessment of the methodological approach was deployed with the support of a group of researchers of the Department of Bioengineering of the *Università degli Studi di Firenze.*

The following section summarizes the steps that led to the definition and implementation of the optimization models.

4.2 Optimization Models

The second activity of this work was focused on developing and implementing a routing and scheduling problem for home care services, considering the introduction of the telepresence robot for supporting operators in monitoring and social support services. To do so, four steps were followed:

1. **Problem definition:** through interviews and meetings with the coordinators of home care services at *Pane e Rose,* the current process was comprehended and mapped, and data was collected from the management software.

2. **Nominal model formulation:** the nominal model was formulated to support the scheduling of traditional home care services within a one-week time frame. The nominal model maximizes the profits deriving from the selection of public projects considering hourly costs of operators and transportation costs.

3. **Model with telepresence robot formulation**: the nominal model was adapted to formulate the new version that allows to identify patients to be served through the telepresence robot, and to consequently schedule services. New variables and constraints were introduced, while the objective function of profits maximization remained unchanged.

4. **Implementation and preliminary results:** both versions of the model were coded in Python-Pyomo using Spyder IDE. The models were tested on small-sized instances derived from the historical data of the cooperative using CPLEX solver.

5 Early HTA of the telepresence robot

In this section, the steps and results of the Early HTA performed through the MACBETH approach will be presented.

The assessment was carried out in all its phases in the context of public patients. With respect to the private sector, the analysis ended with the structuring of the alternative service delivery modes.

The following table shows for each macro-phase of the assessment, the steps that were followed to achieve the desired outputs:

Macro-Phase	Phase
Structuring the problem	Definition of the decision problem and HTA method selection
Structuring the model	Criteria identification – Literature review
	Areas of concern, screening, and evaluation criteria
	Value aspects relevance evaluation
	Structuring the alternatives
	Descriptors of impact construction and validation
	Value functions and weights
Evaluation of alternatives	Target patient identification
	Impact appraisal
	Calculation of the overall value and cost of alternatives
Testing the requisiteness of the model	Sensitivity and robustness analyses
	Model validation and method assessment

Table 2 - Macro-phases and phases

The next table provides details about the meetings and their objectives and outputs:

Meeting	Date	Number of participants	Objective	Output
0	8 June 2023	5	Structuring the problem	- Decision Problem, - HTA method.
1st	20 June 2023	7	Structuring the model	- Areas of concern, - Screening criteria, - Value aspects.
2nd	26 June 2023	8	Structuring the model	- Value aspects relevance evaluation.
3rd	11 July 2023	4	Structuring the model	- Structuring of alternatives, - Validation of descriptors.
4th	19 September 2023	5	Structuring the model	- Determination of value functions and weights.
5th	26 September 2023	5	Evaluation of alternatives	- Identification of target patients, - Impact appraisal.
6th	16 October 2023	6	Testing the requisiteness of the model	- Model validation, - Method assessment with participants.

Table 3 - Meetings

5.1 Structuring the problem

A first kick-off meeting with decision-makers was held to define the goal of the study and to select the best approach to obtain the desired output.

Five members of the *UP* staff were included in the meeting:

- The managing director,
- A project manager,
- A data protection officer,
- A psychologist,
- A financial advisor.

Based on the information gathered during the internship, a document was prepared and shared with the decision-makers. The document was developed to help them understand the different HTA approaches that could be followed to achieve the desired outputs.

The main approaches were briefly described pointing out the outputs, requirements pros and cons of each one of them. The main information was gathered in the following table:

Method	Outputs	Requirements	Pros	Cons
Financial analysis of the profit for the technology owner	Index of profitability for service providers. e.g. NPV (Net Present Value) or PI (profitability index).	Actual data or expectations on costs and revenues. Interaction with stakeholders is necessary for the assessment.	It has already been partially assessed.	It doesn't assess non-economic benefits for patients and other stakeholders.
Comparative study	List of indicators	Complete access to previously performed assessments and to costs already assessed.	Benefits are easy to assess. Both health and social benefits are analyzed.	Only benefits for patients are considered, omitting benefits for other stakeholders. A list of indicators is obtained and not a single and complete indicator.
Analysis of the healthcare benefits for patients	Single complete indicator	Complete access to previously performed assessments and to costs already assessed.	Benefits can be assessed using standard techniques and information. A single and complete indicator is obtained.	Only health benefits for patients are considered omitting other kinds of benefits and the benefits for other stakeholders.
Multi-criteria value model	Single complete indicator of value	Complete access to previously performed assessments and to costs already assessed. Multiple stakeholders will be involved in workshops, Decision conferences, web Delphi activities, interviews, or surveys.	It analyzes benefits relevant to all the main stakeholders. Value measurement considers what is important for stakeholders and is assessed through stakeholder engagement.	Time-consuming and resource-consuming method

Table 4 - HTA methods

The result of the discussion was an agreement of decision-makers on following an approach that allows to consider not only economical aspects, but all possible consequences (both positive and negative) for the main stakeholders involved, including:

- Organization (cooperatives),
- Patient,
- Operator,
- Informal caregiver.

Of the presented methods, only Multi-Criteria Decision Analysis (MCDA) allows considering a multi-stakeholder perspective and leads to the definition of a complete indicator of value. In addition to this, experts' involvement was considered fundamental for the process and the framework of MCDA is the most suitable in this context.

In this phase, it was fundamental to understand if decision-makers were willing to dedicate resources and time to this activity since Multi-Criteria Decision Analysis is the more time-consuming and resource-consuming methodology.

At the conclusion of the meeting, decision-makers were asked to identify the participants to be included in the assessment, and a brief overview of the steps to be followed was given. Participants were selected based on their professional roles, their previous involvement in activities within the *PHArA-ON* project, and their reference cooperative, with the goal of including heterogeneous points of view.

As a result of this discussion, decision-makers unanimously agreed on relying mainly on participants' expertise for the assessment of performances of alternatives in the various criteria, without requiring to directly involve interested parties such as patients and informal caregivers. This was mainly due to the amount of time and resources they were willing to dedicate to the activity.

5.2 Structuring the model

5.2.1 Criteria identification – Literature review

After selecting the methodology to be followed, it was necessary to define the decision problem and identify the criteria to be considered.

The term criteria can be correctly used when the set of selected aspects is unambiguous, comprehensive, direct, operational, and understandable [66]. Until then, these aspects can be generically defined as *value aspects*.

To identify the criteria of interest, a first session of meetings was organized, and as a preparation for the meetings, a literature review was carried out. The goal of this review was to identify the main value aspects that have been considered in HTA analyses when assessing the technology object of the study or similar ones. The information gathered was meant to support participants during the following meeting for criteria identification.

For the identification of scientific papers dealing with the problem, four online databases were consulted:

- Scopus
- Science Direct
- SpringerLink

The main keywords used for the research have been:

- Telepresence,
- Robot,
- Multi-criteria
- MCDA,
- Healthcare,
- HTA,
- Assessment,
- Assistive,
- Social (socially),
- Telemedicine,

Different combinations of the keywords using logic connective "AND" were applied for the research. The following combinations of keywords brought to the identification of at least one useful scientific paper:

- robot AND multi-criteria
- telepresence AND robot AND assessment
- assistive AND robot AND HTA
- social AND robot AND multi-criteria
- MCDA AND telemedicine
- socially AND assistive AND robots
- telepresence AND robot AND healthcare
- telepresence AND robot AND assessment AND healthcare

The research led to the identification of a significantly large number of papers. Since the review aimed to identify the value aspects considered in the assessment of emerging technologies, the research was limited to the most recent articles. We consulted the titles of the most recent ones and examined the abstracts of 24 of them. After this initial screening, we further refined our selection to 14 papers by reading their full texts. Subsequently, a snowballing process was conducted to backtrack older and frequently cited relevant papers. This led to the identification of other 17 articles, for a total of 31 scientific papers included.

The following table lists the selected works with title and publication year, pointing out if they are case studies or reviews, making explicit the category of technologies assessed, and the main tools employed:

Title	Year	Case Study/ Review	Technology category	Methods and tools
Robots for Elderly Care: Review, Multi-Criteria Optimization Model and Qualitative Case Study [99]	2023	Case study	Robots for elderly care	Multi-criteria optimization, Focus groups
Which value aspects are relevant for the evaluation of medical devices? Exploring stakeholders' views through a Web Delphi process [48]	2023	Case study	Medical devices	Web-Delphi
Associations Between Older Adults' Loneliness and Acceptance of Socially Assistive Robots: A Cross-Sectional Study [58]	2023	Case study	Socially Assistive Robots	Questionnaires
Socially assistive robots in health and social care: Acceptance and cultural factors. Results from an exploratory international online survey [90]	2023	Case study	Socially Assistive Robots	Surveys
Prioritizing and Overcoming Barriers to e-Health Use among Elderly People: Implementation of the Analytical Hierarchical Process (AHP) [87]	2022	Case study	E-health	MCDM, AHP
*An integrated decision-making methodology based on Pythagorean fuzzy sets for social robot evaluation [*65]	2022	Case study	Social robots	MCDM, IVPFS method
Health Technology Assessment of Telemedicine Interventions in Diabetes Management: Evidence from UAE [82]	2022	Case study	Telemedicine	MCDM, AHPE

A protocol on the effects of interactive digital assistance on engagement and perceived quality of care of surgery patients and self-efficacy and workload of staff [94]	2022	Case study	Social Humanoid Robots	Statistical analysis
User feedback and remote supervision for assisted living with mobile robots: A field study in long-term autonomy [75]	2022	Case study	Socially Assistive Robots	Questionnaires
Older adults' experiences with and perceptions of the use of socially assistive robots in aged care: A systematic review of quantitative evidence [106]	2021	Review	Socially Assistive Robots	-
Social Telepresence Robots: A Narrative Review of Experiments Involving Older Adults before and during the COVID-19 Pandemic [67]	2021	Review	Social Telepresence Robots	-
A social robot intervention on depression, loneliness, and quality of life for Taiwanese older adults in long-term care [29]	2020	Case study	Social Robots	Interviews
Identifying Features that Enhance Older Adults' Acceptance of Robots: A Mixed Methods Study [31]	2019	Case study	Service-oriented Robots	Questionnaires
Using telepresence for social connection: views of older people with dementia, families, and health professionals from a mixed methods pilot study [85]	2019	Case study	Telepresence Robots	Questionnaires
Robotic Services Acceptance in Smart Environments With Older Adults: User Satisfaction and Acceptability Study [26]	2018	Case study	Robot-Era system	Questionnaires
The Effectiveness of Social Robots for Older Adults: A Systematic Review and Meta-Analysis of Randomized Controlled Studies [96]	2018	Review	Social Robots	-
Social robot selection: a case study in education [91]	2018	Case study	Social Robots	MCDM, TOPSIS method

Using Telehealth to Optimize Healthy Independent Living for Older Adults: A Feasibility Study [6]	2018	Case study	Telepresence Robots	Interviews
Socially Assistive Robots: Measuring Older Adults' Perceptions [82]	2017	Case study	Socially Assistive Robots	Surveys
Change in quality of life in older people with dementia participating in Paro-activity: a cluster-randomized controlled trial [62]	2016	Case study	Robot-assisted group activity	Statistical analysis
Evaluation of an Assistive Telepresence Robot for Elderly Healthcare [69]	2016	Case study	Telepresence Robots	Questionnaires
Long-Term Evaluation of a Telepresence Robot for the Elderly: Methodology and Ecological Case Study [28]	2016	Case study	Telepresence Robots	MARTA methodology
Acceptance of Social Robots by Elder People: Does Psychosocial Functioning Matter? [5]	2016	Case study	Telepresence Robots	Interviews
Benefits and problems of health-care robots in aged care settings: A comparison trial [23]	2016	Case study	Social Robots	Questionnaires and interviews
Using telepresence for social connection: views of older people with dementia, families, and health professionals from a mixed methods pilot study [85]	2014	Case study	Telepresence Robots	Questionnaires
A randomized controlled trial of telemonitoring in older adults with multiple health issues to prevent hospitalizations and emergency department visits [103]	2012	Case study	Tele-monitoring	Statistical analysis
Addressing the long-term evaluation of a telepresence robot for the elderly [27]	2012	Case study	Telepresence Robot	Interviews
Assessing affective response of older users to a telepresence robot using a combination of psychophysiological measures [105]	2012	Case study	Telepresence Robot	Parameters measurement

Mobile Remote Presence Systems for Older Adults: Acceptance, Benefits, and Concerns [17]	2011	Case study	Mobile Remote Presence Systems	Interviews
Reactions to a Remote-Controlled Video-Communication Robot in Seniors' Homes: A Pilot Study of Feasibility and Acceptance [100]	2011	Case study	Remote telepresence	Surveys
Key factors influencing the implementation success of a home telecare application [95]	2011	Case study	Telecare	Interviews

Table 5 - Scientific papers selected

In addition to these papers, works directly related to the *PHArA-ON* project were included, for a total of 36 scientific papers:

Title	**Year**	**Case Study /Review**	**Technology category**	**Methods and tools**
Evaluating telepresence robot for supporting formal and informal caregivers in the care support service: a six-months case study [44]	2023	Case study	Telepresence Robot, Smart TV	Questionnaires
Living with a Telepresence Robot: Results from a Field-Trial [47]	2022	Case study	Telepresence robot	Questionnaires, Interviews
On the Use of Assistive Technology during the COVID-19 Outbreak: Results and Lessons Learned from Pilot Studies [45]	2022	Case study	Telepresence robot, Virtual visit system, etc.	Questionnaires, Interviews
Can assistive technology support social services during Covid-19 emergency? Barriers and opportunities [46]	2021	Case study	Assistive technologies	Questionnaires, Interviews
Multidimensional evaluation of telepresence robot: results from a field trial [43]	2020	Case study	Telepresence Robot	Questionnaires, Interviews

Table 6 - Scientific papers, PHArA-ON project

Three of the selected works are literature reviews, while the others are case studies. Thirty-three of the selected works involve telepresence robots or socially assistive robots, the others deal with other forms of telehealth, and only seven works are not focused on technology applications for the elderly.

Between the selected works, only four use a multi-criteria approach, but none of the works applies the MACBETH method. Mumtaz A. [87] applies MCDA through AHP to prioritize barriers to e-Health. Kaya I. *et al.* [65] propose an integrated fuzzy MCDM methodology based on interval-valued Pythagorean fuzzy to assess which of 5 different social robot is the most appropriate alternative for the market. Mishra V. *et al.* [82] perform a Multi-Criteria Decision Analysis through AHPE for the evaluation of three levels of intervention in the management of diabetes: in-person care, hybrid care and pure telecare. Lastly, G. Papakostas [91] apply TOPSIS, an MCDA method, to select the best social robot for education.

The remaining works do not apply an MCDA method but through different approaches (Delphi method, interviews, questionnaires, focus groups etc.) assess social or telepresence robots considering different value aspects. Only one work [82] considers service delivery modes as alternatives for the assessment.

The articles have been analyzed to identify the main value aspects that are considered in literature when assessing these kinds of technology.

Many value aspects have been found, and a first selection of these was made excluding the ones that were not pertinent to the context of this study. Based on the information gathered during the first kick-off meeting, the identified value aspects have been classified pointing out the stakeholder they refer to.

The following table shows the main value aspects identified for each stakeholder and the works that consider them:

Stakeholder	Value Aspect	Reference papers
Organization	Costs	[48]
	Environmental impact of the production and use of the medical device	[48]
	Financing	[48]
	Public health interest	[48]
	Regulatory status of the medical device	[48]
	Scientific evidence	[48]
	Space for innovation for the healthcare organization	[48]
	Target population	[48]
	Stakeholders' agreement on the adoption of the medical device	[48]
	Market competitivity	[48]
	Organizational aspects	[67]
	Stability and reliability of the technology	[95]
Patient	Adverse events for patient	[48],[82]
	Anxiety	[87], [75], [13], [26], [82], [105]
	Dehumanization	[90]
	Depression	[29], [96], [6], [28], [23], [27]

	Enjoyment	[106], [31], [26]
	Isolation	[17]
	Comfort	[75], [106], [82], [48]
	Loneliness	[58], [29], [96], [28], [5], [27]
	Privacy	[106], [17], [100]
	Perceived Safety	[82], [75], [67]
	Usefulness	[87], [106], [31], [69]
	Perceived quality of care	[94]
	Perceived Social Support	[28], [5], [27]
	Quality of Life	[82], [67], [29], [96], [6], [62], [5], [23], [48]
	Support in managing emergencies	[75]
	Technology ease of use	5 [87], [65], [82], [75], [106], [31], [26], [82], [69], [28]
	Sense of presence	[31], [85]
	Treatment effectiveness	[67], [103], [48]
	Trust	[31], [26]
Operator	Operators' job satisfaction	[23]
	Operators' learning capability	[65], [48]
	Operators' stress	[99]
	Operators' training	[65], [48]
	Operators' travel time	[17]
	Operators' workload	[94], [48]
	Culture (professional acceptance)	[67]
	Current/future intention to use	[106], [31]
	Technology usability for operators	[27],[48]

Table 7 - Value aspects from literature review

None of the selected works considered direct consequences for informal caregivers, but since it was identified as one of the interested parties that would be affected by the introduction of the technology, some of the identified value aspects were adapted to this stakeholder.

The following step was to set up a first meeting to discuss areas of concern and screening and evaluation criteria.

5.2.2 Areas of concern, screening, and evaluation criteria

The 1st meeting was organized in two sessions to face participants' availabilities.

At the beginning of each meeting, a brief description of the analysis was presented, and then all participants were asked to give a short presentation of themselves and specifically their role in their cooperative or organization and their participation in projects involving the robot (e.g., *PHArA-ON*).

To identify areas of concern, participants were asked to discuss the elements of the current service delivery mode that they did not consider satisfactory or competitive and why they considered important to assess robot introduction in their services (areas of concern).

Then the discussion was focused on stakeholders' identification: even though the interested parties were identified in the kick-off meeting, it was necessary to validate them with all participants. Among all the stakeholders involved, the most relevant ones were selected:

- Organization (cooperatives),
- Patient,
- Operator,
- Informal Caregiver.

For each stakeholder, the participants were asked to identify the expected consequences deriving from technology introduction (evaluation criteria).
In this step, the discussion was facilitated by the presentation of a mind map (implemented through *Mirò* software[5]). The mind map featured a branch for each stakeholder, and for each, the value aspects identified from the literature review were presented.

Each element was discussed to exclude the non-relevant ones, include new value aspects that were not cited in literature, and when needed reformulate or adapt the selected ones.

The last part of the meetings was dedicated to the identification of screening criteria: participants were asked to identify features that would make them exclude a specific service delivery mode.

Each meeting, previously recorded, was transcribed and the gathered information was then processed.

The following table summarizes the results obtained:

[5] https://miro.com/it/

Issue	Results of Meeting 1st
Stakeholders	- Organization, - Patients, - Operators, - Informal Caregivers.
Areas of concern	- Improvable quality of care, - Market competitivity.
Screening criteria	- A service delivery mode that does not increase the frequency of visits to the patients through the robot should be excluded, - A service delivery mode that does not consider the extent of the environmental changes required at the patient's home should be excluded, - A service delivery mode that does not imply that operators are perfectly capable of using the telepresence robot should be excluded, - A service delivery mode that considers a technology whose reliability and safety have not been assessed should be excluded.
Evaluation criteria	33 value aspects were identified

Table 8 - Results from Meeting 1st

The next step was to create a set of value aspects that was both relevant, concise, and not redundant. To do so, a second meeting was organized to evaluate the relevance of the selected value aspects and eventually exclude some of them.

Before the meeting, it was essential to give a proper definition of each of the selected value aspects. This involved consulting relevant literature and adapting the gathered information to the specific context of this study.

5.2.3 Value aspects relevance evaluation

The 2nd meeting was organized in two sessions to face participants' availabilities.

Participants were asked to determine which of the identified value aspects was in their opinion relevant for the identification of the best mode for delivering monitoring and social support services.

To facilitate the discussion a questionnaire was used. For each value aspect, the definition was provided, and participants were asked to rate their level of agreement with the following statement: "*Is the following aspect relevant for selecting the best service delivery mode?".*

The possible choices were different levels of agreement:

- *"Strongly disagree",*
- *"Disagree",*
- *"Neither agree nor disagree",*
- *"Agree",*
- *"Strongly agree".*

The results of the questionnaire were gathered and used to stimulate a discussion and to seek unanimous consensus. As a result of the discussion, seven of the initial value aspects were unanimously excluded as considered non-relevant.

A report of the first two meetings was shared with all participants to summarize the results of the discussions, and to ask for eventual feedback.

5.2.4 Structuring the alternatives

The next step involved structuring the potential service delivery modes to consider as alternatives for the assessment. A specific tool, the so-called Strategy Table, was used to support the discussion and to structure the new service delivery modes.

The various decisions to be taken were outlined in the table, and for each building block, the possible options were given. The decisions and the options were defined based on the information gathered during the internship and the previous meetings.

Based on the building blocks, their options, and their combinations, a first structuring of the alternatives can be performed.

The following table lists the elements of decision and the possible options:

	A	B	C	D
1. Patient category	Private	Public		
2. Access to the device	No one	Operator	Operator + Informal Caregiver + Relatives/Friends	Operator + Informal Caregiver + Relatives/Friends + Psychologist
3. Duration	The whole project duration	Variable duration		
4. Service delivery time	Daily service hours are delivered in one visit	Daily service hours are divided into shorter slots		
5. Telepresence robot utilization for service delivery	Service is provided at the patient's home by the operator	Service is partly provided remotely through the telepresence robot	Service is provided remotely through the telepresence robot	Service is partly provided remotely through the telepresence robot. Some of the remote assistance is provided by a psychologist
6. Continuity of care	No continuity	Partial continuity		
7. Telepresence robot additional features	None	Patients can video-call their informal caregiver and decline calls through voice commands		
8. Operators' shifts organization	Operators, within a shift, carry out all the monitoring and social life support activities at the patients' homes	Operators, within a shift, carry out all the monitoring and social life support activities through the telepresence robot	Operators, within a shift, carry out some monitoring and social life support activities at patients' homes and some others through the telepresence robot	

Table 9 - Strategy Table: building blocks

A brief description of each building block will follow:

1. **Patient category**
   The first important element to be identified was the category of potential beneficiaries of the service. It was necessary to define if the service delivery mode would be structured as an offering for private or public patients. The two categories present differences both in revenues for the cooperative and in organizational constraints.

2. **Access to the device**
   A second choice to be taken regards the category of people that will have access to the telepresence robot and use it to reach the patients. The possible choices include:

   - **No one**: this alternative contemplates the possibility of not introducing the robot and delivering the service traditionally.

   - **Operator**: the robot is placed at the patient's home, and only the operator can reach them to provide monitoring and/or social support based on their care plan.

   - **Operator + Informal caregiver + Relatives/Friends:** the robot can be used by the operator, but access to the device is also allowed to the informal caregiver, relatives, or friends of the patients.

   - **Operator + Informal Caregiver + Relatives/Friends + Psychologist**: this option considers the possibility of introducing another professional in the service. Participants (some of whom are experts in this field) expressed interest in the possibility of extending access to the robot to psychologists to deliver psychological support to patients. This kind of intervention goes beyond simple monitoring and social support services: as conceived by participants, it would not be a proper psychological therapy, but an additional form of support for patients with specific needs.

3. **Duration**
   Another important element to be considered in structuring the service delivery mode is the duration of the robot's stay at the patient's home. The first option ("The whole duration of the project") is meant for private patients, who acquire a package of accesses and the duration must be granted for the whole period they are paying for. The second option ("Variable duration") is meant for public patients, whose projects generally have extensive duration, eventually until the patient's death. In this kind of situation, as pointed out by the participants, it is not considerable to assign the robot to the same patient for an indefinite number of years, so it is necessary to define a variable duration of the robot's stay. Participants agreed on setting this duration between 4 and 6 months. This time duration, based on participants' experience, allows the patient to adapt to the technology and at the same time grants the rotation of the device between different patients within a year.

4. **Service delivery time**
   Service delivery time represents the duration and frequency of the operator's intervention in delivering the service. One of the most important characteristics of the service delivery mode when considering robot introduction is, in participants' opinion, the possibility of increasing the frequency with which operators reach the patient.

Potentially, by introducing the robot, the patient will receive the same number of hours of service, but these may be distributed among different moments of the day dividing the service hour into shorter slots. Participants agreed that a duration of 30 minutes is considered optimal for a single intervention.

5. **Telepresence robot utilization for service delivery**
   This building block concerns how service is delivered: it could be performed in the traditional way (option A), it could be performed exclusively through the telepresence robot (option B), it could be a hybrid form (option C), or lastly, it could be remote with the introduction of the psychological support (option D).

6. **Continuity of care**
   Continuity of care is a frequently considered issue in home care. Currently, in this context, continuity of care is not always granted, as patients could be assigned to many different operators. The alternatives in the table indicate the possibility of assigning the patient to many different operators or limiting the number of possible operators to a small group.

7. **Telepresence robot additional features**
   An important issue that emerged during the meetings was the possibility of including additional features to the telepresence robot.
   Two main issues emerged from the discussion: the first was the impossibility, at the current state, for the patient to actively employ the robot to reach their informal caregiver or family in case of emergencies or in ordinary situations. The second instead regarded the impossibility for the patient to easily decline the call. Participants unanimously agreed on the importance of considering the possibility of modifying the device software to enable patients to video call their informal caregivers through voice commands and to decline the call, if necessary, also through voice commands.

8. **Operators' shift organization**
   The introduction of telepresence services will inevitably affect work organization for operators. With the introduction of the robot, operators will have to perform monitoring and support services remotely and to do that, they will have to be at their home and connect to the device. At the current state, there is no plan for setting a dedicated environment to allow operators to deliver remote services, but it will be considered as a future development.
   Based on these considerations, the alternatives include the current service delivery mode (option A), an organization of shifts where operators, during a shift, perform both presence and remote activities (option B), and a last option in which a set of operators, during a shift, is only dedicated to remote activities.

A first validation of the strategy table was carried out with one of the participants, and a third meeting was organized with the others for a final validation and to proceed with the structuring of the alternatives.

The 3rd meeting was structured in two sessions. In the first part of the meetings, the

Strategy Table and Mind Maps were used to select the most relevant combinations of alternatives and define the service delivery modes of interest.

Mind Maps were used to create the possible combinations of alternatives, and branches of the map were excluded if unfeasible, irrelevant, or not of interest.

For example:

- In the public context it was unanimously agreed to exclude the possibility of including the intervention of psychologists, since it would be considered as a different kind of offering and would not be coherent with the project formulated by the social worker.

- Regarding building block number 2 (Access to the device), option C was considered dominant on option B: when introducing the device in the patient's home it is not of interest to limit access to the device only to the operator, but access would always be granted also to the informal caregiver and other relatives or friends.

- As for robot utilization in service delivery, it was necessary to distinguish patients based on the structure of their project. It was agreed that when projects include not only monitoring and social support activities but also activities that imply physical intervention of the operator, monitoring and social support activities can all be delivered remotely. While when the project potentially does not require moments of physical intervention of the operator, the remote activities must be complemented by a certain number of physical accesses.

As a result of this activity, five different branches of the mind map were considered relevant for further analysis. These five options are in addition to the traditional ones both for private and public patients:

	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**
1. Patient category	Private	Private	Private	Public	Public
2. Access to the device	Operator + Informal Caregiver + Relatives/Friends	Operator + Informal Caregiver + Relatives/Friends	Operator + Informal Caregiver + Relatives/Friends + Psychologist	Operator + Informal Caregiver + Relatives/Friends	Operator + Informal Caregiver + Relatives/Friends
3. Duration	The whole project duration	The whole project duration	The whole project duration	Variable duration	Variable duration
4. Service delivery time	Daily service hours are divided into shorter slots	Daily service hours are divided into shorter slots	Daily service hours are divided into shorter slots	Daily service hours are divided into shorter slots	Daily service hours are divided into shorter slots
5. Telepresence robot utilization for service delivery	Service is partly provided remotely through the telepresence robot	Service is partly provided remotely through the telepresence robot	Service is partly provided remotely through the telepresence robot. Some of the remote assistance is provided by a psychologist	Service is partly provided remotely through the telepresence robot	Service is partly provided remotely through the telepresence robot
6. Continuity of care	Partial Continuity	Partial Continuity	Partial Continuity	Partial Continuity	Partial Continuity
7. Telepresence robot additional features	None	Patients can video-call their informal caregiver and decline calls through voice commands	None	None	Patients can video-call their informal caregiver and decline calls through voice commands
8. Operators' shifts organization	Operators, within a shift, carry out some monitoring and social life support activities at patients' homes and some others through the telepresence robot	Operators, within a shift, carry out some monitoring and social life support activities at patients' homes and some others through the telepresence robot	Operators, within a shift, carry out some monitoring and social life support activities at patients' homes and some others through the telepresence robot	Operators, within a shift, carry out some monitoring and social life support activities at patients' homes and some others through the telepresence robot	Operators, within a shift, carry out some monitoring and social life support activities at patients' homes and some others through the telepresence robot

Table 10 - Options

The gathered information was used to structure the possible service delivery modes. Between the many tools that can be used to accomplish this task, we decided to employ the Business Model Canvas. This tool was selected as the most useful for decision-makers and as easily understandable by all participants.

A Business Model Canvas has been developed for each of the options: three for the private sector and two for the public one.

1. Public patients: Service delivery through telepresence robot – Basic version (Figure 2).
2. Public patients: Service delivery through telepresence robot – Version with robot additional features (Figure 3).
3. Private patients: Service delivery through telepresence robot – Basic version (Figure 4).
4. Private patients: Service delivery through telepresence robot – Version with robot additional features (Figure 5).
5. Private patients: Service delivery through telepresence robot – Version with Psychological support (Figure 6).

As a conclusion of this phase, a report of the activity was sent to all participants asking for validation through email. An important conclusion of this phase was to determine which of the structured alternatives needed to be compared in the MCDA; two main results derived from the discussion with decision-makers:

1. In relation to private patients, it is not a matter of the cooperative to decide the kind of service they will receive; it's the patient (or their informal caregiver) the one who selects the best option for their needs. As a consequence of this assertion, decision-makers agreed on considering the definition of the alternatives as a sufficient result for the private context.

2. On the other hand, with public patients another point of view needs to be considered. The cooperatives currently deliver their services according to agreements with the public sanitary system. At present, the public contracting authority does not contemplate the possibility of delivering services through telepresence robots. Decision-makers are therefore interested in understanding what is the best alternative for delivering their public services, and based on this, eventually initiate a negotiation with the public contracting authority for modifying the current reimbursement policies and how projects are structured. Another important aspect to consider is the possible future introduction of an accreditation framework: with this system, public patients are allowed to express their preferences in terms of cooperatives they wish to be served by, which differs from the current practice. This change is urging cooperatives to become more competitive even in the public context, where patients will be enabled to choose the cooperative that best fulfills their needs.

These two results led to the final determination of the alternatives to be assessed through the MACBETH approach:

A. Public patients: Traditional service delivery mode.
B. Public patients: Service delivery through telepresence robot – Basic version.
C. Public patients: Service delivery through telepresence robot – Version with robot additional features.

The following figures illustrate the Business Model Canvases generated from the analysis:

<table>
<tr><th>KEY PARTNERS</th><th>KEY ACTIVITIES</th><th>VALUE PROPOSITIONS</th><th>CUSTOMER RELATIONSHIPS</th><th>CLIENT SEGMENTS</th></tr>
<tr>
<td rowspan="3">-Genius Robotics,
- OhmniLabs,
- Public contracting authority and social workers,
- Company for technical support,
- Insurance Company.</td>
<td>Surveillance and social support services delivered by operators through the telepresence robot, increasing the frequency of intervention, and granting access to the device to informal caregivers and eventually other family members or friends.</td>
<td rowspan="3">- Reduction of patients' loneliness.
- Accessibility and continuous coverage: operators and informal caregivers can reach and check on the patients without any efforts on the patient's part.
- Customization: alternation of sessions delivered through the robot and sessions provided by the operator onsite, to be arranged according to patient's needs.
- Enhanced session effectiveness: shorter and more frequent interventions (approximately 30 minutes in duration).
- Support in managing major emergencies,
- Care continuity: telepresence services will be delivered by a small team of trained patients.
- Reduction in the caregiving burden on informal caregivers.</td>
<td>- Long term,
- Dedicated personal assistance,
- Training of patients and their families,
- Social workers as intermediaries for the drafting of the care plan.</td>
<td rowspan="3">Elderly, disabled, or non-self-sufficient patients, domiciled in Prato with need for monitoring or social support services.

Early Adopters: Public patients with current active projects.</td>
</tr>
<tr><th>KEY RESOURCES</th><th>CHANNELS</th></tr>
<tr>
<td>- Operators,
- Home Care services coordinators,
- Ohmni Robot.</td>
<td>- Public contracting authority,
- Accreditation system,
- Direct interactions with patients,
- Direct interactions with informal caregivers.</td>
</tr>
<tr><th colspan="3">COST STRUCTURE</th><th colspan="2">REVENUE STREAMS</th></tr>
<tr>
<td colspan="3">- Annual depreciation for robot purchase (Basic version of the device),
- Robot installation cost (+ additional costs for router and Wi-fi connection),
- Technical support,
- Insurance costs,
- Cost of operators,
- Training costs (operators + patients + informal caregivers),
- Mileage reimbursement for home care operators.</td>
<td colspan="2">Reimbursement by the public contracting authority.</td>
</tr>
</table>

Figure 2 - Business Model Canvas - Public patients: Service delivery through telepresence robot – Basic version

<table>
<tr><th>KEY PARTNERS</th><th>KEY ACTIVITIES</th><th>VALUE PROPOSITIONS</th><th>CUSTOMER RELATIONSHIPS</th><th>CLIENT SEGMENTS</th></tr>
<tr>
<td rowspan="3">-Genius Robotics,
- OhmniLabs,
- Public contracting authority and social workers,
- Company for technical support,
- Insurance Company,
- Software developers.</td>
<td>Surveillance and social support services delivered by operators through the telepresence robot, increasing the frequency of intervention, granting access to the device to informal caregivers and eventually other family members or friends.
The device will also enable the patient to video-call their family members using voice commands and to reject calls if necessary.</td>
<td rowspan="3">- Reduction of patients' loneliness.
- Accessibility and continuous coverage: operators and informal caregivers can reach and check on the patients without any efforts on the patient's part.
- Customization: alternation of sessions delivered through the robot and sessions provided by the operator onsite, to be arranged according to patient's needs.
- Enhanced session effectiveness: shorter and more frequent interventions (approximately 30 minutes in duration).
- Support in managing major emergencies,
- Care continuity: telepresence services will be delivered by a small team of trained patients.
- Reduction in the caregiving burden on informal caregivers.
- Possibility for the patient to easily reach their family members and/or easily require assistance.</td>
<td>- Long term,
- Dedicated personal assistance,
- Training of patients and their families,
- Social workers as intermediaries for the drafting of the care plan.</td>
<td rowspan="3">Elderly, disabled, or non-self-sufficient patients, domiciled in Prato with need for monitoring or social support services.

Early Adopters:
Public patients with current active projects.</td>
</tr>
<tr><th>KEY RESOURCES</th><th>CHANNELS</th></tr>
<tr>
<td>- Operators,
- Home Care services coordinators,
- Ohmni Robot,
- Software for additional features.</td>
<td>- Public contracting authority,
- Accreditation system,
- Direct interactions with patients,
- Direct interactions with informal caregivers.</td>
</tr>
<tr><th colspan="3">COST STRUCTURE</th><th colspan="2">REVENUE STREAMS</th></tr>
<tr>
<td colspan="3">- Annual depreciation for robot purchase (Developer version of the device),
- Annual depreciation for software development and installation,
- Robot installation cost (+ additional costs for router and Wi-fi connection),
- Technical support,
- Insurance costs
- Cost of operators,
- Training costs (operators + patients + informal caregivers),
- Mileage reimbursement for home care operators.</td>
<td colspan="2">Reimbursement by the public contracting authority.</td>
</tr>
</table>

Figure 3 - Business Model Canvas - Public patients: Service delivery through telepresence robot – Version with robot additional features

<table>
<tr><th>KEY PARTNERS</th><th>KEY ACTIVITIES</th><th>VALUE PROPOSITIONS</th><th>CUSTOMER RELATIONSHIPS</th><th>CLIENT SEGMENTS</th></tr>
<tr>
<td rowspan="3">-Genius Robotics,
- OhmniLabs,
- Company for technical support,
- Insurance Company.</td>
<td>Surveillance and social support services delivered by operators through the telepresence robot, increasing the frequency of intervention, granting access to the device to informal caregivers and eventually other family members or friends.</td>
<td rowspan="3">- Reduction of patients' loneliness.
- Accessibility and continuous coverage: operators and informal caregivers can reach and check on the patients without any efforts on the patient's part.
- Customization: alternation of sessions delivered through the robot and sessions provided by the operator onsite, to be arranged according to patient's needs.
- Enhanced session effectiveness: shorter and more frequent interventions (approximately 30 minutes in duration).
- Support in managing major emergencies,
- Care continuity: telepresence services will be delivered by a small team of trained patients.
- Reduction in the caregiving burden on informal caregivers.</td>
<td>- Long term,
- Dedicated personal assistance,
- Training of patients and their families,
- Direct involvement of patients and their informal caregiver for the drafting of the care plan.</td>
<td rowspan="3">Elderly, disabled, or non-self-sufficient patients, domiciled in Prato with need for monitoring or social support services.

Early Adopters: Private patients with current active projects.</td>
</tr>
<tr><th>KEY RESOURCES</th><th>CHANNELS</th></tr>
<tr>
<td>- Operators,
- Home Care services coordinators,
- Ohmni Robot.</td>
<td>- Direct interactions with patients,
- Direct interactions with informal caregivers,
- Future areas of development: platform for private offering</td>
</tr>
<tr><th colspan="3">COST STRUCTURE</th><th colspan="2">REVENUE STREAMS</th></tr>
<tr>
<td colspan="3">- Annual depreciation for robot purchase (Developer version of the device),
- Robot installation cost (+ additional costs for router and Wi-fi connection),
- Technical support,
- Insurance costs,
- Cost of operators,
- Training costs (operators + patients + informal caregivers),
- Mileage reimbursement for home care operators.</td>
<td colspan="2">Hourly fee payment from patients / Access package / Monthly subscription.</td>
</tr>
</table>

Figure 4 - Business Model Canvas - Private patients: Service delivery through telepresence robot – Basic version

KEY PARTNERS	KEY ACTIVITIES	VALUE PROPOSITIONS	CUSTOMER RELATIONSHIPS	CLIENT SEGMENTS
-*Genius Robotics,* - *OhmniLabs,* - Company for technical support, - Insurance Company, - Software developers.	Surveillance and social support services delivered by operators through the telepresence robot, increasing the frequency of intervention, granting access to the device to informal caregivers and eventually other family members or friends. The device will also enable the patient to video-call their family members using voice commands and to reject calls if necessary. **KEY RESOURCES** - Operators, - Home Care services coordinators, - *Ohmni Robot,* - Software for additional features.	- Reduction of patients' loneliness. - Accessibility and continuous coverage: operators and informal caregivers can reach and check on the patients without any efforts on the patient's part. - Customization: alternation of sessions delivered through the robot and sessions provided by the operator onsite, to be arranged according to patient's needs. - Enhanced session effectiveness: shorter and more frequent interventions (approximately 30 minutes in duration). - Support in managing major emergencies, - Care continuity: telepresence services will be delivered by a small team of trained patients. - Reduction in the caregiving burden on informal caregivers. - Possibility for the patient to easily reach their family members and/or easily require assistance.	- Long term, - Dedicated personal assistance, - Training of patients and their families, - Direct involvement of patients and their informal caregiver for the drafting of the care plan. **CHANNELS** - Direct interactions with patients, - Direct interactions with informal caregivers. - Future areas of development: platform for private offering	Elderly, disabled, or non-self-sufficient patients, domiciled in Prato with need for monitoring or social support services. **Early Adopters:** Private patients with current active projects.

COST STRUCTURE	REVENUE STREAMS
- Annual depreciation for robot purchase (Developer version of the device), - Annual depreciation for software development and installation, - Robot installation cost (+ additional costs for router and Wi-fi connection), - Technical support, - Insurance costs - Cost of operators, - Training costs (operators + patients + informal caregivers), - Mileage reimbursement for home care operators.	Hourly fee payment from patients / Access package / Monthly subscription.

Figure 5 - Business Model Canvas - Private patients: Service delivery through telepresence robot – Version with robot additional features

<table>
<tr><th>KEY PARTNERS</th><th>KEY ACTIVITIES</th><th>VALUE PROPOSITIONS</th><th>CUSTOMER RELATIONSHIPS</th><th>CLIENT SEGMENTS</th></tr>
<tr>
<td rowspan="3">-Genius Robotics,
- OhmniLabs,
- Company for technical support,
- Insurance Company,
- Psychologists.</td>
<td>Surveillance and social support services delivered by operators through the telepresence robot, increasing the frequency of intervention, granting access to the device to informal caregivers and eventually other family members or friends.
The service also includes the integration of psychological support interventions.</td>
<td rowspan="3">- Reduction of patients' loneliness.
- Accessibility and continuous coverage: operators and informal caregivers can reach and check on the patients without any efforts on the patient's part.
- Customization: alternation of sessions delivered through the robot and sessions provided by the operator onsite, to be arranged according to patient's needs.
- Enhanced session effectiveness: shorter and more frequent interventions (approximately 30 minutes in duration).
- Support in managing major emergencies,
- Care continuity: telepresence services will be delivered by a small team of trained patients.
- Reduction in the caregiving burden on informal caregivers.
- Psychological support: sessions of psychological support on a weekly or bi-weekly basis as needed, with a duration of approximately 30 minutes.</td>
<td>- Long term,
- Dedicated personal assistance,
- Training of patients and their families,
- Direct involvement of patients and their informal caregiver for the drafting of the care plan.</td>
<td rowspan="3">Elderly, disabled, or non-self-sufficient patients, domiciled in Prato with need for monitoring or social support services.

Early Adopters: Private patients with current active projects.</td>
</tr>
<tr><th>KEY RESOURCES</th><th>CHANNELS</th></tr>
<tr>
<td>- Operators,
- Home Care services coordinators,
- Ohmni Robot,
- Psychologists.</td>
<td>- Direct interactions with patients,
- Direct interactions with informal caregivers,
- Future areas of development: platform for private offering.</td>
</tr>
<tr><th colspan="3">COST STRUCTURE</th><th colspan="2">REVENUE STREAMS</th></tr>
<tr>
<td colspan="3">- Annual depreciation for robot purchase (Developer version of the device),
- Robot installation cost (+ additional costs for router and Wi-fi connection),
- Technical support,
- Insurance costs,
- Cost of operators,
- Cost of psychologists,
- Training cost (operators + patients + informal caregivers),
- Mileage reimbursement for home care operators.</td>
<td colspan="2">Hourly fee payment from patients / Access package / Monthly subscription.</td>
</tr>
</table>

Figure 6 - Business Model Canvas - Private patients: Service delivery through telepresence robot – Version with Psychological support

5.2.5 Descriptors of impact validation

To make criteria operational for alternatives evaluation, it was necessary to define for each one of them a descriptor of impacts. A descriptor is an ordered set of (quantitative or qualitative) plausible impact levels.

Descriptors allow constructing value functions to transform each option performance into a value score based on the attractiveness of improvements.

The impact levels of each criterion were structured using literature examples and considering the possible performances of the service delivery modes.

The *Neutral* level was determined by considering a performance that would not make the alternative attractive. In contrast, the *Good* level was defined based on the expected performance that would enhance the attractiveness of the alternative. Additional levels, such as *Low, Medium, Excellent,* were defined if significant.

The second part of each session of the 3rd meeting, aimed to validate the defined performance levels of each criterion. This was achieved by presenting the definitions of the levels and allowing each participant to provide comments on their consistency and clarity.

During this phase, discussions with participants brought to a common agreement on the exclusion of some of the previously selected value aspects. The main reason for exclusion was that the value aspect's performance did not depend on how service is delivered, hence it has not been considered as an element for comparing the alternatives. This allowed to define the final set of criteria.

As a result of the validation process, the impact levels of each criterion were correctly defined:

CRITERIA	DEFINITION	IMPACT LEVELS
Demonstrated effectiveness of the service delivery mode	*The existence of empirical evidence on the effectiveness of the service delivery mode.*	- **Good**: There is evidence (e.g., scientific articles) of the effectiveness of the service delivery mode obtained from a significant sample. - **Neutral**: There is evidence of the effectiveness of the service delivery mode obtained from a limited sample (e.g., projects in which cooperatives have been involved) - **Low**: There is no evidence of the effectiveness of the service delivery mode.
Magnitude of organizational changes	*The magnitude of organizational changes that the cooperative will have to face for delivering the service.*	- **Good:** There is no need to recruit new staff. - **Neutral:** New staff needs to be recruited.

Stakeholders' agreement on the service delivery mode	*The extent to which different stakeholders (management, coordinators, operators etc.) agree on how the service is delivered.*	- **Good:** Management, coordinators, and operators agree on how the service is delivered. - **Neutral:** Management and coordinators agree, while operators do not completely agree on how service is delivered. - **Low**: There is no agreement between stakeholders on how service is delivered.
Financing	*The probability that adopting a service delivery mode can facilitate access to financing.*	- **Good**: The service delivery mode will probably facilitate access to financing. - **Neutral**: The service delivery mode will probably not facilitate access to financing.
Market competitivity	*Competitive advantage achieved through the service delivery mode compared to what is already available on the market.*	- **Excellent**: The organization offers a service in a new mode that is hardly imitable by competitors. - **Good**: The organization delivers a service in a new mode that is easily imitable by competitors. - **Neutral**: The organization offers its patients a service that is widely established on the market.
Anxiety	*State of tension or concern that the service delivery mode may induce in the patient.*	- **Good**: During service delivery the patient is calm and relaxed. - **Neutral:** During service delivery the patient does not experience significant tension or concern. - **Low:** During service delivery the patient is very tense and concerned.
Enjoyment	*The sensation of amusement, satisfaction, enjoyment, or appreciation that the patient experiences during service delivery.*	- **Good**: During service delivery, the patient can be amused. - **Neutral**: During service delivery the patient is not particularly amused. - **Low:** During service delivery the patient is bored.
Trust in service delivery	*Trust that the patient has in receiving adequate monitoring and/or social support services.*	- **Good**: The patient is confident in receiving an adequate service. - **Neutral**: The patient thinks they are receiving adequate service. - **Low**: The patient doesn't think they are receiving adequate service.

Perceived ease of use	*The level of effort the patient perceives to be required for receiving service.*	- **Good**: The patient perceives they don't have to make a significant effort to receive the service. - **Neutral**: The patient perceives they have to make an acceptable effort to receive the service (coherently with expectations associated with home care). - **Low**: The patient perceives they must make significant physical and psychological efforts to receive the service.
Comfort	*The extent to which the service delivery mode makes the patient feel comfortable.*	- **Good:** The patient is comfortable with the service delivery mode. - **Neutral**: The patient is partially comfortable with the service delivery mode. - **Low**: The patient is not comfortable with the service delivery mode.
Privacy violation perceived	*The extent of privacy violation the patient considers to be associated with the service delivery mode.*	- **Good:** The patient perceives that the service delivery mode does not violate their privacy. - **Neutral:** The patient perceives that the service delivery mode violates their privacy to an acceptable extent (coherently with expectations associated with home care). - **Low:** The patient perceives that the service delivery mode violates their privacy to an excessive extent.
Techno-stress	*Physical and psychological discomforts caused directly or indirectly by technology utilization.*	- **Good:** The service delivery mode does not cause the patient physical or psychological discomfort associated with the difficulty in managing, understanding, and controlling the technologies employed. - **Neutral:** The service delivery mode causes to the patient a partial physical or psychological discomfort associated with the difficulty in managing, understanding, and controlling the technologies employed (for example, the patient has the feeling of not being able to completely control the technology, they feel upset because something unexpected happened). - **Low:** The service delivery mode causes to the patient an excessive physical or psychological discomfort associated with the difficulty in managing, understanding, and controlling the technologies employed (for example, the patient feels overwhelmed by the technology, is angry because unable to control it etc.).

Loneliness	*Feeling of dissatisfaction stemming from a lack of social relationships or a sense of exclusion from others.*	- **Good**: The service delivery mode results in the patient perceiving a significant reduction in loneliness. - **Neutral**: The service delivery mode results in the patient perceiving a slight reduction in loneliness. - **Low**: The service delivery mode does not significantly impact the patient's loneliness.
Quality of Life	*The combination of physical, psychological, social, and economic conditions that influence the well-being and overall life satisfaction of the patient.*	- **Good**: The service delivery mode results in the patient perceiving a significant improvement in their quality of life. - **Neutral**: The service delivery mode results in the patient perceiving a slight improvement in their quality of life. - **Low**: The service delivery mode does not significantly impact patient's quality of life.
Support in managing emergencies	*Support that the patient perceives they can receive in case of emergencies (the patient doesn't feel good, they don't answer the phone etc.) when service is delivered in a certain mode.*	- **Excellent**: The service delivery mode enables both the patient and the informal caregiver to effectively handle primary emergency situations (for example if the patient falls, they can call their informal caregiver through voice command). - **Good**: The service delivery mode enables the informal caregiver to effectively handle primary emergencies (for example, if the patient doesn't answer the phone, the informal caregiver can use the robot to check the patient). - **Neutral**: The service delivery mode does not allow the patient to receive support in emergencies.
Quality of social care support perceived	*Patient's overall assessment of the experience during service delivery.*	- **Good:** The patient perceives receiving a service of good quality. - **Neutral:** The patient perceives receiving a service of acceptable quality. - **Low:** The patient perceives receiving a service of not acceptable quality.

Impact of travel time	*Ratio between the time spent by the operator on travel required for delivering monitoring and social support services, and the total service delivery time.*	- **Good**: The impact of travel time is less than 0,05%. - **Medium**: The impact of travel time is between 0,05% and 4%. - **Neutral**: The impact of travel time is greater than 4 %.
Perceived workload suitability	*Operators' perception of the quantity and intensity of activities and responsibilities they have to manage during their work.*	- **Good**: Operators perceive their workload as appropriate (they are given tasks that can handle, and they are not overloaded with work). - **Neutral**: Operators perceive their workload as not completely appropriate but overall acceptable. - **Low**: Operators perceive their workload as completely inappropriate and unacceptable.
Informal Caregiver burden perception	*Caregiver perception of their effort in caregiving activities for the patient, in terms of physical, temporal, and psychological (anxiety, stress, concern etc.) efforts.*	- **Good:** The service delivery mode contributes to significantly reducing caregivers' burden perception. - **Neutral:** The service delivery mode contributes to partially reducing caregivers' burden perception. - **Low**: The service delivery mode does not contribute to caregivers' burden perception reduction.

Table 11 - Descriptors of impact

The final value tree of criteria was constructed and implemented in M-MACBETH (Figure 7, Figure 8). The value tree is structured on two hierarchic levels where the first level refers to the stakeholders considered. The hierarchic structure was chosen in order to more easily capture the complexity of the problem and to facilitate criteria pairwise comparison.

With respect to the patient, it was decided to separate the criteria concerning terms of technology acceptability from aspects regarding efficacy of the intervention. This was justified by the consistent differences between the two groups of criteria.

Figure 7 - Macro-Categories

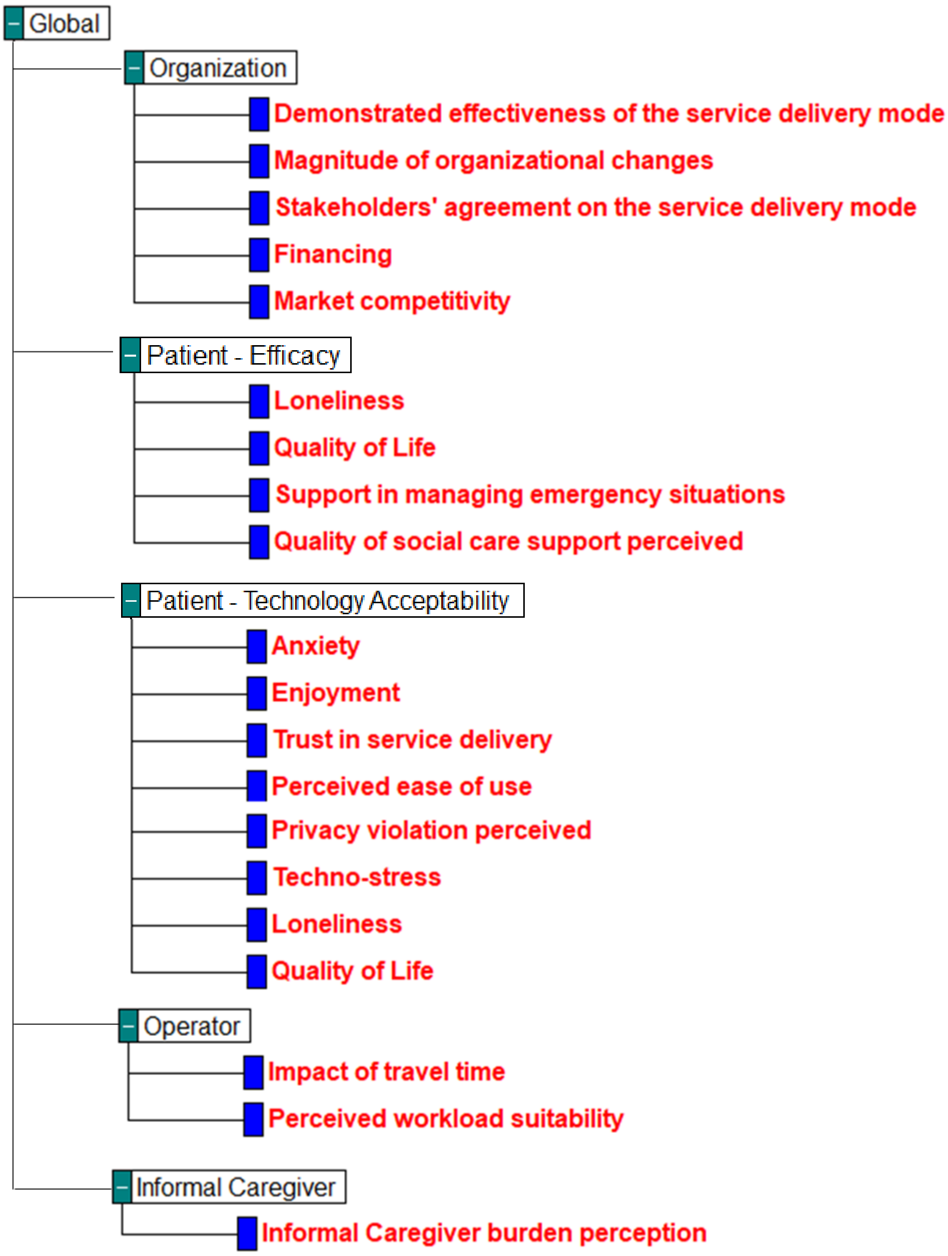


Figure 8 - Value Tree

The following table summarizes the value aspects that have been excluded in the different phases of the assessment and the reason for exclusion:

Value aspect	Reason of exclusion
Stability and reliability of the technology	Stability and reliability of the technology are considered by decision-makers as a prerequisite for this analysis.
Space for innovation in the organization	This value aspect's performance does not change based on the service delivery mode considered; it is not an element for comparing the alternatives.
Environmental impact of production and use of the medical device	Decision-makers agree on considering this element not significant for service delivery mode selection.
Interest for public health	This value aspect is not a leaf of the value tree since it is a mean to reach other goals.
Impact on the sanitary system's budget	Costs are borne by the cooperative, and they do not affect the sanitary system's budget.
Target population	This value aspect is not a leaf of the value tree since it is a mean to reach other goals.
Operator training	The estimated time necessary for operator training is one hour which can be carried out in group sessions. This value was considered non-significant by decision-makers for this assessment.
Patient and informal caregiver training	The estimated time necessary for patients and informal caregivers training is one hour which can be carried out in group sessions (each patient with their family). This value was considered non-significant by decision-makers for this assessment.
Magnitude of environmental changes to be carried out at the patient's home	This value aspect was considered in the screening criteria: the assessment should not take into account a solution that does not consider the magnitude of environmental changes to be made; when assigning the robot, it is fundamental to assess the feasibility of the intervention.
Risks and difficulties related to technology introduction	Decision-makers agree on the absence of relevant risks for patients, the only aspect to consider is privacy.
Perceived safety	Is considered a prerequisite for the assessment.
Current/future intention of use	This value aspect is not a leaf of the value tree since it is a mean to reach other goals.
Usefulness perceived	This value aspect is entirely covered by other criteria identified; it does not add relevant elements.
Dehumanization	The absence of dehumanization is a prerequisite for this study and does not affect the selection of the best option.
Patient's living conditions	Patient's living conditions could affect techno-stress and other acceptability criteria; it is not a leaf of the value tree.

Depression	Depression is a clinical condition that cannot be assessed in a social care context.
Number of hospitalizations	Not pertinent with the context.
Isolation	Isolation is usually assessed as an objective condition, in this context what is relevant is the patient's perception of isolation, which is directly expressed in the loneliness criterion.
Ease of use for operators	It is a prerequisite that the selected operators for service delivery do not have difficulties in using the technology.
Operators' job satisfaction	Not considered relevant for the assessment.
Operators' learning curve	Decision-makers agreed on not considering the learning curve an issue since operators showed quick learning of device utilization.
Operators' stress	It was not considered a leaf of the value tree since its interest is directly related to operators' workload.
Operators' attitude to change	This value aspect is covered by the agreement between stakeholders.
Informal caregiver's stress	These elements are not of interest if considered separately, decision-makers agreed on grouping them in one criterion defined as informal caregiver's burden perception.
Technology ease of use perceived by the informal caregiver	
Informal caregiver's travel time reduction	
Benefits perceived by the informal caregiver	

Table 12 - Excluded value aspects

5.2.6 Value functions and weights

The following step of the method consists of determining value functions and weights of each criterion.

This phase was structured in two steps. Firstly, two questionnaires were sent to participants, and secondly, a meeting was scheduled to validate the results and complete the assessment. The questionnaires[6,7] were implemented using Qualtrics[8].

It was decided to share the questionnaires with participants for them to compile autonomously due to their length. This allowed participants to take their time for the compilation, eventually in more than one session. The use of questionnaires also allowed to reach more participants than the ones that took part in the 4th meeting. Support by facilitators was granted and provided when necessary, during questionnaires compilation.

The results of both questionnaires were collected, and the 4th meeting was scheduled to validate the results and proceed with the definition of value functions and weights. The M-MACBETH software was used as support for the meeting.

Value functions

To determine the value functions, it was necessary assess the attractiveness of performance improvements in the selected criteria. To do so, in the first questionnaire, participants were asked to rate the attractiveness of performance level swings within each criterion (e.g., “From *Neutral* To *Good*”, “From *Low* To *Neutral*”, etc.) with possible options:

- *Null,*
- *Very Weak,*
- *Weak,*
- *Moderate,*
- *Strong,*
- *Very Strong,*
- *Extreme,*
- *Don’t know/Don’t want to answer.*

[6] Questionnaire 1: https://qfreeaccountssjc1.az1.qualtrics.com/jfe/form/SV_1TcA5cblxjaj4we

[7] Questionnaire 2: https://qfreeaccountssjc1.az1.qualtrics.com/jfe/form/SV_8p2GjLizc2E4J3U

[8] https://www.qualtrics.com/it/

	Nessuna	Molto bassa	Bassa	Moderata	Forte	Molto forte	Estrema	Preferisco non rispondere / Non so rispondere
1) Da BASSO a NEUTRALE	○	○	○	○	○	○	○	○
2) Da BASSO a BUONO	○	○	○	○	○	○	○	○
3) Da NEUTRALE a BUONO	○	○	○	○	○	○	○	○

Figure 9 - Questionnaire 1

Each question was preceded by the definition of the criterion and its performance levels. The results of questionnaires were gathered and only elements on which there was no agreement between participants were object of discussion during the 4th meeting.

For example, for the criterion regarding perceived privacy violation (Figure 10), participants considered extremely desirable switching from a *Low* level to a *Neutral* level, which was considered a minimum requirement. As for an improvement from *Neutral* to *Good*, it was agreed to assign a *Weak* level of attractiveness since home care services imply an acceptance by patients of a minimum violation of their privacy and spaces.

The M-MACBETH software interface was used to facilitate discussion and visualization of results:

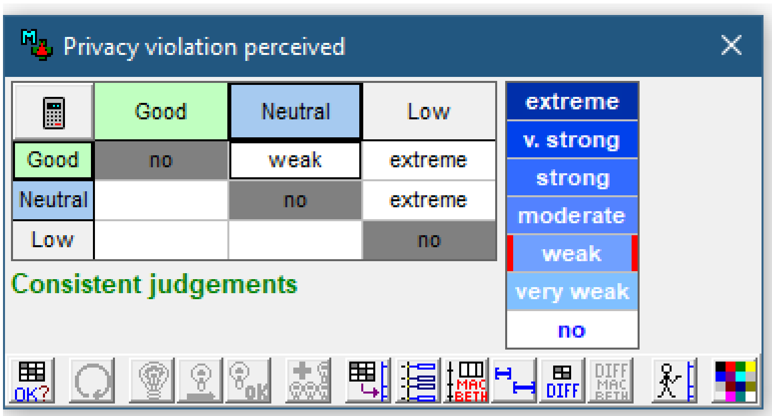


Figure 10 - Privacy violation perceived – Attractiveness of improvements

The M-MACBETH software automatically converts qualitative judgements into numeric values but allows to manually change them within a range of admissibility. As we can see from Figure 11, the qualitative judgements of attractiveness in criterion "Perceived privacy violation" are automatically converted into numbers by the software, but the values can be modified within a determined range maintaining consistent judgements.

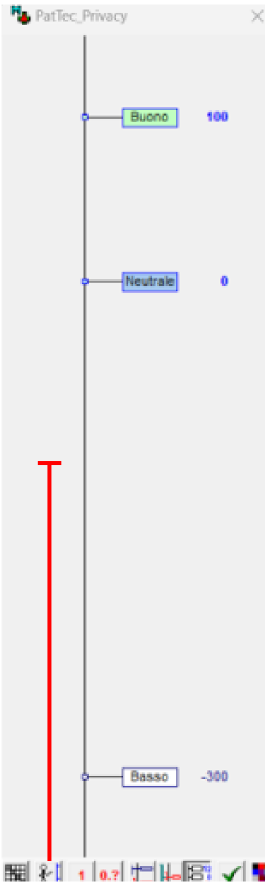


Figure 11 - Range of admissibility

This feature can be used when the numbers generated by the software are not significant, or when they are not fully representative of participants opinions.

Criteria weight determination

In the second questionnaire, a question for each macro-category of criteria (Organization, Patient- technology acceptability, Patient- Efficacy, Operator, Informal Caregiver) was structured.

In each question, participants were asked to rank the sub-criteria based on their relative importance. It was specified that the relative importance had to be assessed in terms of the swing from the *Neutral* level to the *Good* level. Definitions of criteria and levels were provided.

Results were collected and elaborated, and during the second part of the 4th meeting, the ranking of the sub-criteria for each macro-category was validated reaching unanimous consensus:

Macro-category	**Criteria**
Organization	1. Demonstrated effectiveness of the service delivery mode 2. Market competitivity 3. Financing 4. Stakeholders' agreement on the service delivery mode 5. Magnitude of organizational changes
Patient – Technology acceptability	1. Trust in service delivery 2. Perceived ease of use 3. Anxiety 5. Privacy violation perceived 6. Comfort 7. Enjoyment
Patient – Efficacy	1. Quality of social care support perceived 2. Support in managing emergencies 3. Quality of Life 4. Loneliness
Operator	1. Perceived workload suitability 2. Impact of travel time
Informal caregiver	1. Informal Caregiver burden perception

Table 13 - Ranking of sub-criteria within macro-categories

The ranking of sub-criteria was necessary for the following step: to determine weights of the sub-criteria, participants were asked to rate the attractiveness of the *Neutral - Good* swings between two different criteria pairwise. Criteria were ordered in the matrix based on the previously defined ranking:

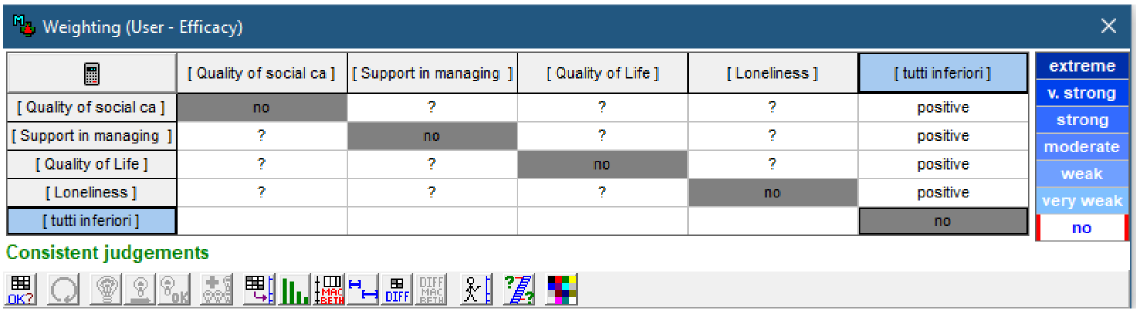


Figure 12 - Attractiveness between sub-criteria within macro-categories

With reference to Figure 12, all cells of the matrix needed to be compiled, but due to its symmetric form it was sufficient to fill the upper triangular of the matrix.

To do so, participants were asked to rate the attractiveness of the *Neutral-Good* swings between two different criteria pairwise with options:

- *Null,*
- *Very Weak,*
- *Weak,*
- *Moderate,*
- *Strong,*
- *Very Strong,*
- *Extreme.*

The process was repeated for each macro-category and the relative weight of the criteria within a macro-category was assessed:

Macro-category	**Criteria**	**Relative weight**
Organization	Demonstrated effectiveness of the service delivery mode	32,43%
	Market competitivity	32,43%
	Financing	21,62%
	Stakeholders' agreement on the service delivery mode	10,81%
	Magnitude of organizational changes	2,71%
Patient – Technology acceptability	Trust in service delivery	25,37%
	Perceived ease of use	22,39%
	Anxiety	16,42%
	Techno-stress	14,93 %
	Privacy violation perceived	11,94%
	Comfort	7,46%
	Enjoyment	1,49%
Patient – Efficacy	Quality of social care support perceived	44%
	Support in managing emergencies	32%
	Quality of Life	20%
	Loneliness	4%
Operator	Perceived workload suitability	75%
	Impact of travel time	25%
Informal caregiver	Informal Caregiver burden perception	100%

Table 14 - Relative weights

Since the selected criteria are organized in a hierarchic structure, it was then necessary to assess the weights and attractiveness of improvements of macro-categories. Two different approaches can be followed in hierarchic value trees:

- Relative importance can be assessed by comparing the *Neutral - Good* swing of all elements within a macro-category with the *Neutral - Good* swing of all elements in another one.

- One sub-criterion is selected from each category and *Neutral - Good* swings are compared pairwise.

For this analysis it was decided to follow the first approach since the criteria within the same macro-category are very different from each other, and selecting only one of them could lead to misleading results. It was therefore necessary to build the *Neutral* and *Good* levels for each macro-category. The levels were built as an aggregation of *Neutral* and *Good* levels of the most relevant criteria within each category:

Macro-category	Good	Neutral
Organization	There is evidence obtained from a significant sample regarding the effectiveness of the service delivery mode; the organization can deliver a service in a new mode, but easily imitable by competitors, and this mode will probably facilitate access to financing.	There is evidence obtained from a limited sample regarding the effectiveness of the service delivery mode; the organization delivers a service in a mode that is widely established on the market and this mode will probably not facilitate access to financing.
Patient – Technology acceptability	The patient is confident in receiving an adequate service and perceives they don't have to make a significant effort to receive the service; during service delivery they are relaxed and don't perceive a privacy violation.	The patient thinks they are receiving an adequate service and perceives they must make an acceptable effort to receive the service, during service delivery they do not experience significant tension or concern and perceive an acceptable level of privacy violation.
Patient – Efficacy	The informal caregiver can manage the main emergencies, the patient perceives they are receiving a service of good quality, and they perceive a significant improvement in the level of loneliness and quality of life.	The patient perceives they are receiving a service of acceptable quality, they perceive a slight improvement in the level of loneliness and quality of life, but the service delivery mode does not allow the patient to receive support in emergencies.
Operator	Operators perceive their workload as appropriate, and the impact of travel time is less than 0,05%.	Operators perceive their workload as not completely appropriate but overall acceptable and the impact of travel time is greater than 4 **%**.
Informal Caregiver	The service delivery mode contributes to significantly reducing caregivers' burden perception.	The service delivery mode contributes to partially reducing caregivers' burden perception.

Table 15 - Macro-categories performance levels

It was then necessary to determine the value functions of macro-categories, to do so, the *Neutral - Good* swings were assessed in terms of attractiveness for each macro-category:

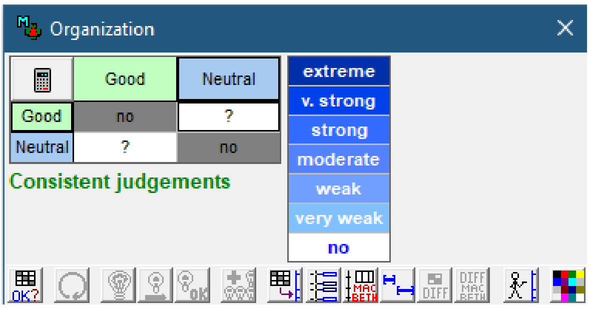


Figure 13 - Attractiveness of improvements in macro-categories

As for weights, participants were firstly asked to rank the macro-categories based on the attractiveness of their *Neutral-Good* swing. After discussing and reaching unanimous consensus the following ranking was generated:

Ranking	Macro-category
1	Organization
2	Patient – Efficacy
3	Patient – Technology acceptability
4	Informal caregiver
5	Operator

Table 16 - Ranking of macro-categories

Participants were then asked to rate the attractiveness of the *Neutral-Good* swing between two different macro-categories pairwise. The upper triangular of the matrix in Figure 14 was filled to determine the weights of macro-categories:

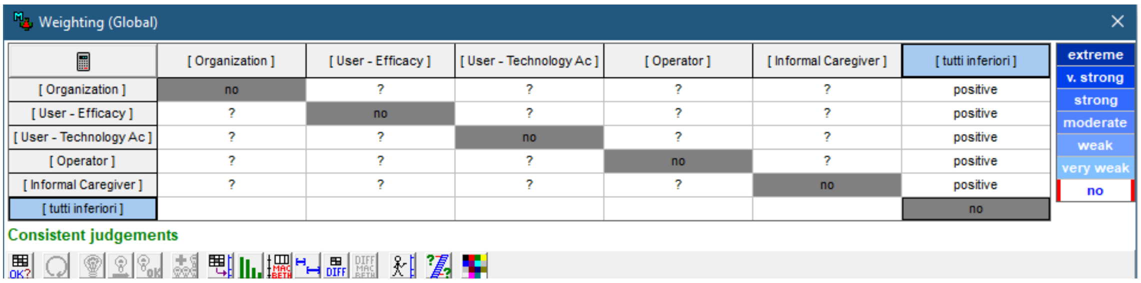


Figure 14 - Attractiveness of swings between macro-categories

The results of the previously performed steps led to the calculation of weights of macro-categories:

Macro-category	Macro-category weight
Organization	36,67%
Patient – Efficacy	30,00%
Patient – Technology acceptability	20,00%
Informal caregiver	10,00%
Operator	3,33%

Table 17 - Macro-categories weights

The following table shows for each criterion its overall weight, calculated as the product of its relative weight and the weight of the macro-category it refers to:

Criteria	Criteria overall weight
Quality of social care support perceived	13,20%
Demonstrated effectiveness of the service delivery mode	11,89%
Market competitivity	11,89%
Informal Caregiver burden perception	10,00%
Support in managing emergencies	9,60%
Financing	7,93%
Quality of Life	6,00%
Trust in service delivery	5,07%
Perceived ease of use	4,48%
Stakeholders' agreement on the service delivery mode	3,96%
Anxiety	3,28%
Techno-stress	2,99%
Perceived workload suitability	2,48%
Privacy violation perceived	2,39%
Comfort	1,49%
Loneliness	1,20%
Magnitude of organizational changes	0,99%
Impact of travel time	0,83%
Enjoyment	0,30%

Table 18 - Criteria overall weight

5.3 Evaluation of alternatives

5.3.1 Target patient identification and impact appraisal

The next phase of the MACBETH approach is focused on assigning to each alternative, its performance in each of the selected criteria. A pre-requisite to this phase was to identify the target patients to consider. To accomplish this, the 5th meeting was scheduled.

Target patient identification

The first part of the meeting was dedicated to the identification of the target patients for each alternative:

a. Public patients: Traditional home care service delivery,

b. Public patients: Service delivery through telepresence robot – Basic version,

c. Public patients: Service delivery through telepresence robot – Version with robot additional features.

Alternatives will shortly be referred to as:

(A) *Traditional,*

(B) *Robot_Base*,

(C) *Robot_Plus.*

The first topic of discussion was the identification of the categories of patients that currently receive services for monitoring and social support. This will allow defining the target patients for alternative (A).

With reference to the projects compiled by the social worker, patients are generally classified into:

- Disabled (minors or adults),
- Elderly not-self-sufficient,
- Self-sufficient (minors, adults, elderly, or people with mental distress).

Based on participants' experience, currently, patients from each of these categories receive monitoring and social support services.

The following step was to define what physical, psychological or social characteristics of patients would make it impossible to introduce the robot, or what characteristics would make the offering not interesting for the patient. This allowed to define the target patients for alternative (B). Independently from the category specified in the projects, the only element that was considered as a constraint to robot introduction was the presence of severe forms of psychological distress. Patients with severe forms of psychological distress may not accept the robot in their homes and perceive the device as a disturbing element.

To understand the target patients for alternative (C), the discussion focused on what specific characteristics of patients would make them not benefit from the additional features of the device. Participants agreed that patients with cognitive deficits would not be able to actively use the device and consequently would not benefit from the additional feature that enables them to call their family members or decline the calls.

Finally, participants agreed on the impossibility of further segmenting patients since other elements of distinction would be extremely subjective.

Based on this discussion, two different groups of patients were structured:

(1) Disabled (minors or adults), Elderly not-self-sufficient, Self-sufficient patients that do not present severe forms of psychological distress,

(2) Disabled (minors or adults), Elderly not-self-sufficient, Self-sufficient patients that do not present severe forms of psychological distress nor cognitive deficits.

Respectively, for group (1) just alternatives (A) and (B) are suitable, as for group (2) all three alternatives are admissible.

Impact appraisal

The second part of the meeting was dedicated to the assignment of performances to each alternative in each criterion.

Participants were asked to discuss each alternative's performance in each criterion and select a level from the defined descriptors.

Table of performances

Options	Loneliness	Quality of Life	Support in managing	Quality of social ca
Traditional	?	?	?	?
Robot_Base	?	?	?	?
Robot_Plus	?	?	?	?

Figure 15 - Table of performances

The following table summarizes the performances of each option in each criterion:

CRITERIA	(A) *Traditional*	(B) *Robot_Base*	(C) *Robot_Plus*
Demonstrated effectiveness of the service delivery mode	Good	Neutral	Low
Magnitude of organizational changes	Good	Good	Good
Stakeholders' agreement on the service delivery mode	Good	Neutral	Neutral
Financing	Neutral	Good	Good
Market competitivity	Neutral	Good	Excellent
Anxiety	Good	Good	Good
Enjoyment	Neutral	Neutral	Good
Trust in service delivery	Neutral	Neutral	Good
Perceived ease of use	Good	Good	Good
Comfort	Neutral	Neutral	Neutral
Privacy violation perceived	Neutral	Low	Neutral
Techno-stress	Good	Good	Neutral
Loneliness	Neutral	Neutral	Good
Quality of Life	Good	Good	Good
Support in managing emergencies	Neutral	Good	Excellent
Quality of social care support perceived	Neutral	Good	Good
Impact of travel time	Neutral	Good	Good
Perceived workload suitability	Neutral	Good	Good
Informal Caregiver burden perception	Neutral	Good	Good

Table 19 - Performances

For example, an interesting result emerged from the discussion on the criterion regarding "Anxiety". Participants agreed that, based on their experience within trials with the device in question, anxiety was not an issue for patients after using the robot a few times. Based on this assertion, a *Good* level of performance was assigned to all alternatives in this criterion. Concerning services' impact on patient's quality of life, participants agreed on assigning a *Good* level of performance to all alternatives since, based on their experience, any form of monitoring or social support services has a significant impact on patient's quality of life. A last example worth mentioning is the criterion regarding the patient's loneliness. In this case, participants agreed on assigning a neutral level to alternatives (A) and (B), while option (C), in participants' opinion, could significantly reduce patient's loneliness enabling them to actively use the device to reach their families.

Finally, participants were also asked to identify, where existing, differences in performances based on the group of patients, but unanimously agreed on not distinguishing performance levels between different patients. The value functions previously defined, allowed to transform qualitative judgements into value scores, as summarized in the following table:

CRITERIA	(A) *Traditional*	(B) *Robot_Base*	(C) *Robot_Plus*
Demonstrated effectiveness of the service delivery mode	100	0	-50
Magnitude of organizational changes	100	100	100
Stakeholders' agreement on the service delivery mode	100	0	0
Financing	0	100	100
Market competitivity	0	100	250
Anxiety	100	100	100
Enjoyment	0	0	100
Trust in service delivery	0	0	100
Perceived ease of use	100	100	100
Comfort	0	0	0
Privacy violation perceived	0	-300	0
Techno-stress	100	100	0
Loneliness	0	0	100
Quality of Life	100	100	100
Support in managing emergencies	0	100	225
Quality of social care support perceived	0	100	100
Impact of travel time	0	100	100
Perceived workload suitability	0	100	100
Informal Caregiver burden perception	0	100	100

Table 20 - Scores

5.3.2 Calculation of the overall value and cost of alternatives

Once all performances were collected, it was possible to determine the overall value of each alternative as a combination of overall weights and scores:

$$V(o) = \sum_{j=1}^{J} w_j s_j(o)$$

with:

$$\sum_{j=1}^{J} w_j = 1$$

and:

$$w_j = w_{r\_j} * w_{mc\_j}$$

where:

- j=1,…,J indicates the criterion,
- o=1,…,O indicates the alternative options,
- $s_j(o)$ represents the score of alternative o in criterion j,
- w_j is the overall weight of criterion j, corresponding to the product of the relative weight of criterion j within its reference macro-category (w_{r_j}) and the weight of the macro-category (w_{mc_j}),
- $V(o)$ is the overall value of option o.

The following table summarizes the overall values of options for the different categories of patients:

Overall value	**(A) *Traditional***	**(B) *Robot_Base***	**(C) *Robot_Plus***
Patient (1)	3.294	6.653	-
Patient (2)	3.294	6.653	10.120

Table 21 - Overall values

This allowed to identify the final ranking of alternatives:

Ranking	**Alternative**
1	(C) *Robot_Plus*
2	(B) *Robot_Base*
3	(A) *Traditional*

Table 22 - Ranking of alternatives

Then, the cost of each option was determined. For this phase, it was chosen to assess only differential costs of the new options compared to the current one, and to evaluate them annually. To do so, historical data and information from previous assessments were collected and some hypotheses were made:

1. Based on historical data, the target number of patients to serve annually with the robot was 15 patients,
2. The device would be assigned to the same patient for 4 months,
3. To serve 15 patients within a year it is necessary to purchase 5 *Ohmni Robots*,
4. Based on historical data, it was hypothesized that each patient needs on average four weekly hours of monitoring and social support services,
5. Based on historical data, the average number of kilometers traveled by the operators for each hour of service is approximately 2,14 km,
6. 40% of patients have projects that involve only monitoring and social support services; for these patients, if service is delivered through the telepresence robot, it is necessary to plan a weekly visit of 30 minutes to be performed at the patient's home,

Based on these hypotheses, the annual differential cost of each option was evaluated:

Alternative	Annual additional cost [€]
(A) *Traditional*	0
(B) *Robot_Base*	5.251,29
(C) *Robot_Plus*	7.288,79

Table 23 - Cost of alternatives

The following graph plots the options in a Cost – Benefit Map, identifying the efficient frontier and showing the net growth of the overall value for option (C):

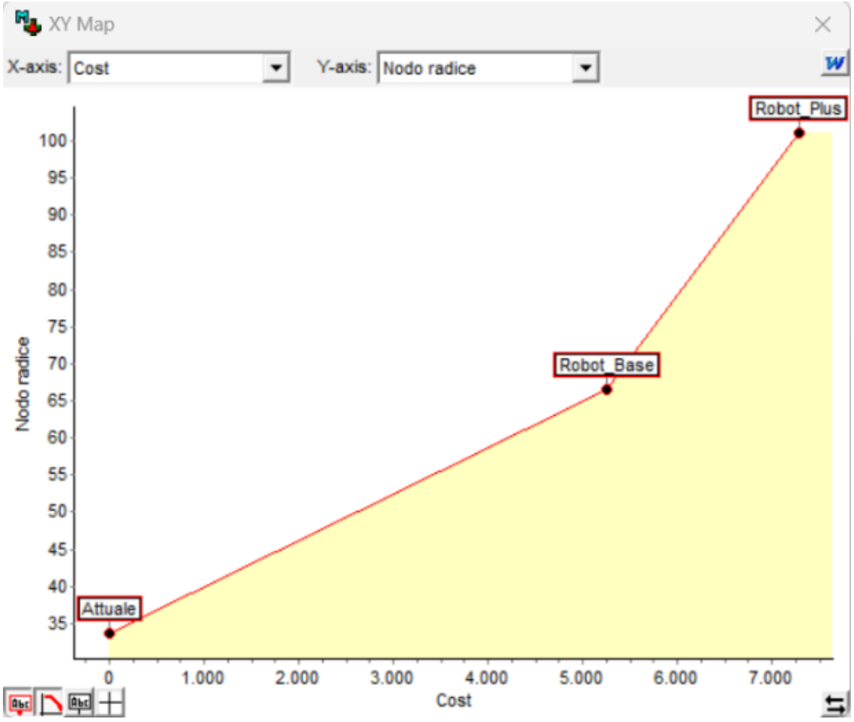


Figure 16 - Cost-Benefit Map

As an additive result, that was not relevant for the implementation of the MACBETH method, the Net Present Value (NPV) of the investments was assessed. Within the analysis of the NPV, a sensitivity analysis was performed on the elements of the cost model whose variation has a significant impact on costs.

The elements whose variation has a significant impact on costs and that could offer guidelines to cooperatives' choices are:

- The number of weekly hours of monitoring and social support services required by each patient served through the telepresence robot,
- The kilometers to be traveled on average by operators to deliver services, per hour of service.

The following table reports the NPV considering a 4-year time horizon with a discount rate of 5%, four weekly hours of service for each patient, and 2,14 kilometers to be traveled on average for each hour of service:

NPV	
(B) *Robot_Base*	**(C) *Robot_Plus***
- € 13.154,57	- € 18.192,49

Table 24 - NPV

The results show that, in the public context, with the current average values of service hours per patient, kilometers of travel per hour of service and with the current revenues deriving from the payment by the public contracting authority, the investment is not convenient with a NPV significantly lower than zero.

The parameters that can be object of variation in order to obtain a positive NPV are:

- The hourly fee of reimbursement by the public contracting authority,
- The number of weekly hours of monitoring and social support services required by each patient served through the telepresence robot,
- The kilometers to be traveled on average by operators to deliver services, per hour of service.

The following table shows the hourly fee increment needed to obtain a positive NPV of the investment, with the hypothesis of maintaining a discount rate of 5% but with different values of weekly service hours and kilometers of travel per hour of service:

Weekly service hours per patient [h/week]	**Km of travel per hour of service [km/h]**	**Δ Hourly Fee *Robot_ Base* (A) [€/h]**	**Δ Hourly Fee *Robot_ Plus* (B) [€/h]**
4	2,14	+6	+8,4
5	2,14	+4,5	+6,4
6	2,14	+3,4	+5
7	2,14	+2,7	+4
4	5	+3,9	+6,2
5	5	+2,4	+4,2
6	5	+1,3	+2,8
7	5	+0,6	+1,9
4	10	+0,7	+2,9
5	10	0	+0,9
6	10	0	0
7	10	0	0
4	15	0	+0,4
5	15	0	0
6	15	0	0
7	15	0	0

Table 25 - Sensitivity analysis NPV

The results show how the considered parameters have a strong impact on the convenience of the investment: the choice of the right set of patients to serve remotely is crucial for the profitability of the investment.

5.4 Testing the requisiteness of the model

5.4.1 Sensitivity and robustness analyses

Before the last meeting, where results were presented and discussed with participants, sensitivity and robustness analyses of the model were performed.

Sensitivity analysis

A sensitivity analysis was performed on criteria weight to understand the extent to which the model's recommendation, in terms of the best option, would vary as a result of changes in the weights of each criterion.

M-MACBETH allows to visualize, for each criterion, if changes in its weight would affect the overall value of the options to an extent that would modify their final ranking. The identification of elements in which a minor variation in weight has an impact on the result, may be the object of discussion with participants, that may want to reiterate the process.

For example, as we can see from Figure 17, for option (C) to lose the top position to option (B), the weight of criterion "Perceived privacy violation" would have to increase from 2,39% to 12,2%.

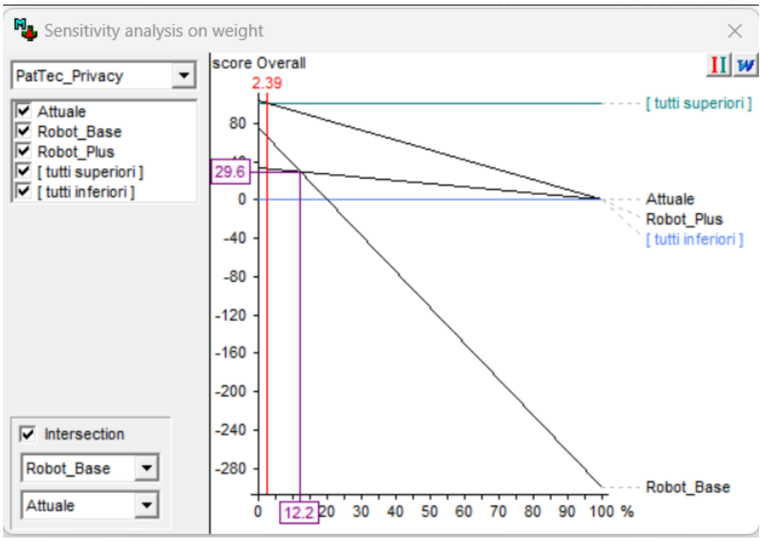


Figure 17 - Sensitivity analysis on weight - Privacy

As for the criterion "Techno-stress", its weight should increase from 3% to 28% for option (A) to become the best one.

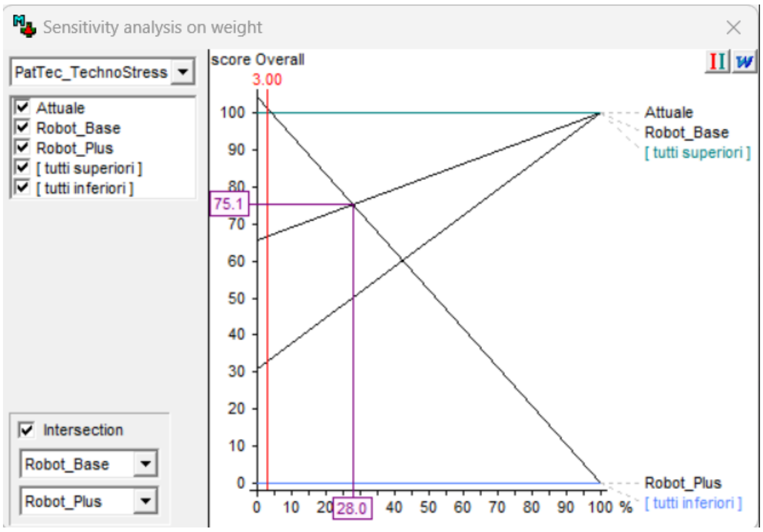


Figure 18 - Sensitivity analysis on weight – Techno-stress

All the criteria were checked in terms of sensitivity to identify elements that, with a small change in weight, would significantly affect the final result.

For some criteria, no variation in their weight would make the result change. As for others, to obtain a different best option, the variation in weight should be greater than 9 percentage points. A change of this entity would not be justifiable and does not characterize the model as sensitive to weights variation.

As a conclusion of the sensitivity analysis, it was possible to assert that there were not sufficient elements to assume that the model is sensitive to weights variation, and no element was discussed with participants.

Robustness analysis

Robustness analysis is a tool that allows to consider uncertainty that may affect the decision-making process. It allows to determine whether the result of the best alternative changes with a variation of up to a predefined percentage of uncertainty on each criterion scale and on criteria weights. In M-MACBETH, robustness analysis is developed on the concept of "additive dominance" [11]. An option dominates another when it is at least as attractive as another option in all criteria and outperforms it on at least one criterion. This dominance is represented with a red triangle in M-MACBETH software. An option additively dominates another option if it is more attractive in all criteria than another using an additive model under a set of information constraints. Additive dominance is represented with a green cross in M-MACBETH software [92].

M-MACBETH allows to perform a robustness analysis in three forms, using different information:

- ***Ordinal*** information refers only to rank, thereby excluding any information pertaining to differences of attractiveness (strength of preference),

- ***MACBETH*** information includes the qualitative judgements implemented into the model; however, it does not distinguish between any of the possible numerical scales compatible with those judgements,

- ***Cardinal*** information denotes the specific quantitative scale validated by the decision-maker (value functions, weights).

The robustness analysis was performed in all three forms. Each criterion was firstly analyzed individually, checking if considering uncertainty on their judgement would affect the result. Then, if none of the criteria taken singularly had an impact on the result, uncertainty was included for all criteria and results were analyzed.

As for the ordinal information, considering uncertainty on all criteria, we can see that the *Robot_Plus* option is the only one that is not dominated by an ideal good option (“*tutti superiori*” in Figure 19) that has a *Good* performance on each criterion. This is due to the fact that the *Robot_Plus* option has an *Excellent* performance on some criteria. On the other hand, the *Traditional* option is the only one that dominates the ideal bad option (“*tutti inferiori*” in Figure 19) that has a *Neutral* performance on each criterion.

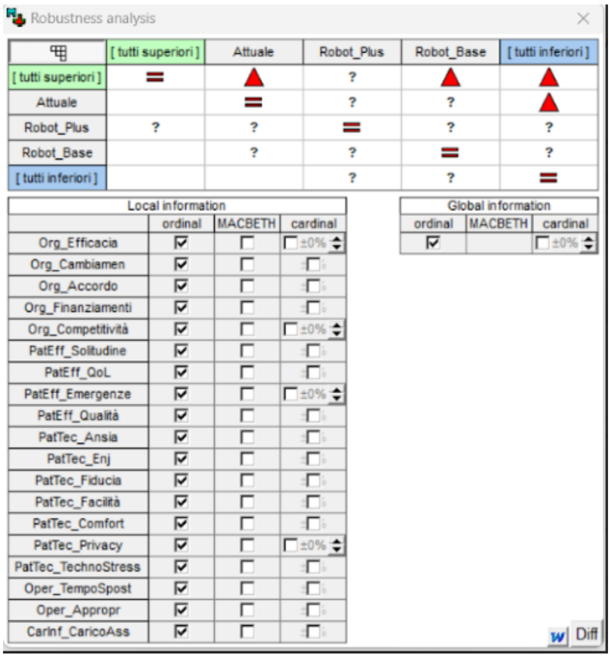


Figure 19 - Robustness analysis – Ordinal information

In relation to MACBETH information, the first row of the matrix in Figure 20 shows how the ideal best option dominates alternative (A) and (B) but there are not sufficient elements to assert that it also dominates alternative (C) when considering the qualitative judgements implemented in the model. As for the second row, we can assert that option (C) has an additive dominance on the other options, and that the *Traditional* option (A) additively dominates the (B) option.

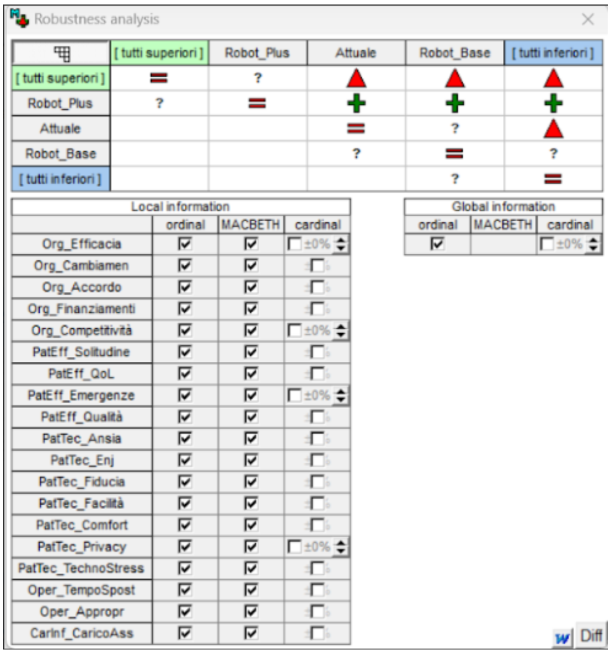


Figure 20 - Robustness analysis – MACBETH information

Introducing cardinal information and checking for changes when uncertainty is included on each criterion, an important evidence emerged. A criterion that has a significant impact on the evaluation is the “Perceived privacy violation”. When uncertainty is included for this criterion, option (B) additively dominates the *Traditional* (A) option (Figure 21).

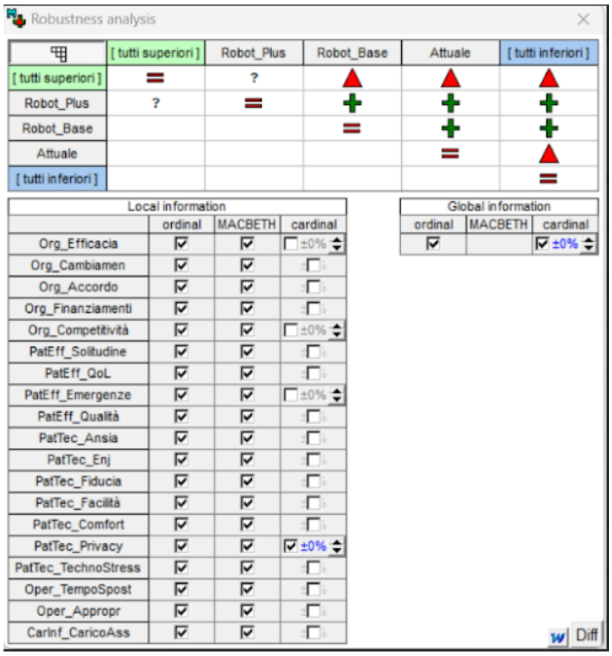


Figure 21 - Robustness analysis – Cardinal information, Privacy

When uncertainty is assigned to all criteria no major changes occur (Figure 22).

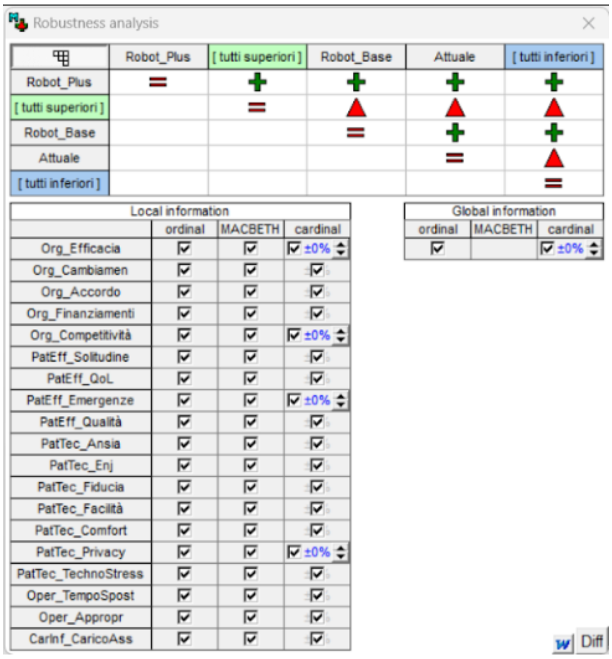


Figure 22 - Robustness analysis – Cardinal information

These analyses show that the inclusion of quantitative judgements has strong impact on the results, and that particular attention needs to be dedicated to quantitative scores on the "Perceived privacy violation" criterion.

As a matter of fact, its strong role is due to the quantitative scores in the value function: a value of -300 was assigned to a *Low* level of performance (Figure 23), and this extremely negative value strongly affects the results. Visualizing the range of values that could be assigned without changing the qualitative judgements, it was possible to see that the scale could increase up to -101 maintaining consistent judgements.

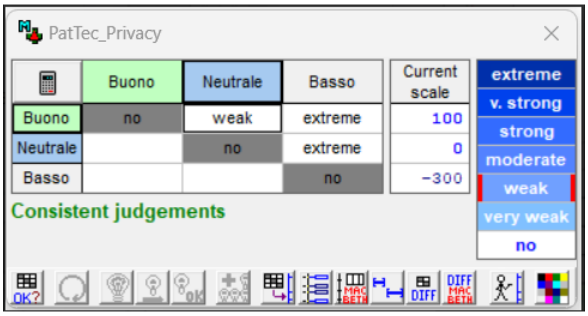


Figure 23 - Value function - Privacy

This last result was the only one worth discussing with participants during the last meeting.

5.4.2 Model validation and method assessment

A last meeting was scheduled to discuss results and assess the method through direct questions to participants.

Results were presented, and participants unanimously agreed on their coherence and consistency with the previous steps. The costs to be incurred with the new service delivery modes were considered coherent with the increase of the overall value of the solutions.

The "Perceived privacy violation" criterion was discussed in terms of the quantitative judgements generated by the software, but the current result was validated unanimously, mostly because the interviewed were not able to express their judgement in quantitative terms.

Participants were asked if the results obtained through the analysis were what they expected and if some element was lacking to support their decision-making process. Some participants pointed out that a further element to work on would be the structuring of a possible new form of payment, through monthly subscriptions.

To assess the requisiteness of the method, participants were asked if the process supported them in the identification of the service delivery modes enabled by the introduction of the technology and if, without carrying out the multi-criteria analysis they would have selected the same alternative as the best. All participants agreed on the important support of the process for the structuring of the alternatives, allowing them to "*better visualize the details and structure everything with a more analytical perspective*" (participant n° 5). Another insight emerged from this question was that the best option at the beginning of the process had never been considered before, so *"the method supported the construction of the best alternative*" (participant n°1).

The method was unanimously considered as useful, reliable, and the results fundamental for the decision-making process.

As for the weaknesses and difficulties of the process, the following observations emerged from the discussion:

- The method was time consuming,
- Not all the steps were immediately comprehended by all participants, and the support of facilitators was fundamental in all the phases.

The final part of the meeting was dedicated to the discussion of the methodological decisions taken during the process, and of eventual forms of bias introduced during the activities.

The following decisions were discussed:

1. **The structuring of alternatives followed value aspects identification:** the chronological order of activities was a methodological decision that needed to be evaluated with participants. All of them agreed on the suitability of the decision since the previous discussion of value aspects supported and facilitated the structuring of the alternatives, focusing their attention on the elements of interest.

2. **The use of the Business Model Canvas**: despite most participants were not familiar with the tool, they expressed positive opinions on its use, since they found it clear to understand, comprehensive in the information presented and useful for future development.

3. **The use of questionnaires:** three questionnaires were used during the process, the first, during the 2nd meeting to assess relevance of value aspects, the second and the third were compiled autonomously by participants for the assessment of value functions and weights. For the first one, participants agreed that it was useful to firstly reflect individually on the questions, and then discuss with others. In addition, the compilation of the questionnaire within the meeting increased their commitment to the activity. As for the second and third questionnaires, it was considered useful to have a first introduction to the topic of the following meeting, which allowed to carry out the discussion more easily.

4. **The use of the M-MACBETH interface:** the use of the interface was judged as very useful as it allowed to better visualize the topic of discussion.

5. **Impact appraisal:** the activity of impact appraisal only relied on the experts' experience and opinions. This methodological choice was due to time and resource constraints defined by decision-makers, but participants unanimously agreed that, for a first assessment, the results obtained through their judgements allowed to reach a significant result. As a possible development, some of the participants suggested the possibility of including further points of view, such as the one of informal caregivers or patients.

6. **Value aspects generation:** for the generation of value aspects, it was decided to perform a literature review to identify a first set of elements, to support the discussion with participants during the 1st meeting. The presentation of a defined list of elements could have introduced a bias and limited the opinions of participants. This form of bias was excluded since participants unanimously agreed on the usefulness of the presented list, which provided support to their reflections and stimulated the discussion.

7. **Reaching of consensus**: the validation phases, where the reaching of unanimous consensus was necessary to obtain significant results, may have introduced forms of bias due to the possible higher influence of some of the people involved. This kind of bias was excluded too, due to the agreement of participants on how, during the discussion, they were all able to freely express their opinions.

The following table summarizes the results of the evaluation of the method with participants:

Likes	**Criticisms**
• Structuring of service delivery modes following identification of value aspects, • Use of questionnaires, • Use of Business Model Canvas, Mind Maps, Strategy Tables, • Use of the M-MACBETH interface to support discussion.	• High number of phases.
Dislikes	**Ideas and suggestions**
• Time and resource consuming method, • Complexity of some of the steps.	• Include further points of view (informal caregivers, patients…), • Structure a monthly subscription system for the delivery of services.

Table 26 - Method assessment with participants

Lastly, the method and the results were presented and discussed with a group of researchers of the Department of Bioengineering of the *Università degli Studi di Firenze* that are currently involved in the *PHArA-ON* project.

The main insights deriving from this discussion were related to the scalability of the analysis and its reproducibility in other contexts or with different assistive technologies. In addition to this, it emerged that particular attention needs to be dedicated to costs and to the decision elements that have a strong impact on them.

Lastly, it was pointed out that the use of quantitative terms for the definition of the "Impact of travel time" criterion, may have led to a not clear understanding of levels by participants.

With reference to the replicability of the analysis in other cooperatives of the network, the only elements that need to be adapted are quantitative elements such as costs and the only criterion defined with quantitative levels: "Impact of travel time". These fields could be adapted to the specific cooperative, where different distances may need to be covered by operators during their shifts. As for this element, a first assessment on how the convenience of the investment changes based on the average distance to be covered, has been given in Section 5.3.2.

Concerning the replicability with other assistive technologies, the value model itself is not directly usable, but the methodological approach proposed could be successfully replicated.

Then, with regard to costs evaluation, information related to costs and travel time of operators could be complemented and enriched with the use of the optimization model presented in Section 6.2, that could give a clearer understanding of costs and guide the selection of patients to serve through the device.

The following table summarizes the results of the evaluation with researchers:

Likes	Criticisms
• Holistic approach that allows to include different points of view, • Robust approach, • The judgements of participants were based on previous experiences with the device.	• Some of the outcomes are contextual to the cooperative considered as a case study and at the moment of the assessment, • Scalability of the analysis to other contexts or assistive technologies, • Impact of travel time: use of numerical values for the definition of the descriptor.
Dislikes	**Ideas and suggestions**
• Limited sample of participants, • Only one participant in particular represented the direct point of view of decision-makers, • Complexity of some of the steps.	• Identify the elements that have a significant impact on costs and on which the cooperatives could act to improve the efficiency of the service, • Hypothesize alternatives to the direct purchase of devices (e.g., rental). • Extend the scope of analysis to further third parties (Regional Sanitary System, insurance companies, etc.)

Table 27 - Method assessment with researchers

The following section reports the formulation and implementation of the optimizations model for the scheduling of home care services.

6 Optimization models formulation and implementation

In this section, the two formulations of the Home Care optimization problems will be presented together with preliminary computational results.

6.1 Nominal model formulation

The nominal model presented in this section, is structured on what is the current organization of home care services, without considering the introduction of the telepresence robot.

Problem description:

- Each project (patient) can be accepted or not,
- Each project consists in a set of service requests,
- Each project is characterized by a weekly revenue, based on the number of service hours required,
- The planning horizon is one week, which consists of seven working days,
- Each day is characterized by two sessions: morning and afternoon sessions,
- Shifts for operators can be of three types: morning shifts (from 7:00 to 12:00), afternoon shifts (from 16:00 to 21:30), all day shifts (from 7:00 to 11:00, and from 18:00 to 21:30). The starting and ending time of a shift can be in every moment within a session,
- Operators can express their availabilities for the upcoming week,
- Operators are characterized by a set of skills, that enable them to perform a certain category of services,
- Operators have a maximum number of hours of work within a week,
- Operators may have a different hourly rate based on their qualifications,
- The logistic network is defined for each day and for each operator as the set of active requests on that day, and the nodes that characterize the operators' domiciles,
- Requests may require the co-presence of two operators,
- Requests are characterized by a required skill,
- Requests have a defined time duration,
- Requests have a time window for service to begin,
- Each shift for each operator begins and ends at their own domicile.

The following decisions must be taken:

- Accept a project or not (design decision),
- For each accepted project, schedule the services required by the project, i.e., set the starting time of each activated service (scheduling decisions),

- Assign each activated service to the proper number of operators while respecting skill constraints (assignment decisions),
- For each operator, for each day, decide if they work the morning shift, the afternoon one, or both (rostering decisions),
- Define the sequence according to which each operator on each day visits the assigned services (routing decisions),
- For each operator working a shift, define the start and end times of the shift (rostering decisions).

The following notation is used:

- P set of projects (patients),
- R set of service requests,
- D set of days in the planning horizon,
- $S = \{m, a\}$ set of time sessions in each day,
- O set of operators,
- $O_d \subseteq O$ set of operators available on day d, for each $d \in D$,
- K set of skills,
- $V = R \cup_{o \in O} \{b_o, e_o\}$ set of vertices in the logistic network,
- A set of arcs in the logistic network; the network is assumed to be complete,
- k_o skill of operator o,
- b_o starting node for operator o,
- e_o ending node for operator o,
- h_o maximum weekly working hours for operator o
- n_p number of services required in project p,
- p_i project which service i refers to,
- d_i day on which service i is required,
- q_i number of operators required for service i,
- k_i skill required for service i,
- t_i service time of service i,
- $[\alpha_i, \beta_i]$ time window for starting time of service i,
- τ_{ij} traveling time from node i to node j, $(i, j) \in A$,
- c_o hourly cost of operator o,
- g_p weekly revenue for accepting project p,
- θ reimbursement for travel time.

We make use of the following variables:

- $$\boldsymbol{z_p} = \begin{cases} 1 \; if \; project \; p \; is \; accepted \\ 0 \;\; otherwise \end{cases} \quad p \in P$$

- $$\boldsymbol{x_{ij}^{od}} = \begin{cases} 1 \; if \;\; operator \; o \; travels \; along \; (i,j) \; on \; day \; d \\ 0 \;\; otherwise \end{cases} \quad (i,j) \in A, d \in D, o \in O_d$$

- $\boldsymbol{y^{ods}} = \begin{cases} 1\ if\ operator\ o\ works\ on\ day\ d\ in\ session\ s \\ 0\ \ otherwise \end{cases} \quad s \in S,\ d \in D,\ o \in O_d$

- $\boldsymbol{u_i^o} = \begin{cases} 1\ if\ \ operator\ o\ serves\ request\ i \\ 0\ \ otherwise \end{cases} \quad i \in R,\ o \in O_d$

- $\boldsymbol{w_i^o}$ $is\ the\ starting\ time\ of\ service\ i\ when\ done\ by\ operator\ o, i \in R, o \in O_d, d = d_i$

- $\boldsymbol{w_i^{ods}}$ $is\ the\ time\ at\ which\ operator\ o\ on\ day\ d\ in\ session\ s\ begins/$ $ends\ the\ working\ shift, d \in D, s \in S, o \in O_d, i\ \in\ \{b_o, e_o\}$

The nominal model can be defined as follows:

$$max \sum_{p \in P} g_p z_p - \sum_{d \in D}\sum_{o \in O}\sum_{s \in S} c_o\,(w_{e_o}^{ods} - w_{b_o}^{ods}) - \sum_{d \in D}\sum_{o \in O}\sum_{s \in S} \theta x_{ij}^{od} \tau_{ij}$$

$$\sum_{(b_o,j) \in A} x_{b_o j}^{od} = \sum_{s \in S} y^{ods} \ \ \forall d \in D,\ \forall o \in O_d \qquad (2)$$

$$\sum_{(i,j) \in A} x_{ij}^{od} = \sum_{(j,i) \in A} x_{ji}^{od} \ \ \forall j \in R, \forall d \in D, \forall o \in O_d \qquad (3)$$

$$\sum_{(i,e_o) \in A} x_{ie_o}^{od} = \sum_{s \in S} y^{ods} \ \ \forall d \in D,\ \forall o \in O_d \qquad (4)$$

$$\sum_{(i,j) \in A} x_{ij}^{od} = u_i^o\ \forall i \in R, \forall d \in D, \forall o \in O_d, s.t. d = d_i \qquad (5)$$

$$u_i^o \le z_p\ \forall p \in P, \forall i \in R, s.t.\ p_i = p, \forall o \in O_d, s.t. d = d_i \qquad (6)$$

$$\sum_{o \in O_d} u_i^o \ge q_i z_p\ \forall p \in P, \forall i \in R, s.t. p_i = p, d = d_i \qquad (7)$$

$$w_{b_o}^{odm} \ge 7y^{odm}\ \forall d \in D, \forall o \in O_d \qquad (8)$$

$$w_{e_o}^{odm} \le 11y^{odm} - y^{oda} + 1\ \forall d \in D, \forall o \in O_d \qquad (9)$$

$$w_{b_o}^{oda} \ge 18y^{oda} + 2y^{odm} - 2\ \ \forall d \in D, \forall o \in O_d \qquad (10)$$

$$w_{e_o}^{oda} \le 21.30y^{oda}\ \ \forall d \in D, \forall o \in O_d \qquad (11)$$

$$w_i^o + t_i + \tau_{ij} \leq w_j^o + M\left(1 - x_{ij}^{od}\right) \quad \forall d \in D, \forall o \in O_d, \forall\, i,j \in R,\ s.t.\, k_o = k_j = k_i, d_o = d_j = d_i \quad (12)$$

$$w_{b_o}^{ods} + \tau_{b_o j} \leq w_j^o + M(1 - x_{b_o j}^{od}) \ \forall s \in S, \forall\, d \in D, \forall o \in O_d, \forall j \in R, s.t.\, k_o = k_j, d = d_j \quad (13)$$

$$w_i^o + t_i + \tau_{ie_o} \leq w_{e_o}^{ods} + M(1 - x_{ie_o}^{od}) \ \forall d \in D, \forall o \in O_d, \forall i \in R, s.t.\, k_o = k_i, d = d_i \ (14)$$

$$\alpha_i u_i^o \leq w_i^o \leq \beta_i u_i^o \ \forall i \in R, \forall o \in O_d, s.t.\, k_o = k_i, d = d_i \quad (15)$$

$$\sum_{d \in D} \sum_{s \in S} (w_e^{ods} - w_{b_o}^{ods}) \leq h_o \quad \forall o \in O \quad (16)$$

$$y^{ods} \leq \sum_{i \in s\,,\ d = d_i} u_i^o \ \forall s \in S, \forall d \in D, \forall o \in O_d \quad (17)$$

$$w_{b_o}^{ods} \leq M\, y^{ods} \quad \forall s \in S, \forall d \in D, \forall o \in O_d \quad (18)$$

$$w_i^{o_1} \leq w_i^{o_2} - M(u_i^{o_1} + u_i^{o_2} - 2) \ \forall i \in R, s.t.\, m_i = 2, \forall o_1, o_2 \in O_d, s.t.\ d = d_i, k_{o1} = k_{o2} = k_i \quad (19)$$

$$w_i^{o_1} \geq w_i^{o_2} + M(u_i^{o_1} + u_i^{o_2} - 2) \ \forall i \in R, s.t.\, m_i = 2, \forall o_1, o_2 \in O_d, s.t.\ d = d_i, k_{o1} = k_{o2} = k_i \quad (20)$$

$$w_{e_o}^{ods} - w_{e_o}^{ods} \geq \sum_{i \in s\,,\ d = d_i} t_i u_i^o \ \forall\, s \in S, \forall\, d \in D, \forall\, o \in O_d \quad (21)$$

$$z_p \in \{0\,, 1\} \quad \forall\, p \in P \quad (22)$$

$$x_{ij}^{od} \in \{0\,, 1\} \quad \forall\, (i,j) \in A, \forall\, d \in D, \forall\, o \in O_d \quad (23)$$

$$y^{ods} \in \{0\,, 1\} \quad \forall\, s \in S, \forall\, d \in D, \forall\, o \in O_d \quad (24)$$

$$u_i^o \in \{0\,, 1\} \quad \forall i \in R\ , \forall\, o \in O_d\,, d = d_i \quad (25)$$

$$w_i^o \geq 0 \quad \forall i \in R\ , \forall\, o \in O_d\,, d = d_i \quad (26)$$

$$w_i^{ods} \geq 0 \quad \forall\, s \in S, \forall\, d \in D, \forall\, o \in O_d, \forall i \in \{b_o, e_o\} \quad (27)$$

A brief description of the elements of the model will follow:

- The objective function (1) maximizes the revenues deriving from the accepted projects while considering human resources costs and transportation costs,

- Constraints (2) guarantee that the number of times in which operator *o* leaves its domicile on day *d* to serve a certain request *i* must correspond to the number of sessions in which the operator is working on day *d.*

- Constraints (3) guarantee that the routing flow is kept balanced for all the nodes (if an operator visits a node, they also must leave the node).

- Constraints (4) guarantee that the number of times in which operator *o* enters its domicile on day *d* to serve a certain request *i* must correspond to the number of sessions in which the operator is working on day *d.*

- Constraints (5) guarantee that if a request is served by an operator, the operator must traverse a network arc that takes to said request,

- Constraints (6) impose that if a project is accepted, all its requests must be scheduled,

- Constraints (7) guarantee that each request is served by the required number of operators,

- Constraints (8) impose that the morning shift does not start before 7:00,

- Constraints (9) assign the maximum ending time to the morning shift, depending on how many shifts each operator works within a day. If the operator needs to work a double shift, the morning one should end before 11:00, otherwise it should end before 12:00.

- Constraints (10) assign the minimum starting time to the afternoon shift, depending on how many shifts each operator works within a day. If the operator needs to work a double shift, the afternoon one should start later than 18:00, otherwise it should start later than 16:00.

- Constraints (11) impose that the afternoon shift ends at last at 21:30,

- Constraints (12) guarantee the right sequencing of two consecutive services performed by the same operator, considering service times and travel times,

- Constraints (13) guarantee that the last activity within a shift ends in time for the patient to conclude the shift,

- Constraints (14) guarantee that the first service of the shift begins after the starting time of the shift and considering travel time of operators from their home,

- Constraints (15) impose the time window constraints for service to begin,

- Constraints (16) guarantee that the number of hours each operator works within a week do not exceed the corresponding maximum number of weekly working hours,
- Constraints (17) guarantee that only operators that are assigned to a request in a shift effectively work in that shift,
- Constraints (18) impose that only operators that work in a shift must have a shift starting time greater than zero,
- Constraints (19)-(20) guarantee that two operators assigned to the same request begin the service at the same time (dependency among routes constraints).
- Constraints (21) guarantee that the duration of a shift is at least equal to the duration of services the operator performs within the shift.
- Constraints (22)-(27) define the domain of the variables.

6.2 Model with telepresence robot formulation

This section describes the formulation of the model for scheduling of home care services considering the possibility of assigning to a maximum number of patients the telepresence robot (TR) and eventually perform remotely some of their requests.

As emerged from the discussions with participants for the Early Health Technology Assessment, when the TR is introduced in services, the frequency of interventions may be increased to enhance the perceived service quality. For this reason, when service is delivered through the TR, a request can be divided into shorter interventions to perform in different moments of the day, generally one in the morning and one in the afternoon.

The problem addressed with the new model is an extension of the nominal one, considering some additional elements:

- Some of the requests could be performed remotely,
- For each request (referred as *Main* request), that can be delivered remotely, the alternative is characterized by two different requests to be performed one in the morning and one in the afternoon. Each of these has a duration equal to half of the duration of the *Main* corresponding request. If the request is decided to be performed remotely, both interventions (Morning and Afternoon) must be scheduled.

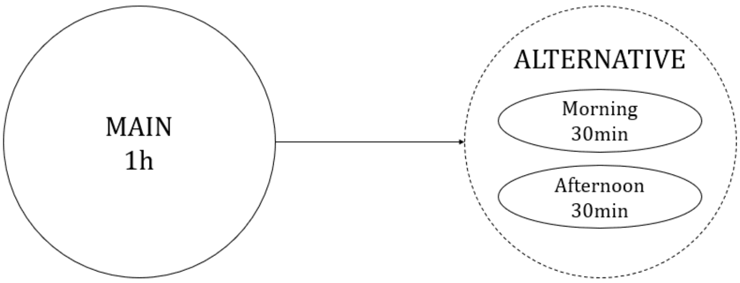


Figure 24 - Main and alternative requests

- To perform requests remotely, operators must be qualified with a specific skill,
- If a project includes requests that can be performed remotely, then the telepresence robot may be assigned to said project (patient),
- The maximum number of robots that can be assigned is defined,
- Remote requests must be served at the beginning of each shift by the operators from their own domicile,
- Requests that can be served remotely do not need co-presence of operators.

In addition to the already defined decisions, the following ones must be taken:

- Determine which of the patients will receive the TR,

- For each request that can be performed through the TR, decide if the *Main* request or the alternative request, composed with two interventions, will be performed,

- Determine the operators that will perform the requests through the TR and consequently determine their tour.

The following additional notation is introduced:

- $\tilde{P}$ set of projects that cannot be served through the TR,
- P' set of projects that can be served through the TR,
- $\tilde{R} \subseteq R$ set of service requests that cannot be performed through the TR,
- $R' \subseteq R$ set of service requests that can be performed through the TR (*Main* requests),
- $R'' \subseteq R$ set of service alternative requests performed through the TR,
- $R''_i \subseteq R''$set of corresponding alternative requests performed through the TR for each *Main* request $i \in R'$
- $O'_d \subseteq O$ set of operators available on day d, for each $d \in D$ able to perform services through the TR,
- π maximum number of telepresence robots assignable.

In addition to the variables defined in the nominal model, a new binary variable is introduced, to identify the patients to whom the TR is assigned:

$$\boldsymbol{f_p} = \begin{cases} 1 \; if \; telepresence \; robot \; is \; assigned \; to \; user \; p \\ 0 \; otherwise \end{cases} \quad p \in P'$$

The new version of the model can be defined as follows:

$$max \sum_{p \in P} g_p z_p - \sum_{d \in D} \sum_{o \in O} \sum_{s \in S} c_o \left(w_{e_o}^{ods} - w_{b_o}^{ods} \right) - \sum_{d \in D} \sum_{o \in O} \sum_{s \in S} \theta x_{ij}^{od} \tau_{ij}$$

$$\sum_{(b_o, j) \in A} x_{b_o j}^{od} = \sum_{s \in S} y^{ods} \quad \forall d \in D, \forall o \in O_d \qquad (2)$$

$$\sum_{(i,j) \in A} x_{ij}^{od} = \sum_{(j,i) \in A} x_{ji}^{od} \quad \forall j \in R, \forall d \in D, \forall o \in O_d \qquad (3)$$

$$\sum_{(i, e_o) \in A} x_{ie_o}^{od} = \sum_{s \in S} y^{ods} \quad \forall \, d \in D, \, \forall \, o \in O_d \qquad (4)$$

$$\sum_{(i,j) \in A} x_{ij}^{od} = u_i^o \quad \forall i \in R, \forall d \in D, \forall o \in O_{d,} \; s.t. \, d = d_i \qquad (5)$$

$$u_i^o \le z_p \, \forall p \in \tilde{P}, \forall i \in \tilde{R}, s.t. p_i = p, \forall o \in O_{d,} \, s.t. d = d_i \qquad (6)$$

$$\sum_{o \in O_d} u_i^o \ge q_i z_p \, \forall p \in \tilde{P}, \forall i \in \tilde{R}, s.t. p_i = p, d = d_i \qquad (7)$$

$$w_{b_o}^{odm} \ge 7y^{odm} \, \forall d \in D, \forall o \in O_d \qquad (8)$$

$$w_{e_o}^{odm} \le 11y^{odm} - y^{oda} + 1 \, \forall d \in D, \forall o \in O_d \qquad (9)$$

$$w_{b_o}^{oda} \ge 18y^{oda} + 2y^{odm} - 2 \, \forall d \in D, \forall o \in O_d \qquad (10)$$

$$w_{e_o}^{oda} \le 21.30y^{oda} \, \forall d \in D, \forall o \in O_d \qquad (11)$$

$$w_i^o + t_i + \tau_{ij} \le w_j^o + M\left(1 - x_{ij}^{od}\right) \, \forall d \in D, \forall o \in O_d, \forall i, j \in R, \, s.t. k_o = k_j = k_i, d = d_j = d_i \quad (12)$$

$$w_{b_o}^{ods} + \tau_{b_o j} \le w_j^o + M(1 - x_{b_o j}^{od}) \, \forall s \in S, \forall d \in D, \forall o \in O_d, \forall j \in R, s.t. k_o = k_j, d = d_j \quad (13)$$

$$w_i^o + t_i + \tau_{ie_o} \le w_{e_o}^{ods} + M(1 - x_{ie_o}^{od}) \, \forall d \in D, \forall o \in O_d, \forall i \in R, s.t. k_o = k_i, d = d_i \quad (14)$$

$$\alpha_i u_i^o \le w_i^o \le \beta_i u_i^o \, \forall i \in R, \forall o \in O_d, s.t. k_o = k_i, d = d_i \qquad (15)$$

$$\sum_{d \in D} \sum_{s \in S} (w_e^{ods} - w_{b_o}^{ods}) \le h_o \, \forall o \in O \qquad (16)$$

$$y^{ods} \le \sum_{i \in s, \, d = d_i} u_i^o \, \forall s \in S, \forall d \in D, \forall o \in O_d \qquad (17)$$

$$w_{b_o}^{ods} \le M \, y^{ods} \, \forall s \in S, \forall d \in D, \forall o \in O_d \qquad (18)$$

$$w_i^{o_1} \le w_i^{o_2} - M(u_i^{o_1} + u_i^{o_2} - 2) \, \forall i \in R, s.t. m_i = 2, \forall o_1, o_2 \in O_d, s.t. \, d = d_i, k_{o1} = k_{o2} = k_i \quad (19)$$

$$w_i^{o_1} \ge w_i^{o_2} + M(u_i^{o_1} + u_i^{o_2} - 2) \, \forall i \in R, s.t. m_i = 2, \forall o_1, o_2 \in O_d, s.t. \, d = d_i, k_{o1} = k_{o2} = k_i \quad (20)$$

$$w_{e_o}^{ods} - w_{e_o}^{ods} \ge \sum_{i \in s, \, d = d_i} t_i u_i^o \, \forall s \in S, \forall d \in D, \forall o \in O_d \qquad (21)$$

$$\sum_{o \in O'_d, \, d = d_i} (u_i^o + u_{i'}^o) = z_p \, \forall p \in P', \forall i \in R', \forall i' \in R''_{i}, \, s.t. p_{i'} = p_i = p_o \qquad (22)$$

$$\sum_{o \in O'_d, \, d = d_i} u_{i'}^o = \sum_{o \in O'_d, \, d = d_i} u_{i''}^o \qquad \forall i', i'' \in R''_i, \forall i \in R' \qquad (23)$$

$$w_{i'}^{o} + t_{i'}u_{i'}^{o} + \tau_{b_o j}\, x_{i'j}^{od} \geq w_j^{o} \quad \forall\, d \in D, \forall\, o \in O'_d\,, s.t.\, d = d_j = d_{i'}, \forall\, i' \in R'', \forall\, j \in \tilde{R} \qquad (24)$$

$$\sum_{p \in P} f_p \leq \pi \qquad (25)$$

$$2n_p f_p \geq \sum_{o \in O'_d,\; d = d_{i'}} \sum_{i' \in R'',\; p_{i'} = p} u_{i'}^{o} \quad \forall\, p \in P' \qquad (26)$$

$$f_p \leq z_p \;\; \forall\, p \in P' \qquad (27)$$

$$f_p \leq \sum_{o \in O'_d,\; d = d_{i'}} \sum_{i' \in R'',\; p_{i'} = p} u_{i'}^{o} \quad \forall\, p \in P' \qquad (28)$$

$$z_p \in \{0\,, 1\} \quad \forall\, p \in P \qquad (29)$$

$$r_p \in \{0,1\} \quad \forall\, p \in P' \qquad (30)$$

$$x_{ij}^{od} \in \{0\,, 1\} \quad \forall\, (i,j) \in A, \forall\, d \in D, \forall\, o \in O_d \qquad (31)$$

$$y^{ods} \in \{0\,, 1\} \quad \forall\, s \in S, \forall\, d \in D, \forall\, o \in O_d \qquad (32)$$

$$u_i^{o} \in \{0\,, 1\} \quad \forall i \in R\;, \forall\, o \in O_d\,, d = d_i \qquad (33)$$

$$w_i^{o} \geq 0 \quad \forall i \in R\;, \forall\, o \in O_d\,, d = d_i \qquad (34)$$

$$w_i^{ods} \geq 0 \quad \forall\, s \in S, \forall\, d \in D, \forall\, o \in O_d, \forall i \in \{b_o, e_o\} \qquad (35)$$

A brief description of the additional or differential constraints with respect to the nominal model will follow:

- Constraints (6)-(7) are limited in this case only to projects that cannot be performed through the TR,

- Constraints (22) impose the choice between delivering the service through the *Main* request or its remote alternative,

- Constraints (23) guarantee that if the alternative service is selected, both requests (Morning and Afternoon) are scheduled,

- Constraints (24) guarantee that requests delivered through TR are performed at the beginning of the shift (dependency within routes),

- Constraint (25) guarantees that a maximum of π TR can be assigned,
- Constraints (26) guarantee that, if the TR is not assigned to a patient, none of their requests can be performed remotely,
- Constraints (27) impose that only accepted projects may be served through TR,
- Constraints (28) impose that the TR may be assigned only to projects for which at least one request is served remotely,
- Constraint (30) defines the domain of the new variable.

6.3 Implementation and preliminary results

The nominal and the new formulations of the model were coded in Python-Pyomo using Spyder IDE and solved using CPLEX 20.1, on a PC equipped with a CPU Intel(R) CORE (TM) i7-7500U CPU @2.70GHz and 8.0 GB of RAM.

Both models have been tested on instances structured on real data derived from the *Pane e Rose* database. The dimensions of the instances were limited to the computational capacity of the device employed and the selection of projects and operators for the instances was random. The optimality gap was set at 1%.

In particular, the models have been tested on instances with a fixed number of operators, equal to 3, and on a growing number of patients, from 3 to 8. Given the limited dimensions of the instances, the maximum number of robots assignable (π) was set to 2.

Table 28 reports details of the instances tested:

Instance	Number operators	Number patients	Total service hours [h]	Number of patients that can be served through TR	% Service hours that can be performed through TR
1	3	3	18	3	100%
2	3	4	23	3	78%
3	3	5	29	4	83%
4	3	6	33,5	4	72%
5	3	7	38,5	5	75%
6	3	8	43,75	5	66%

Table 28 - Instances details

The model proved to be extremely sensitive to small increases of instance dimensions, with a significant variation of computational time for the identification of the optimal solution. The following table reports computational times needed for the identification of the optimal solution for the two models, with varying number of patients considered:

Number of patients	Computational time	
	Nominal Model	Model with TR
3	0,64 sec	6,61 sec
4	0,84 sec	11,02 sec
5	3,88 sec	342,45 sec
6	99,31 sec	4,87 h
7	4,27 h	6,31 h
8	6,76 h	10,53 h

Table 29 - Computational time

Similarly, the number of variables and constraints significantly increases with the number of patients, as shown in Table 30:

Number of patients	Number of variables		Number of Constraints	
	Nominal Model	Model with TR	Nominal Model	Model with TR
3	363	966	649	1.459
4	415	1.039	478	1.585
5	560	1.530	952	2.217
6	741	1.777	1.192	2.584
7	844	2.253	1.334	3.190
8	1.077	2.571	1.643	3.659

Table 30 - Number of variables and constraints

With respect to the objective function and the number of projects accepted for each instance, as shown in Table 31, the new model always grants a higher value of the objective function and an equal or greater number of projects accepted:

Number of patients	Objective function		Projects accepted	
	Nominal Model	Model with TR	Nominal Model	Model with TR
3	21,22	59,74	2	3
4	32,70	73,32	3	4
5	52,56	86,03	5	5
6	70,16	102,86	6	6
7	80,47	114,09	7	7
8	94,01	128,29	8	8

Table 31 - Objective function and number of projects accepted

From the previous table, we can see how the nominal model, in the first two instances where the number of users is very limited, does not accept all projects. In fact, accepting all projects would grant a lower value of the objective function. This is related to the structure of both the network and the projects, but also to the low margins that social cooperatives have. When introducing a higher number of patients, the acceptance of all projects becomes convenient even in the nominal model.

The following table reports details on the assignment of the device and of the number of service hours performed remotely:

Number of patients	Patients served through TR	Total service hours [h]	Service hours performed through TR [h]	% Service hours performed through TR
3	Patient 1, Patient 2	18	11	61%
4	Patient 2, Patient 3	23	14	61%
5	Patient 2, Patient 5	29	13	45%
6	Patient 2, Patient 3	33,5	14	42%
7	Patient 2, Patient 3	38,5	14	36%
8	Patient 2, Patient 7	43,75	12	27%

Table 32 - Device assignment

The following table reports details of the objective function, pointing out the effective revenue deriving from the accepted projects, and the costs of human resources and transportation costs:

Number of patients	Nominal Model			Model with TR		
	Revenue	Costs	Costs/ Revenue	Revenue	Costs	Costs/ Revenue
3	215,6	194,38	90%	352,8	293,06	83%
4	313,6	280,9	90%	450,8	377,48	84%
5	568,4	515,84	91%	568,4	482,37	85%
6	656,6	586,44	89%	656,6	553,74	84%
7	754,6	674,16	89%	754,6	639,7	84%
8	857,5	763,49	89%	857,5	729,21	85%

Table 33 - Objective function: details

As shown in Figure 25, the model with the TR always grants an increase of the objective function with respect to the nominal one, and the variation is nearly homogeneous between instances:

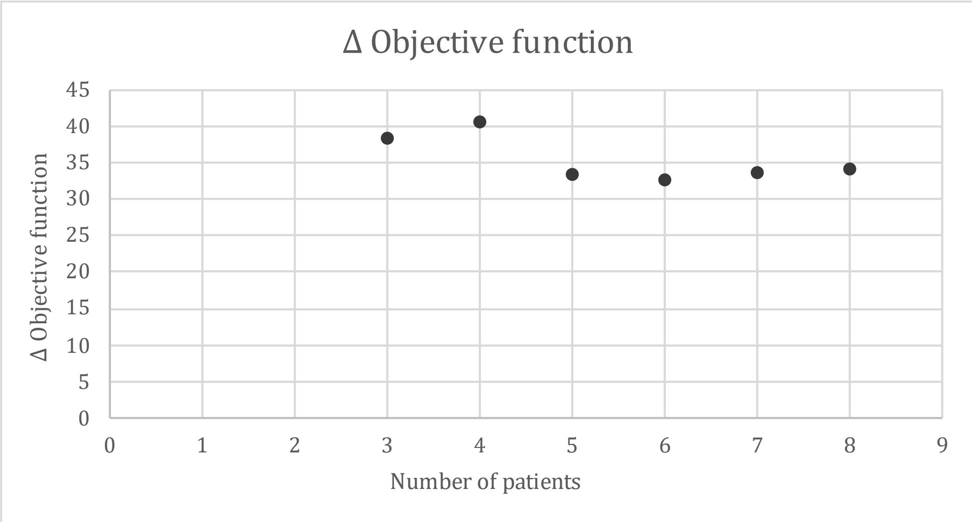


Figure 25 - Δ Objective function

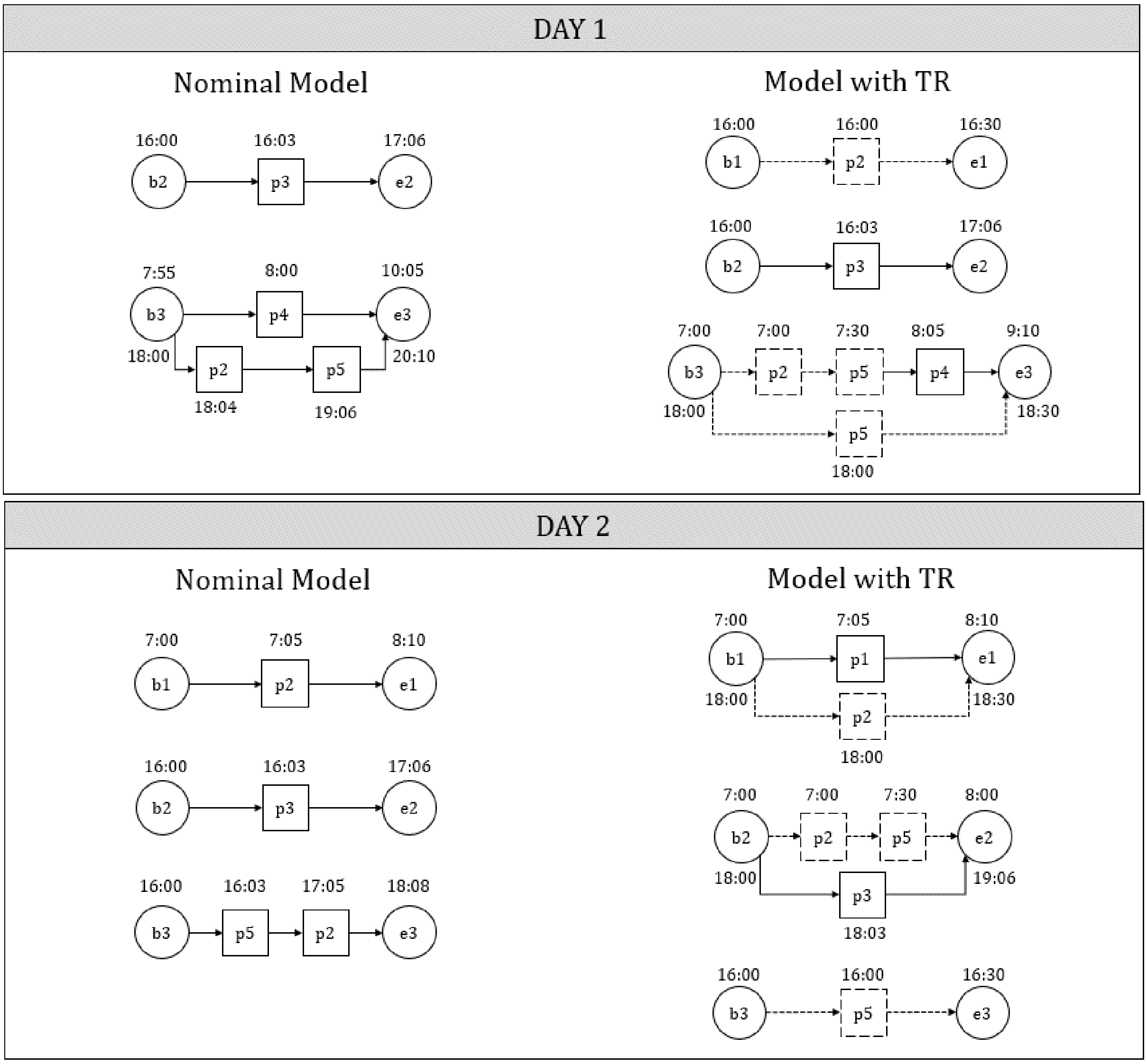
The following table summarizes the percentage increase of the objective function for the nominal model, obtained in each instance with the introduction of the device. The first two instances grant a greater increase due to the acceptance of a higher number of projects with respect to the nominal model. As for the others, the increase of the objective function is only related to a reduction of costs.

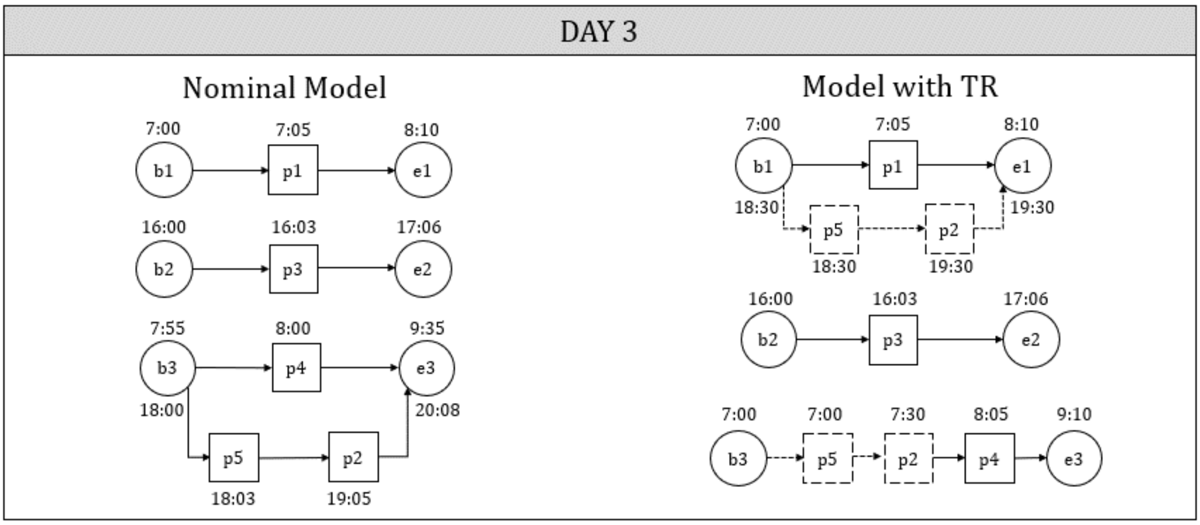
Number of patients	**% Increase objective function**
3	+ 182%
4	+ 124%
5	+ 64%
6	+ 47%
7	+42%
8	+36%

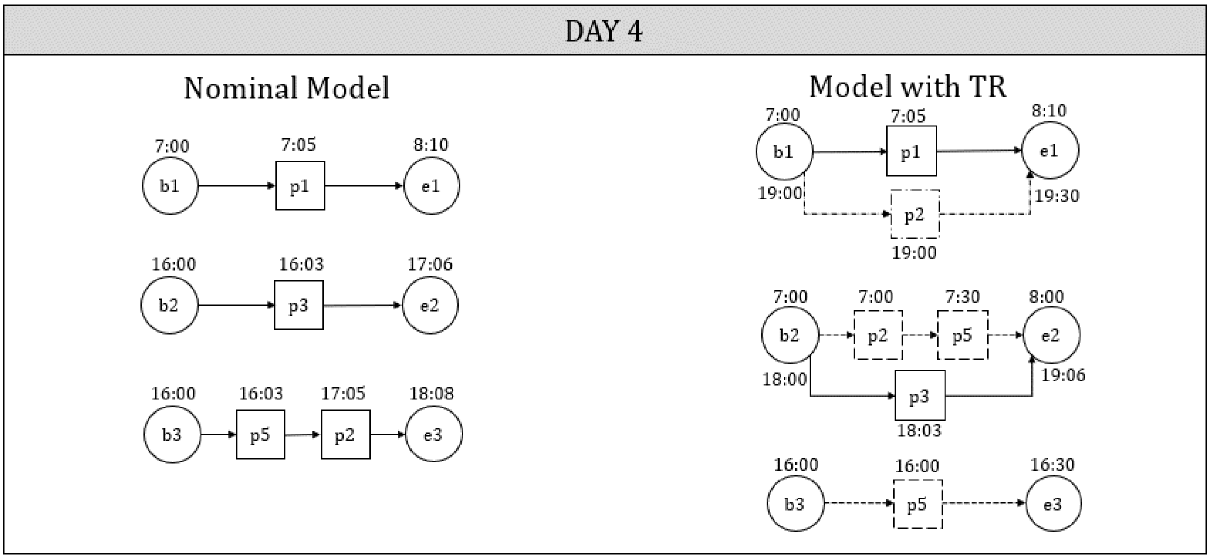
Table 34 - % Increase objective function

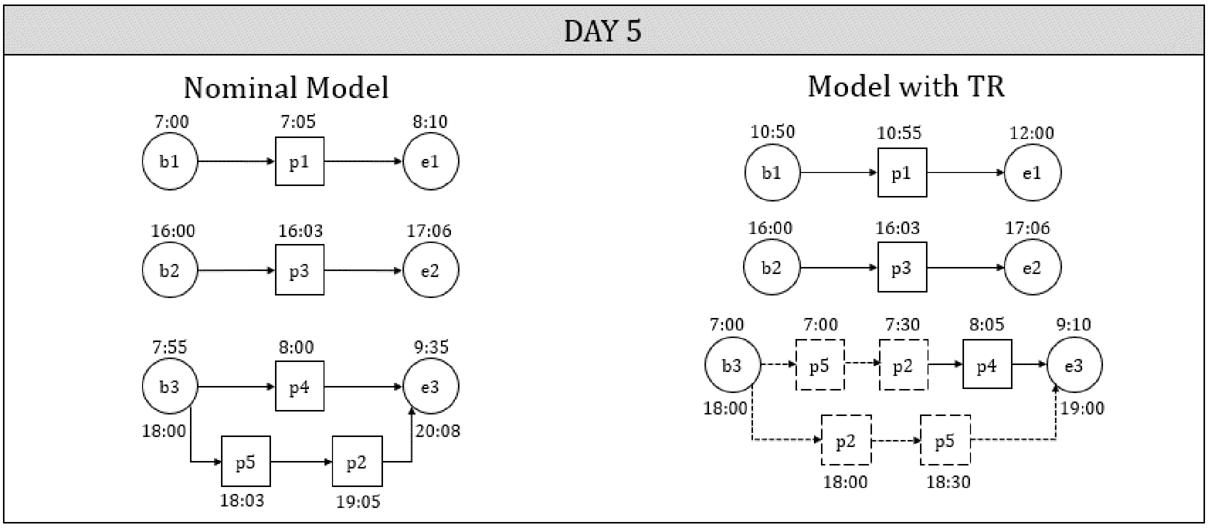
The following figure reports the graphical representation of the optimal solution identified by both models with instance number 3 (3 operators, 5 patients). In particular, the nodes representing the operators' homes are depicted as circles (*b1,e1*, *b2*, *e1*, *b3*, *e3*), while patients are represented by squares (*p1*, *p2*, *p3*, *p4*, *p5*).

As for the formulation of the model with robot introduction, requests performed remotely are represented with dashed lines. The figure reports the results of the scheduling for all seven days of the week and for both models:


DAY 1
Nominal Model
Model with TR
DAY 2
Nominal Model
Model with TR


DAY 3
Nominal Model
7:00
7:05
8:10
b1
p1
e1
16:00
16:03
17:06
b2
p3
e2
7:55
8:00
9:35
b3
p4
e3
18:00
20:08
p5
p2
18:03
19:05
Model with TR
7:00
7:05
8:10
b1
p1
e1
18:30
19:30
p5
p2
18:30
19:30
16:00
16:03
17:06
b2
p3
e2
7:00
7:00
7:30
8:05
9:10
b3
p5
p2
p4
e3


DAY 4
Nominal Model
7:00
7:05
8:10
b1
p1
e1
16:00
16:03
17:06
b2
p3
e2
16:00
16:03
17:05
18:08
b3
p5
p2
e3
Model with TR
7:00
7:05
8:10
b1
p1
e1
19:00
19:30
p2
19:00
7:00
7:00
7:30
8:00
b2
p2
p5
e2
18:00
19:06
p3
18:03
16:00
16:00
16:30
b3
p5
e3


DAY 5
Nominal Model
7:00
7:05
8:10
b1
p1
e1
16:00
16:03
17:06
b2
p3
e2
7:55
8:00
9:35
b3
p4
e3
18:00
20:08
p5
p2
18:03
19:05
Model with TR
10:50
10:55
12:00
b1
p1
e1
16:00
16:03
17:06
b2
p3
e2
7:00
7:00
7:30
8:05
9:10
b3
p5
p2
p4
e3
18:00
19:00
p2
p5
18:00
18:30

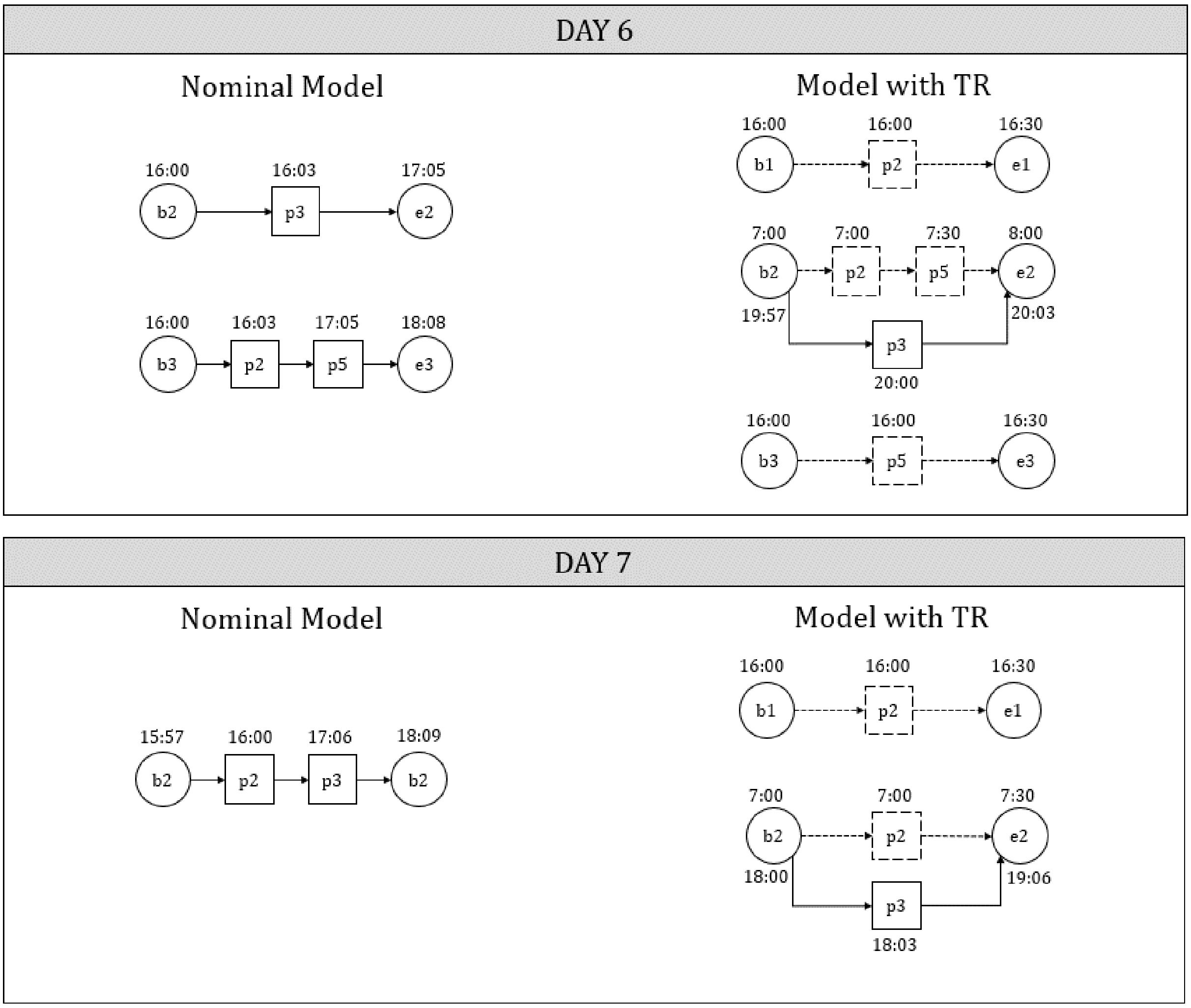


Figure 26 - Results instance 3

The results demonstrate that the model can identify the optimal schedule of home care services considering the introduction of the telepresence robot. It is able of identifying the optimal set of patients to serve remotely and for each of these decide which of the requests to perform through the device. The results also show that even with small-sized instances, the introduction of the device leads to reduced operational costs and to the increase of intervention frequency for the patients served remotely. This cost saving, on a full-scale instance, should be compared with the additional costs related to the introduction of the robots.

7 Conclusions

7.1 Implications for theory

The present work proposed a novel methodological approach to Early HTA problems when the alternatives to be assessed are not clear at the beginning of the analysis. It also introduced a novel model for the scheduling of home care services considering the possibility of delivering some of these using a telepresence robot.

The traditional Early HTA approaches normally require a clear and comprehensive definition of the alternatives to be assessed before undertaking the analysis. For the decision problem object of this study, the alternatives represented the potential service delivery modes enabled by the introduction of a telepresence robot within home care services. Decision-makers did not have an explicit understanding of these, for this reason, it was necessary to expand the classical approaches to Early HTA to the generation of the alternatives. Multi-Criteria Decision Analysis was selected as the more suitable approach to the decision problem, and it was extended to incorporate phases of alternatives structuring. The definition of the alternatives was based on the identification of the value aspects and relied on the adoption of user-friendly tools like Mind Maps, Strategy Tables, and the Business Model Canvas. The involvement of experts of the field was fundamental for the success of the process. The method was assessed with participants and with a group of researchers involved in the *PHArA-ON* project proving to be robust and reliable.

With reference to the model for the scheduling of home care services, a novel adaptation of the classical HHCRSP was presented. The proposed model is meant to support decision-makers in the identification of the optimal set of patients to which to assign the robot, and to consequently schedule services. This model represents an original contribution in the home care literature, which to date, to the best of my knowledge has not yet addressed the problem of simultaneously scheduling both in-person and remote visits.

7.2 Implications for practice

A complete Multi-Criteria Decision Analysis was performed through the MACBETH approach to support decision-makers in the identification of the best mode for delivering part of their home care services. The process allowed to structure the new service delivery modes enabled by technology introduction, both for the private and public context. For the public one, the analysis allowed to identify the one that could bring the higher value to all stakeholders involved. The results of the assessment gathered approval both by participants and researchers of the *PHArA-ON* project. The evidence of the assessment could support the cooperatives in the first phases of an effective introduction of the device in their services and assist them in the future negotiations with the public contracting authority.

The optimization model for home care services, although with computational limitations, allows to identify the optimal set of patients for remote care and to optimally schedule home care services accordingly with the new framework.

8 Limitations and future research

The methodological approach proposed, when implemented for the decision problem under study, successfully identified the alternatives and allowed for their comparison through the MACBETH method. This approach, which involves the definition of the alternatives within the Multi-Criteria Decision Analysis process, requires further testing in other decision scenarios.

The optimization model demonstrated sensitivity to the dimensions of the instances tested, leading to computational limitations. To effectively apply it to real-sized problems, improving its computational efficiency is necessary e.g., through the introduction of valid inequalities or metaheuristics. Once the computational challenges are resolved, expanding the experimental campaign is essential to gain insights from real-sized instances. With these developments, the model may support the cooperatives in the transitional phases following technology introduction and eventually relieve the dispatching resources from the burden of scheduling services when dealing with a high number of patients.

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Appendix

Appendix A. The MACBETH approach

MACBETH (Measuring Attractiveness by a Category-Based Evaluation Technique) is a decision-aid approach to multi-criteria value measurement. This approach has been developed to allow measurement of attractiveness of options through a non-numerical pairwise comparison [11].

In this technique, the decision-makers need to compare two alternatives at a time with qualitative judgments about their difference in attractiveness based on a pre-defined semantic judgment scale. This method not only provides the facility to check consistency of the decision-maker's judgements but also suggests improvements in the judgments if they are found to be inconsistent. The qualitative judgments are then transformed into a suitable numerical scale, identified as the MACBETH scale. Finally, the weighted global scores representing the overall attractiveness of the considered alternatives are computed using an additive aggregation model to rank the alternatives. This method is supported by M-MACBETH software, developed using an algorithm based on linear programming models. [64]

As described by Bana E Costa *et al*. [10], the main steps to be followed when applying the MACBETH approach to MCDA are:

1. Characterization of the decision context,
2. Definition of screening and evaluation criteria,
3. Construction of a descriptor of impacts for each evaluation criterion,
4. Determination of relative weights,
5. Impact appraisal and partial evaluation of the options,
6. Calculation of the overall value of each option,
7. Sensitivity and robustness analyses of the results.

Characterization of the decision context

The first important step in structuring the analysis, is to correctly define the decision problem. Boundaries, objectives, outputs, and inputs must be defined. All available information needs to be collected and actors involved in the decision process must be selected.

Definition of screening and evaluation criteria

Once the context is clearly defined, the analysis can start with the identification of the areas of concern by understanding what of the current solution is not satisfactory. Then, screening and evaluation criteria need to be discussed. Screening criteria represent the deliberate intention to make options comply with thresholds of admissibility. These criteria will allow to exclude possible alternatives. On the other hand, evaluation criteria are relevant elements for the analysis or attributes that need to be considered when selecting the best option. Each evaluation criterion should be an independent axis of comparative evaluation. The set of evaluation criteria should be as concise as possible avoiding redundancy. Several levels of specification may be considered in defining the evaluation criteria; in these cases, it is useful to represent the criteria and sub-criteria in a tree structure. Usually, value trees are used to give a visual overview of the structure of the concerns in several levels of increasing specification.

Construction of a descriptor of impacts for each evaluation criterion

To make a criterion (or sub-criterion) operational for alternatives evaluation, a descriptor of impacts needs to be associated with it. By definition, a descriptor is an ordered set of (quantitative or qualitative) plausible impact levels. Depending on the context, an evaluation criterion can be operationalized by a natural or direct, proxy or indirect, or a constructed descriptor. When possible, natural descriptors are an appropriate choice as they are objective and don't cause ambiguity. Indirect descriptors, on the other hand, may not be directly related to the key concern, and their levels usually indicate causes more than effects. Finally, constructed descriptors are defined as a combination of several indicators.

A descriptor of impacts is an ordered set of plausible impact levels associated with a key concern. It is intended to [11] :

- Operationalize the appraisal of impacts (performances or consequences) of options in a key concern, that is to measure (quantitatively or qualitatively) the degree to which the key concern is satisfied.
- Describe, as much as possible objectively, the impacts of options with respect to that key concern.
- Better frame the evaluation model, by restricting, whenever appropriate, the range of impact levels to a plausibility domain.
- Verify the ordinal independence of the corresponding key-concern. If dependence is detected in this phase, feedback is necessary to re-structure the family of key-concerns, so that "all other things being equal" comparisons of options may be made individually against each key-concern.

To define the descriptors, it is necessary to set two reference levels of intrinsic value for each criterion that operationalize the idea of a good option and a neutral option (that is, neither attractive nor repulsive): the *Good* and *Neutral* levels. Other levels can then be defined to cover the plausible impact range. For each criterion, this performance scale is converted to a value scale by means of qualitative judgements of differences in attractiveness between performance levels, two at a time (e.g., "From *Neutral* to *Good*"). To facilitate each pairwise comparison the decision-makers are asked to choose one of the MACBETH qualitative categories of difference in attractiveness: "Null", "Very Weak", "Weak", "Moderate", "Strong", "Very Strong", Or "Extreme" (Table 35) [64]. Successively a value function is constructed upon the defined descriptor of performances and is used to transform each option performance into a value score.

Semantic scale	Equivalent numeric scale	Meaning
Null	0	Indifference between alternatives
Very Weak	1	An alternative is very weakly attractive over another
Weak	2	An alternative is weakly attractive over another
Moderate	3	An alternative is moderately attractive over another
Strong	4	An alternative is strongly attractive over another
Very Strong	5	An alternative is very strongly attractive over another
Extreme	6	An alternative is extremely attractive over another

Table 35 - Semantic and numeric scales

Determination of relative weights

The next step involves assigning a value of relative importance to each of the selected criteria. When criteria are defined on more than one level (sub-criteria), it is necessary to apply a hierarchic model for weight evaluation. In the MACBETH approach the overall value is assessed through an additive model that aggregates partial values. If sub-criteria are present, the procedure is applied firstly for each group of sub-criteria sharing the same parent criterion, and then to the macro-categories. To determine the weights of sub-criteria, decision-makers are asked to rank them for each macro-category based on the attractiveness of the "*Neutral* to *Good*" swings. Once criteria are ranked within a macro-category, the attractiveness of "*Neutral* to *Good*" swings is assessed by comparing criteria pairwise. This process allows to determine the relative weight of elements within macro-categories. Then, the weights of parent criteria must be determined. To do so, two approaches can be followed. The first compares the swing of all sub-criteria of the same parent criteria with the swing of all sub-criteria of another parent criteria. The relative importance is defined, and the weights of sub-criteria are normalized based on their internal relative importance. The other approach selects only one sub-criteria for each parent criterion and compares their swings pairwise. The value obtained is used to normalize the relative weights of all sub-criteria.

Impact appraisal and partial evaluation of the options

In this phase, the performances of the selected options in each criterion need to be assessed. To do so, stakeholders need to be questioned about each alternative's behavior in each criterion and asked to consequently assign a level of performance defined in the descriptors. The value functions convert the option's impact of an evaluation criterion into a score that measures its value on that evaluation criterion, that is, a relative value score [12].

Calculation of the overall value of each option

The relative value scores are then combined with the previously determined weights to obtain an overall value of each option. An additive aggregation model is used:

$$V(o) = \sum_{j=1}^{J} w_j s_j(o)$$

with:

$$\sum_{j=1}^{J} w_j = 1$$

and:

$$w_j = w_{r\_j} * w_{mc\_j}$$

where:

- j=1,…,J indicates the criterion,
- o=1,…,O indicates the alternative options,
- $s_j(o)$ represents the score of alternative b in criterion j,
- w_j is the overall weight of criterion j, corresponding to the product of the relative weight of criterion j within its reference macro-category (w_{r_j}) and the weight of the macro-category (w_{mc_j}),
- $V(o)$ is the overall value of option o.

The cost of the alternatives can be both considered as a criterion or assessed separately and compared to benefits. Following the second approach, the analysis will characterize each option with its value and its costs.

Sensitivity and robustness analyses of the results

As pointed out by C. Bana e Costa *et al.* [13], decision-making processes often involve imprecise data and uncertain information. M-MACBETH incorporates visual interactive tools to develop extensive sensitivity and robustness analyses to address the different types of uncertainty phenomena that can affect the results of the model. Sensitivity analysis is widely used in decision analysis and is limited to the effects on the overall desirability scores caused by varying only one type of parameter in the model at a time, either a single-objective score or a weight. Dealing with the two types simultaneously requires a robustness analysis, which can be operationally defined as an extension of classical sensitivity analysis to allow for simultaneous variations of several model parameters. There are various types of robustness analyses, and to carry out meaningful robustness analysis, it must be made clear which unknown quantities and parameters are to be considered for the analysis, and what the variation or uncertainty is reflecting. In M-MACBETH, robustness analysis is developed on the concept of "additive dominance". An option additively dominates another option if it is always found to be more desirable than the other, that is, the difference between the multi-criteria desirability scores of the former and the latter given by the model is always positive, under some constraints to the variation of input data under different scenarios.

In conclusion, we report that MACBETH has been applied in many different contexts with very different purposes.

For example, C. Bana e Costa *et al*. applied MACBETH for auditing a Predictive Maintenance Program [9]. O. E. Demesouka *et al*. [37] apply MACBETH to GIS-based raster-driven suitability analysis. In the context of healthcare, examples of MACBETH method application can be found in the works of J.M. Hummel *et al*. [57], where MACBETH is used to perform an MCDA to select a portfolio of robotic innovations for minimal invasive surgical interventions, and of R. Cox *et al*. [33] where MACBETH is used to prioritize emerging or re-emerging infectious diseases associated with climate change in Canada.

Appendix B. Costs evaluation

For the evaluation of the annual differential cost of each alternative, data were collected from previous assessments and from the cooperative selected as a case study. In addition, some assumptions were made with validation by the decision-makers involved in the analysis.

In particular, the following hypotheses were made:

1. Costs and revenues do not change in the 4 years of time-horizon considered.

2. The number of patients to serve every year for monitoring and social support services through the telepresence robot is 15. This number was determined based on historical data.

3. The duration of robot's stay at one patient's home is of four months. This duration was identified during the meetings as the most suitable.

4. To cover the yearly demand, it is necessary to purchase 5 *Ohmni Robots*. As stated by the interviewed stakeholders, the cooperative would not need to resort to loans to cover the initial investment.

5. The number of weekly hours of monitoring and social support services for each patient is on average four hours. When performed remotely, the four hours are distributed as slots of 30 minutes in the morning and 30 minutes in the afternoon for four days a week.

6. 40% of patients have a project that only involves monitoring and social support services. As agreed during the meetings, if the robot is assigned to these patients, it is necessary to plan an intervention onsite of the operator of 30 minutes a week.

7. Training costs for operators correspond to one hour of training to be completed before the introduction of the new service. Since the value of this cost is not significant and the expense must be incurred only once, it was agreed to exclude it from the calculation of the overall cost. It is also assumed that the current available human resources are capable of performing the services through the telepresence robot after one hour of training.

8. The installation of the device at the patient's home is a very simple task and can be performed in one hour by the operator. The cost of this activity is recorded as the hourly rate of the operator.

9. Training for patients and their informal caregiver is performed by the operator at the moment of the installation of the device at the patient's home and has a duration of one hour for each patient. These costs are recorded as the hourly rate of operators.

10. The telepresence services are performed by the operator from their domicile using their internet connection. The cooperative has not additional costs for spaces and energy for the delivery of remote services.

11. The cooperative must provide the patient with a router for internet connection if they don't already own it. As a worst-case scenario, it is assumed that none of the patients to be served yearly owns the router. Once the device is removed from one patient's home, the ownership of the router is retained by the cooperative.

12. The cooperative must cover the costs for internet connection for each patient.

13. With the introduction of the accreditation framework the cooperative will invest in an advertising campaign for the promotion of its services to both public and private patients. Since this investment would take place in each of the future scenarios (even if the current service delivery mode is maintained), it would not be a differential cost between options.

14. A monthly insurance must be paid for each device.

15. The acquisition cost of the robots, the routers, the software development and installation costs are covered with a depreciation over a period of four years. Even though software development costs are typically depreciated over five years, their functioning is strictly related to the hardware. Therefore, it was decided to consider the hardware and software as a single system and depreciate them accordingly.

16. The introduction of the telepresence robot allows to reduce travel time for operators. The saved time is hypothesized to be allocated to other home care activities.

The following table summarizes information for costs calculation:

		(A)	(B)	(C)
1	Number of patients to serve yearly	15	15	15
2	Duration of robot's stay at one patient's home [months]	-	4	4
3	Number of robots to purchase	-	5	5
4	Robot purchase cost [€/unit]	-	3000	3600
5	Router purchase cost [€/unit]	-	70	70
6	Total cost for robot and router purchase [€]	-	15350	18350
7	Depreciation rate (hardware)	-	0,25	0,25
8	**Annual total cost for robot and router purchase [€]**	**-**	**3838**	**4588**
9	Monthly fee for internet connection [€/month per unit]	-	15	15
10	**Annual total cost for internet connection**	**-**	**900**	**900**
11	Annual cost for technical assistance [€/unit]	-	300	300
12	**Annual total cost for technical assistance [€]**	**-**	**1500**	**1500**
13	Monthly cost for device insurance[€/unit]	-	180	180
14	**Annual total cost for device insurance [€]**	**-**	**900**	**900**
15	Operator hourly rate [€/h]	15,68	15,68	15,68
16	Training time per patient [h/patient]	-	1	1
17	**Annual total cost for patient training [€]**	**-**	**235,2**	**235,2**
18	Robot installation time [h/patient]	-	1	1
19	**Annual total cost for robot installation [€]**	**-**	**235,2**	**235,2**
20	Software development cost [€]	-	-	4700
21	Software installation cost [€]	-	-	450
22	Depreciation rate (software)	-	-	0,25
23	**Annual cost software development and installation [€]**	**-**	**-**	**1288**
24	Revenue per hour of service [€/h]	-	-	19,60
25	Weekly hours of service per patient [h/patient]	4	4	4
26	Total weekly hours of service [h]	20	20	20
27	Total annual hours of service [h]	1040	1040	1040
28	Percentage patients with only monitoring and social support services [%]	40	40	40
29	Weekly hours of services to be performed on site [h]	20	0,8	0,8
30	Reimbursement of travel costs [€/km]	0,44	0,44	0,44
31	Average distance traveled per service hour [km/h]	2,14	2,14	2,14
32	Annual total time spent on travel [h]	44,51	2,23	2,23
33	Annual gained added value time [h]	-	40,48	40,48
34	**Annual additional revenue [€]**	**-**	**793,4**	**793,4**
35	**Annual cost for reimbursement of travel costs [€]**	**979,26**	**50,66**	**50,66**
36	**Annual cost for time spent by operators in travel [€]**	**697,95**	**63,28**	**63,28**
37	**TOTAL (8+10+12+14+17+19+23-34+35+36)**	**1677,2**	**6928,5**	**8966,0**
38	**Δ TOTAL**	**-**	**5251,3**	**7288,8**

Table 36 - Costs evaluation

Appendix C. Net Present Value

In this appendix details about the calculation of the Net Present Value will be given.

It was decided to assess the NPV over four years, coherently with the number of years selected for the depreciation of the device. It was hypothesized that at the end of the fourth year each robot will be sold to a different patient at the 15% of the acquisition price. The initial value of the discount rate (i) was set to 5%:

$$NPV = \sum_{t=0}^{n} \frac{FCCF_t}{(1+i)^t}$$

Where:

- $FCCF_t$ = Free Cash Flow to the Firm in period t,
- i = discount rate,
- t = number of time periods.

The following table summarize information for NPV calculation in the two scenarios enabled by the introduction of the device:

Robot_Base (A)					
Year		**1**	**2**	**3**	**4**
a. Differential revenues	0	793,3	793,3	793,3	793,3
b. Depreciation expense	0	3.837,5	3.837,5	3.837,5	3.837,5
c. Other differential operational costs	0	2.841,8	2.841,8	2.841,8	2.841,8
d. Differential operational costs (b + c)	0	6.679,3	6.679,3	6.679,3	6.679,3
e. Differential operating result (a - d)	0	-5.886,0	-5.886,0	-5.886,0	-5.886,0
f. Differential extraordinary result	0	0	0	0	2.250,0
g. Differential Operating + Extraordinary result (e + f)	0	-5.886,0	-5.886,0	-5.886,0	-3.636,0
h. Differential theoretical taxes	0	-2.354,4	-2.354,4	-2.354,4	-1.454,4
i. Differential Operating + Extraordinary Net Result (g - h)	0	-3.531,6	-3.531,6	-3.531,6	-2.181,6
j. - ΔCCNO	0	0	0	0	0
k. Cash flow for investments	-15.350,0	0	0	0	2.250,0
l. **$FCCF_t$ (i - f + b - j + k)**	**-15.350,0**	**305,9**	**305,9**	**305,9**	**1.655,9**

Table 37 - $FCCF_t$ calculation, Robot_Base

Robot_Plus (B)					
Year		**1**	**2**	**3**	**4**
m. Differential revenues	0	793,3	793,3	793,3	793,3
n. Depreciation expense	0	5.875,0	5.875,0	5.875,0	5.875,0
o. Other differential operational costs	0	2.841,8	2.841,8	2.841,8	2.841,8
p. Differential operational costs (b + c)	0	8.716,8	8.716,8	8.716,8	8.716,8
q. Differential operating result (a - d)	0	-7.923,5	-7.923,5	-7.923,5	-7.923,5
r. Differential extraordinary result	0	0	0	0	2.700
s. Differential Operating + Extraordinary result (e + f)	0	-7.923,5	-7.923,5	-7.923,5	-5.223,5
t. Differential theoretical taxes	0	-3.169,4	-3.169,4	-3.169,4	-2.089,4
u. Differential Operating + Extraordinary Net Result (g - h)	0	-4.754,1	-4.754,1	-4.754,1	-3.134,1
v. - ΔCCNO	0	0	0	0	0
w. Cash flow for investments	-23.500,0	0	0	0	2700
x. **$FCCF_t$ (i - f + b - j + k)**	**-23.500,0**	**1.120,9**	**1.120,9**	**1.120,9**	**2.740,9**

Table 38 - $FCCF_t$ calculation, Robot_Plus

The following table reports the sensitivity analysis performed on the discount rate (from 1% to 10%) maintaining the same parameters of weekly service hours and kilometers of travel for service hour:

	NPV	
Discount Rate	**(B) *Robot_Base***	**(C) *Robot_Plus***
1%	-€ 12.858,98	-€ 17.569,41
2%	-€ 12.937,94	-€ 17.735,20
3%	-€ 13.013,40	-€ 17.894,07
4%	-€ 13.085,55	-€ 18.046,39
5%	-€ 13.154,57	-€ 18.192,49
6%	-€ 13.220,62	-€ 18.332,69
7%	-€ 13.283,87	-€ 18.467,31
8%	-€ 13.344,46	-€ 18.596,62
9%	-€ 13.402,52	-€ 18.720,88
10%	-€ 13.458,20	-€ 18.840,35

Table 39 – NPV, discount rate sensitivity

Appendix D. Script Nominal Model

```
import pyomo
from pyomo.environ import (AbstractModel, Any, maximize, minimize, Set, Var, Constraint,
Objective, Param, Binary, NonNegativeReals, SolverFactory, value)
import sys
import os
from openpyxl import Workbook, load_workbook
import pandas as pd
import numpy as np
import itertools as it
import linecache
import math
from datetime import datetime

def Redirect(filename, mode='w'):
    old_stdout, old_stderr = sys.stdout, sys.stderr
    with open(filename, mode) as f:
        sys.stdout, sys.stderr = f, f
        yield
    sys.stdout, sys.stderr = old_stdout, old_stderr

class Redirect:
    def __init__(self, filename, mode='w'):
        self.filename = filename
        self.mode = mode
        self.old_stdout = None
        self.old_stderr = None
    def __enter__(self):
        self.old_stdout = sys.stdout
        self.old_stderr = sys.stderr
        self.file = open(self.filename, self.mode)
        sys.stdout = self.file
        sys.stderr = self.file
        return self
    def __exit__(self, exc_type, exc_value, traceback):
        sys.stdout = self.old_stdout
        sys.stderr = self.old_stderr
        if self.file:
            self.file.close()

filename="Nominal.txt"
nProjects = int(linecache.getline(filename, 1))
nOperators = int(linecache.getline(filename, 2))
nSkills= int(linecache.getline(filename, 3))
nDays = int(linecache.getline(filename, 4))
nRequests = int(linecache.getline(filename, 5))

dctOperatorsSkills={}
dctSkillsOperators={}
dctOperatorsDays={}
dctOperatorsHCost={}
dctOperatorsMaxHours={}
dctProjectRevenue={}
dctProjectNRequests={}
```

```
dctRequestsAttributes={}

for r in range(6,6+nOperators):
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    for x in range(len(lst)):
        o=int(lst[0])
        lstSkills=lst[1:1+nSkills]
        lstDays=lst[1+nSkills:1+nSkills+nDays]
        maxH=float(lst[1+nSkills+nDays:1+nSkills+nDays+1][0])
        hCost=float(lst[1+nSkills+nDays+1:1+nSkills+nDays+1+1][0])
    k=0
    for kIndex in lstSkills:
        k=k+1
        kIndex=int(kIndex)
        if kIndex>0:
            dctOperatorsSkills.setdefault(o,[]).append(int(k))
            dctSkillsOperators.setdefault(k,[]).append(int(o))
    d=0
    for dIndex in lstDays:
        d=d+1
        dIndex=int(dIndex)
        if dIndex>0:
            dctOperatorsDays.setdefault(o,[]).append(int(d))
    dctOperatorsMaxHours[o]=maxH
    dctOperatorsHCost[o]=hCost

for r in range(6+nOperators,6+nOperators+nProjects):
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    dctProjectRevenue[int(lst[0])]=float(lst[1])
    dctProjectNRequests[int(lst[0])]=int(lst[2])

for r in range(6+nOperators+nProjects,6+nOperators+nProjects+nRequests):
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    for c in range(1,len(lst)-1):
        attr=float(lst[c])
        dctRequestsAttributes.setdefault("r"+str(lst[0]),[]).append(attr)

dctSitesTt={}
lstSites=[]
count_r=0
for r in
range(6+nOperators+nProjects+nRequests,6+nOperators+nProjects+nRequests+nOperators*2+nPr
ojects):
    count_r=count_r+1
    if count_r<=nOperators*2:
        x1=math.ceil(count_r/2)
        if (count_r % 2) == 0:
            y1="e"
        else:
            y1="b"
        site1="o"+str(x1)+str(y1)
    else:
```

```
            site1="p"+str(count_r-2*nOperators)
        if site1 not in lstSites:
            lstSites.append(site1)
        count_c=0
        row=linecache.getline(filename, r)
        lst=(row.split(" "))
        for c in range(0,len(lst)-1):
            count_c=count_c+1
            if count_c<=nOperators*2:
                x2=math.ceil(count_c/2)
                if (count_c % 2) == 0:
                    y2="e"
                else:
                    y2="b"
                site2="o"+str(x2)+str(y2)
            else:
                site2="p"+str(count_c-2*nOperators)
            tt=float(lst[c])
            dctSitesTt[(site1,site2)]=tt

lstProjects1=dctProjectRevenue.keys()
lstProjects=[]
for p in lstProjects1:
    lstProjects.append(p)

lstRequests1=dctRequestsAttributes.keys()
lstRequests=[]
for r in lstRequests1:
    lstRequests.append(r)

lstOperators1=dctOperatorsDays.keys()
lstOperators=[]
for o in lstOperators1:
    lstOperators.append(o)

lstDays=list(range(1,nDays+1))

lstTimeSessions=[1,2]

lstSkills=list(range(1,nSkills+1))

dctDaysOperators={}
for o in dctOperatorsDays.keys():
    lstD= dctOperatorsDays[o]
    for d in lstD:
        dctDaysOperators.setdefault(d,[]).append(o)

dctDaysRequests={}
dctRequestsDays={}
for d in lstDays:
    for r in dctRequestsAttributes.keys():
        lst=dctRequestsAttributes[r]
        day=lst[1]
        if (day==d):
            dctDaysRequests.setdefault(d,[]).append(r)
```

```
            dctRequestsDays[r]=d

dctRequestRefProject={}
dctRequestSkill={}
dctRequestNOp={}
dctRequestServiceTime={}
dctRequestStartingTime={}
dctRequestEndingTime={}

for r in lstRequests:
    lst=dctRequestsAttributes[r]
    ReqProject=int(lst[0])
    ReqSkill=int(lst[2])
    ReqNOp=int(lst[3])
    ServiceTime=lst[4]
    StartingTime=lst[5]
    EndingTime=lst[6]
    dctRequestRefProject[r]="p"+str(ReqProject)
    dctRequestSkill[r]=ReqSkill
    dctRequestNOp[r]=ReqNOp
    dctRequestServiceTime[r]=ServiceTime
    dctRequestStartingTime[r]=StartingTime
    dctRequestEndingTime[r]=EndingTime

lstBeginNodes=[]
lstEndNodes=[]
lstOperatorsHome=[]
for o in lstOperators:
     lstOperatorsHome.append("o"+str(o)+"b")
     lstOperatorsHome.append("o"+str(o)+"e")
     lstBeginNodes.append("o"+str(o)+"b")
     lstEndNodes.append("o"+str(o)+"e")

lstV=lstOperatorsHome+lstRequests

lstOperatorsHome=[]
for o in lstOperators:
    lstOperatorsHome.append(("o"+str(o)+"b","o"+str(o)+"e"))

dctOperatorsHome={}
for o in lstOperators:
    dctOperatorsHome.setdefault(o,[]).append("o"+str(o)+"b")
    dctOperatorsHome.setdefault(o,[]).append("o"+str(o)+"e")

dctOperatorsHomeBegin={}
for o in lstOperators:
    dctOperatorsHomeBegin[o]=("o"+str(o)+"b")

dctOperatorsHomeEnd={}
for o in lstOperators:
      dctOperatorsHomeEnd[o]=("o"+str(o)+"e")

dctDaysSessions={}
for d in lstDays:
    for s in lstTimeSessions:
```

```
            dctDaysSessions.setdefault(d,[]).append(s)

dctRequestDaySession={}
for r in lstRequests:
        d=dctRequestsDays[r]
        if dctRequestStartingTime[r] <= 12 :
            dctRequestDaySession[r]=(d,1)
        else:
            dctRequestDaySession[r]=(d,2)

dctDaysSessionsRequests={}
for d in lstDays:
        lst=dctDaysRequests[d]
        for r in lst:
                x=dctRequestDaySession[r][1]
                dctDaysSessionsRequests.setdefault((d,x),[]).append(r)

dctDaysSessionsOperators={}
for d in lstDays:
        for s in dctDaysSessions[d]:
                for o in dctDaysOperators[d]:
                        dctDaysSessionsOperators.setdefault((d,s),[]).append(o)

dctOperatorsDaysArcs={}
for d in lstDays:
        for o in dctDaysOperators[d]:
                begin=dctOperatorsHomeBegin[o]
                end=dctOperatorsHomeEnd[o]
                for s in dctDaysSessions[d]:
                  if (d,s) in dctDaysSessionsRequests.keys():
                        requests=dctDaysSessionsRequests[d,s]
                        for r in requests:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((begin,r))
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,end))
                                for x in requests:
                                        if r!=x:
                                            dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))

dctOperatorsDaysArcsMatch={}
lstOperatorsDaysArcsMatch=[]
lstOperatorsDaysRequestsArcsMatch=[]
for o in lstOperators:
        for d in dctOperatorsDays[o]:
                  lst=dctOperatorsDaysArcs[o,d]
                  for a in lst:
                        skillo=dctOperatorsSkills[o]
                        if a[0]=="o"+str(o)+"b":
                                skilli=dctOperatorsSkills[o]
                                skillj=dctRequestSkill[a[1]]
                                for si in skilli:
                                        if skillj==si:
                                            dctOperatorsDaysArcsMatch.setdefault((o,d),[]).append(a)
                                            lstOperatorsDaysArcsMatch.append((o,d,a[0],a[1]))
                        else:
                                skilli=dctRequestSkill[a[0]]
```

```
                if a[1]=="o"+str(o)+"e" or a[1]=="o"+str(o)+"b":
                    skillj=dctOperatorsSkills[o]
                    for s in skillj:
                        for so in skillo:
                            if skilli==s:
                                if a not in dctOperatorsDaysArcsMatch[(o,d)]:
                                    dctOperatorsDaysArcsMatch.setdefault((o,d),[]).append(a)
                                    lstOperatorsDaysArcsMatch.append((o,d,a[0],a[1]))
                else:
                    skillj=dctRequestSkill[a[1]]
                    if skillj in skillo:
                        if skilli in skillo:
                            if a not in dctOperatorsDaysArcsMatch[(o,d)]:
                                dctOperatorsDaysArcsMatch.setdefault((o,d),[]).append(a)
                                lstOperatorsDaysArcsMatch.append((o,d,a[0],a[1]))
                                lstOperatorsDaysRequestsArcsMatch.append((o,d,a[0],a[1]))

lstOperatorsDaysSessions=[]
for o in dctOperatorsDays:
    lst1=dctOperatorsDays[o]
    lstOperatorsDaysSessions1= list(it.product(lst1 , lstTimeSessions))
    for dpl in lstOperatorsDaysSessions1:
        d=dpl[0]
        s=dpl[1]
        lstOperatorsDaysSessions.append((o,d,s))

lstRequestsDaysOperatorsMatch=[]
dctRequestsOperatorsMatch={}
dctOperatorsRequestsMatch={}
lstRequestsOperatorsMatch=[]
for r in lstRequests:
    d=dctRequestsDays[r]
    lst=dctDaysOperators[d]
    for o in lst:
        skills=dctOperatorsSkills[o]
        if dctRequestSkill[r] in skills:
            dctOperatorsRequestsMatch.setdefault(o,[]).append(r)
            dctRequestsOperatorsMatch.setdefault(r,[]).append(o)
            lstRequestsOperatorsMatch.append((r,o))
            lstRequestsDaysOperatorsMatch.append((r,d,o))

lstOperatorsDaysSessionHome=[]
for o in lstOperators:
    lstd=dctOperatorsDays[o]
    lsth=dctOperatorsHome[o]
    prod=list(it.product(lstd,lstTimeSessions,lsth))
    for x in prod:
        d=x[0]
        s=x[1]
        i=x[2]
        lstOperatorsDaysSessionHome.append((o,d,s,i))

lstOperatorDaySessionRequests=[]
for r in lstRequests:
    d=dctRequestDaySession[r][0]
```

```
        s=dctRequestDaySession[r][1]
        lsto=dctRequestsOperatorsMatch[r]
        for o in lsto:
            lstOperatorDaySessionRequests.append((o,d,s,r))

dctDaySessionOperatorRequests={}
for d in lstDays:
        for s in dctDaysSessions[d]:
            if (d,s) in dctDaysSessionsRequests.keys():
                req=dctDaysSessionsRequests[d,s]
                for o in dctDaysSessionsOperators[d,s]:
                    for r in req:
                        if r in dctOperatorsRequestsMatch[o]:
                            dctDaySessionOperatorRequests.setdefault((d,s,o),[]).append(r)

dctOperatorsDaysExist={}
lstOperatorsDaysExist=[]
for (o,d) in dctOperatorsDaysArcsMatch.keys():
      dctOperatorsDaysExist.setdefault(o,[]).append(d)
      lstOperatorsDaysExist.append((o,d))

lstOperatorsDaysSessionsExist=[]
dctOperatorsDaysSessionsExist={}
for (d,s,o) in dctDaySessionOperatorRequests.keys():
      lstOperatorsDaysSessionsExist.append((o,d,s))
      dctOperatorsDaysSessionsExist.setdefault((o,d),[]).append(s)

lstOperatorsDaysArcsBegin=[]
for x in lstOperatorsDaysArcsMatch:
      for o in lstOperators:
         if x[2]== 'o'+ str(o) + 'b':
            lstOperatorsDaysArcsBegin.append(x)

dctOperatorsDaysArcsBegin={}
for x in lstOperatorsDaysArcsBegin:
      o,d,i,j= x
      dctOperatorsDaysArcsBegin.setdefault((o,d),[]).append((i,j))

dctOperatorsDaysSessions={}
for x in lstOperatorsDaysSessionsExist:
      o,d,s=x
      dctOperatorsDaysSessions.setdefault((o,d),[]).append(s)

lstOperatorsDays=[]
for o in dctOperatorsDays.keys():
      lst=dctOperatorsDays[o]
      for d in lst:
          lstOperatorsDays.append((o,d))

dctOperatorsDaysRequestsOut={}
dctOperatorsDaysRequestsIn={}
for o in lstOperators:
      for d in dctOperatorsDays[o]:
            for j in dctDaysRequests[d]:
               if (o,d) in dctOperatorsDaysArcsMatch.keys():
```

```
                for x in dctOperatorsDaysArcsMatch[o,d]:
                    if x[0]==j:
                        dctOperatorsDaysRequestsOut.setdefault((o,d,j),[]).append(x[1])

for o in lstOperators:
    for d in dctOperatorsDays[o]:
        for j in dctDaysRequests[d]:
            if (o,d) in dctOperatorsDaysArcsMatch.keys():
                for x in dctOperatorsDaysArcsMatch[o,d]:
                    if x[1]==j:
                        dctOperatorsDaysRequestsIn.setdefault((o,d,j),[]).append(x[0])


lstOperatorsDaysArcsEnd=[]
for x in lstOperatorsDaysArcsMatch:
    for o in lstOperators:
        if x[3]== 'o'+ str(o) + 'e':
            lstOperatorsDaysArcsEnd.append(x)

dctOperatorsDaysArcsEnd={}
for x in lstOperatorsDaysArcsEnd:
    o,d,i,j= x
    dctOperatorsDaysArcsEnd.setdefault((o,d),[]).append((i,j))

lstProjectRequestOperator=[]
for r in lstRequests:
    lst=dctRequestsAttributes[r]
    p=int(lst[0])
    lst1=dctRequestsOperatorsMatch[r]
    for o in lst1:
        lstProjectRequestOperator.append((p,r,o))

dctOperatorsDaysRequestsArcs={}
for o in lstOperators:
    for d in dctOperatorsDays[o]:
        for j in dctDaysRequests[d]:
            if (o,d) in dctOperatorsDaysArcsMatch.keys():
                for x in dctOperatorsDaysArcsMatch[o,d]:
                    if x[0]==j:
                        dctOperatorsDaysRequestsArcs.setdefault((o,d,j),[]).append(x)

lstProjectRequests=[]
for r in lstRequests:
    lst=dctRequestsAttributes[r]
    p=lst[0]
    lstProjectRequests.append((p,r))

lstDaysOperators=[]
for d in lstDays:
    lst=dctDaysOperators[d]
    for o in lst:
        lstDaysOperators.append((d,o))

lstOperatorsDaysMorning=[]
for x in lstOperatorsDaysSessionsExist:
```

```
    if x[2]==1:
        lstOperatorsDaysMorning.append((x[0],x[1]))

lstOperatorsDaysMorningAfternoon=[]
for o in lstOperators:
    for d in dctOperatorsDaysExist[o]:
       x=dctOperatorsDaysSessionsExist[o,d]
       if 1 in x and 2 in x:
        lstOperatorsDaysMorningAfternoon.append((o,d))

lstOperatorsDaysAfternoon=[]
for x in lstOperatorsDaysSessionsExist:
    if x[2]==2:
      lstOperatorsDaysAfternoon.append((x[0],x[1]))

dctNodesTt={}
for i in lstV:
    if i[0]=="o":
        x=i
    else:
        x=dctRequestRefProject[i]
    for j in lstV:
        if j[0]=="o":
            y=j
        else:
            y=dctRequestRefProject[j]
        dctNodesTt[i,j]=dctSitesTt[x,y]

lstArcs=[]
lstArcs=list(it.product(lstV , lstV))


lstRequestOperatorOperator=[]
for i in lstRequests:
    if dctRequestNOp[i]==2:
        skill=dctRequestSkill[i]
        for o1 in lstOperators:
            if skill in dctOperatorsSkills[o1] and i in dctOperatorsRequestsMatch[o1]:
               for o2 in lstOperators:
                   if o1!=o2:
                       if skill in dctOperatorsSkills[o2] and i in
dctOperatorsRequestsMatch[o2]:
                            lstRequestOperatorOperator.append((i,o1,o2))

model=AbstractModel()

model.Projects= Set(dimen=1,initialize=lstProjects)
model.Requests= Set(dimen=1,initialize=lstRequests)
model.Days= Set(dimen=1,initialize=lstDays)
model.TimeSessions= Set(dimen=1,initialize=lstTimeSessions)
model.Operators= Set(dimen=1,initialize=lstOperators)
model.A=Set(dimen=4, initialize=lstOperatorsDaysArcsMatch)
model.Ods=Set(dimen=3, initialize=lstOperatorsDaysSessionsExist)
model.Io=Set(dimen=2, initialize=lstRequestsOperatorsMatch)
model.OperatorsDays=Set(dimen=2, initialize=lstOperatorsDaysExist)
```

```
model.RequestsDaysOperators=Set(dimen=3, initialize=lstRequestsDaysOperatorsMatch)
model.ProjectRequestOperator=Set(dimen=3, initialize=lstProjectRequestOperator)
model.ProjectRequests=Set(dimen=2, initialize=lstProjectRequests)
model.OperatorsDaysSessionHome=Set(dimen=4, initialize=lstOperatorsDaysSessionHome)
model.DaysOperators=Set(dimen=2, initialize=lstDaysOperators)
model.Odij=Set(dimen=4, initialize=lstOperatorsDaysRequestsArcsMatch)
model.Odsj=Set(dimen=4, initialize=lstOperatorDaySessionRequests)
model.Arcs=Set(dimen=2, initialize=lstArcs)
model.OperatorsDaysMorning=Set(dimen=2, initialize=lstOperatorsDaysMorning)
model.OperatorsDaysAfternoon=Set(dimen=2, initialize=lstOperatorsDaysAfternoon)
model.OperatorsDaysMorningAfternoon=Set(dimen=2,
initialize=lstOperatorsDaysMorningAfternoon)
model.RequestOperatorOperator=Set(dimen=3, initialize= lstRequestOperatorOperator)

model.MaxWeeklyHours= Param(model.Operators, initialize=dctOperatorsMaxHours, within=Any)
model.ReqnOperators= Param(model.Requests, initialize=dctRequestNOp, within=Any)
model.ServiceTime= Param(model.Requests, initialize= dctRequestServiceTime, within=Any)
model.StartingTime=Param(model.Requests, initialize= dctRequestStartingTime, within=Any)
model.EndingTime=Param(model.Requests, initialize= dctRequestEndingTime, within=Any)
model.TravelTime= Param(model.Arcs, initialize=dctNodesTt, within=Any)
model.HourlyCost= Param(model.Operators, initialize=dctOperatorsHCost, within=Any)
model.RevenueProj= Param(model.Projects, initialize=dctProjectRevenue, within=Any)
model.OperatorsDaysAvailability=Param(model.Operators, initialize=dctOperatorsDays,
within=Any)

model.z= Var(model.Projects, within =Binary)
model.x= Var(model.A, within=Binary)
model.y= Var(model.Ods, within=Binary)
model.u= Var(model.Io, within=Binary)
model.w= Var(model.Io, within=NonNegativeReals)
model.f= Var(model.OperatorsDaysSessionHome, within=NonNegativeReals)

def OBJ_rule(model):
    return sum(model.RevenueProj[p]*model.z[p] for p in model.Projects) -
(sum((model.HourlyCost[o])*((model.f[o,d,s,dctOperatorsHomeEnd[o]]) -
(model.f[o,d,s,dctOperatorsHomeBegin[o]])) for o in lstOperators for d in dctOperatorsDaysExist[o]
for s in dctOperatorsDaysSessions[o,d]))    -(sum (22*model.TravelTime[i,j]*model.x[o,d,i,j] for o in
lstOperators for d in dctOperatorsDaysExist[o] for (i,j) in dctOperatorsDaysArcsMatch[o,d]))
model.OBJ=Objective(rule=OBJ_rule, sense=maximize)


def CONS2_rule(model,o,d):
    return sum(model.x[o, d, i, j] for (i,j) in dctOperatorsDaysArcsBegin[o,d]) ==
sum(model.y[o,d,s] for s in dctOperatorsDaysSessionsExist[o,d])
model.CONS2=Constraint(model.OperatorsDays, rule=CONS2_rule)

def CONS3_rule(model,j,d,o):
    return sum(model.x[o,d,i,j] for i in dctOperatorsDaysRequestsIn[o,d,j]) == sum(model.x[o,d,j,i]
for i in dctOperatorsDaysRequestsOut[o,d,j])
model.CONS3=Constraint(model.RequestsDaysOperators, rule=CONS3_rule)

def CONS4_rule(model,o,d):
    return sum (model.x[o,d,i,j] for (i,j) in dctOperatorsDaysArcsEnd[o,d]) == sum (model.y[o,d,s]
for s in dctOperatorsDaysSessions[o,d])
model.CONS4=Constraint(model.OperatorsDays, rule= CONS4_rule)
```

```
def CONS5_rule(model,i,d,o):
        return sum (model.x[o,d,i,j] for (i,j) in dctOperatorsDaysRequestsArcs[o,d,i]) ==
model.u[i,o]
model.CONS5=Constraint(model.RequestsDaysOperators, rule=CONS5_rule)

def CONS6_rule(model,p,i,o):
    return model.u[i,o] <= model.z[p]
model.CONS6=Constraint(model.ProjectRequestOperator, rule=CONS6_rule)

def CONS7_rule(model, p,i):
        return sum(model.u[i,o] for o in dctRequestsOperatorsMatch[i]) >=
model.ReqnOperators[i]*model.z[p]
model.CONS7=Constraint(model.ProjectRequests, rule=CONS7_rule)

def CONS8_rule(model,o,d):
    return model.f[o,d,1,dctOperatorsHomeBegin[o]] >= 7*model.y[o,d,1]
model.CONS8=Constraint(model.OperatorsDaysMorning, rule=CONS8_rule)

def CONS9_rule(model, o,d):
    return model.f[o,d,1,dctOperatorsHomeEnd[o]] <= (11*model.y[o,d,1]) - model.y[o,d,2]+1
model.CONS9=Constraint(model.OperatorsDaysMorningAfternoon, rule=CONS9_rule)

def CONS10_rule(model, o,d):
    return model.f[o,d,2,dctOperatorsHomeBegin[o]] >= 18*model.y[o,d,2] + (2*model.y[o,d,1]) - 2
model.CONS10=Constraint(model.OperatorsDaysMorningAfternoon, rule=CONS10_rule)

def CONS11_rule(model,o,d):
    return model.f[o,d,2,dctOperatorsHomeEnd[o]] <= 21.5*model.y[o,d,2]
model.CONS11=Constraint(model.OperatorsDaysAfternoon, rule=CONS11_rule)

def CONS12_rule(model,o,d,i,j):
    return model.w[i,o] + model.ServiceTime[i] + model.TravelTime[i,j]<= model.w[j,o] +21.5*(1-
model.x[o,d,i,j])
model.CONS12=Constraint(model.Odij, rule=CONS12_rule)

def CONS13_rule(model, o,d,s,j):
    return model.f[o,d,s,dctOperatorsHomeBegin[o]] +
model.TravelTime[dctOperatorsHomeBegin[o],j] <= model.w[j,o] + 21.5*(1-
model.x[o,d,dctOperatorsHomeBegin[o],j])
model.CONS13=Constraint(model.Odsj, rule=CONS13_rule)

def CONS14_rule(model, o,d,s,i):
        return model.w[i,o] + model.ServiceTime[i] +
model.TravelTime[i,dctOperatorsHomeEnd[o]]<= model.f[o,d,s,dctOperatorsHomeEnd[o]] +
21.5*(1-model.x[o,d,i,dctOperatorsHomeEnd[o]])
model.CONS14=Constraint(model.Odsj, rule=CONS14_rule)

def CONS15_rule(model, i,o):
    return model.StartingTime[i]*model.u[i,o] <= model.w[i,o]
model.CONS15=Constraint(model.Io, rule=CONS15_rule)

def CONS15b_rule(model, i,o):
    return model.w[i,o] <= model.EndingTime[i]*model.u[i,o]
model.CONS15b=Constraint(model.Io, rule=CONS15b_rule)
```

```
def CONS16_rule(model,o):
    return sum((model.f[o,d,s,dctOperatorsHomeEnd[o]]) -
(model.f[o,d,s,dctOperatorsHomeBegin[o]]) for d in model.OperatorsDaysAvailability[o] for s in
model.TimeSessions) <= model.MaxWeeklyHours[o]
model.CONS16=Constraint(model.Operators, rule=CONS16_rule)

def CONS17_rule(model,o,d,s):
    return model.y[o,d,s] <= sum (model.u[i,o] for i in dctDaySessionOperatorRequests[d,s,o])
model.CONS17=Constraint(model.Ods, rule=CONS17_rule)

def CONS18_rule(model,o,d,s):
    return model.f[o,d,s,dctOperatorsHomeBegin[o]] <= 22*model.y[o,d,s]
model.CONS18=Constraint(model.Ods, rule=CONS18_rule)

def CONS19_rule(model,i,o1,o2):
    return model.w[i,o1] <= model.w[i,o2] - 22*(model.u[i,o1] + model.u[i,o2]-2)
model.CONS19=Constraint(model.RequestOperatorOperator, rule=CONS19_rule)

def CONS20_rule(model,i,o1,o2):
    return model.w[i,o1] >= model.w[i,o2] + 22*(model.u[i,o1] + model.u[i,o2]-2)
model.CONS20=Constraint(model.RequestOperatorOperator, rule=CONS20_rule)

def CONS21_rule(model,o,d,s):
    return model.f[o,d,s,dctOperatorsHomeEnd[o]] - model.f[o,d,s,dctOperatorsHomeBegin[o]] >= 0
model.CONS21=Constraint(model.Ods, rule=CONS21_rule)

def CONS22_rule(model,o,d,s):
    return model.f[o,d,s,dctOperatorsHomeEnd[o]] - model.f[o,d,s,dctOperatorsHomeBegin[o]] >=
sum(model.ServiceTime[i]*model.u[i,o] for i in dctDaySessionOperatorRequests[d,s,o])
model.CONS22=Constraint(model.Ods, rule=CONS22_rule)

projectFolderPath= os.path.dirname(os.path.realpath("__file__"))

logPath=(projectFolderPath+"\\logs\\log.txt")
outPath=(projectFolderPath+"\\logs\\out.txt")
executableCplexPath = projectFolderPath + "\\solver\\cplex.exe"

instance=model.create_instance()
dateTimeObj = datetime.now()
timeStampInstanceCreated = dateTimeObj.strftime("%Y-%m-%d %H:%M:%S")
print("Instance created=" +str(timeStampInstanceCreated))

opt = SolverFactory("cplex", solver_io="lp", executable=executableCplexPath)
gaplimit=0.01

opt.options['mipgap']=gaplimit
opt.options['emphasis mip'] = 2
opt.options['mip display'] = 2

with Redirect(logPath, 'w'):
        results = opt.solve(instance, tee=True)
        model.solutions.load_from(results)
results.write()
dctSol_y={}
```

```
dctSol_x={}
dctSol_u={}
dctSol_w={}
dctSol_f={}
dctSol_z={}

exprobject=getattr(instance,'y')
for index in exprobject:
    dctSol_y.setdefault((index[0],index[1],index[2]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'x')
for index in exprobject:
    dctSol_x.setdefault((index[0],index[1],index[2],index[3]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'u')
for index in exprobject:
    dctSol_u.setdefault((index[0],index[1]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'w')
for index in exprobject:
      dctSol_w.setdefault((index[0],index[1]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'f')
for index in exprobject:
    dctSol_f.setdefault((index[0],index[1],index[2],index[3]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'z')
for index in exprobject:
    dctSol_z.setdefault((index),[]).append(value(exprobject[index]))

lstSol_y=[]
for k in dctSol_y.keys():
    if dctSol_y[k][0]>0.1:
        lstSol_y.append([k[0],k[1],k[2], dctSol_y[k][0]])
lstHeader_y=["o","d","s","y"]
dfSol_y=pd.DataFrame(lstSol_y, columns=lstHeader_y)
dfSol_y=dfSol_y.sort_values(['o', 'd', 's', 'y'], ascending=[True,True, True, True])
dfSol_y.to_csv(projectFolderPath+"\\logs\\dfSol_y.csv", header=True, index=None, sep='|',
mode='w')

lstSol_x=[]
for k in dctSol_x.keys():
    if dctSol_x[k][0]>0.1:
        lstSol_x.append([k[0],k[1],k[2],k[3],dctSol_x[k][0]])
lstHeader_x=["o","d","i","j", "x"]
dfSol_x=pd.DataFrame(lstSol_x, columns=lstHeader_x)
dfSol_x=dfSol_x.sort_values(['o', 'd', 'i','j', 'x'], ascending=[True,True, True, True, True])
dfSol_x.to_csv(projectFolderPath+"\\logs\\dfSol_x.csv", header=True, index=None, sep='|',
mode='w')

lstSol_u=[]
for k in dctSol_u.keys():
    if dctSol_u[k][0]>0.1:
        lstSol_u.append([k[0],k[1], dctSol_u[k][0]])
lstHeader_u=["i" ,"o", "u"]
```

```
dfSol_u=pd.DataFrame(lstSol_u, columns=lstHeader_u)
dfSol_u=dfSol_u.sort_values(['i','o', 'u'], ascending=[True,True, True])
dfSol_u.to_csv(projectFolderPath+"\\logs\\dfSol_u.csv", header=True, index=None, sep='|',
mode='w')

lstSol_f=[]
for k in dctSol_f.keys():
    if dctSol_f[k][0]>0.1:
        lstSol_f.append([k[0],k[1],k[2],k[3],dctSol_f[k][0]])
lstHeader_f=["o","d","s","i","t",]
dfSol_f=pd.DataFrame(lstSol_f, columns=lstHeader_f)
dfSol_f=dfSol_f.sort_values(['o', 'd', 's','i','t'], ascending=[True,True, True, True, True])
dfSol_f.to_csv(projectFolderPath+"\\logs\\dfSol_f.csv", header=True, index=None, sep='|',
mode='w')

lstSol_w=[]
for k in dctSol_w.keys():
    if dctSol_w[k][0]>0.1:
        lstSol_w.append([k[0],k[1],dctSol_w[k][0]])
lstHeader_w=["i","o","w"]
dfSol_w=pd.DataFrame(lstSol_w, columns=lstHeader_w)
dfSol_w=dfSol_w.sort_values(['o','i','w'], ascending=[True,True, True])
dfSol_w.to_csv(projectFolderPath+"\\logs\\dfSol_w.csv", header=True, index=None, sep='|',
mode='w')

lstSol_z=[]
for k in dctSol_z.keys():
    if dctSol_z[k][0]>0.1:
        lstSol_z.append([k,dctSol_z[k][0]])
lstHeader_z=["p","z"]
dfSol_z=pd.DataFrame(lstSol_z, columns=lstHeader_z)
dfSol_z=dfSol_z.sort_values(['p','z'], ascending=[True,True])
dfSol_z.to_csv(projectFolderPath+"\\logs\\dfSol_z.csv", header=True, index=None, sep='|',
mode='w')
```

Appendix E. Script New Model

```
import pyomo
from pyomo.environ import (AbstractModel, Any, maximize, minimize, Set, Var, Constraint,
Objective, Param, Binary, NonNegativeReals, SolverFactory, value)
import sys
import os
from openpyxl import Workbook, load_workbook
import pandas as pd
import numpy as np
import itertools as it
import linecache
import math
from datetime import datetime
import re

def Redirect(filename, mode='w'):
    old_stdout, old_stderr = sys.stdout, sys.stderr
    with open(filename, mode) as f:
        sys.stdout, sys.stderr = f, f
        yield
    sys.stdout, sys.stderr = old_stdout, old_stderr

class Redirect:
    def __init__(self, filename, mode='w'):
        self.filename = filename
        self.mode = mode
        self.old_stdout = None
        self.old_stderr = None

    def __enter__(self):
        self.old_stdout = sys.stdout
        self.old_stderr = sys.stderr
        self.file = open(self.filename, self.mode)
        sys.stdout = self.file
        sys.stderr = self.file
        return self

    def __exit__(self, exc_type, exc_value, traceback):
        sys.stdout = self.old_stdout
        sys.stderr = self.old_stderr
        if self.file:
            self.file.close()

filename="Robot.txt"

nProjects = int(linecache.getline(filename, 1))
nOperators = int(linecache.getline(filename, 2))
nSkills= int(linecache.getline(filename, 3))
nDays = int(linecache.getline(filename, 4))
nRequests = int(linecache.getline(filename, 5))

dctOperatorsSkills={}
dctSkillsOperators={}
dctOperatorsDays={}
```

```
dctOperatorsHCost={}
dctOperatorsMaxHours={}
dctProjectRevenue={}
dctProjectNRequests={}
dctRequestsAttributes={}
for r in range(6,6+nOperators):
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    for x in range(len(lst)):
        o=int(lst[0])
        lstSkills=lst[1:1+nSkills]
        lstDays=lst[1+nSkills:1+nSkills+nDays]
        maxH=float(lst[1+nSkills+nDays:1+nSkills+nDays+1][0])
        hCost=float(lst[1+nSkills+nDays+1:1+nSkills+nDays+1+1][0])
    k=0
    for kIndex in lstSkills:
        k=k+1
        kIndex=int(kIndex)
        if kIndex>0:
            dctOperatorsSkills.setdefault(o,[]).append(int(k))
            dctSkillsOperators.setdefault(k,[]).append(int(o))
    d=0
    for dIndex in lstDays:
        d=d+1
        dIndex=int(dIndex)
        if dIndex>0:
            dctOperatorsDays.setdefault(o,[]).append(int(d))
    dctOperatorsMaxHours[o]=maxH
    dctOperatorsHCost[o]=hCost

for r in range(6+nOperators,6+nOperators+nProjects):
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    dctProjectRevenue['p'+str(int(lst[0]))]=float(lst[1])
    dctProjectNRequests['p'+str(int(lst[0]))]=int(lst[2])

for r in range(6+nOperators+nProjects,6+nOperators+nProjects+nRequests):
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    for c in range(1,len(lst)-1):
        attr=str(lst[c])
        dctRequestsAttributes.setdefault("r"+str(lst[0]),[]).append(attr)

dctSitesTt={}
lstSites=[]
count_r=0
for r in
range(6+nOperators+nProjects+nRequests,6+nOperators+nProjects+nRequests+nOperators*2+nPr
ojects):
    count_r=count_r+1
    if count_r<=nOperators*2:
        x1=math.ceil(count_r/2)
        if (count_r % 2) == 0:
            y1="e"
        else:
```

```
            y1="b"
        site1="o"+str(x1)+str(y1)
    else:
        site1="p"+str(count_r-2*nOperators)
    if site1 not in lstSites:
        lstSites.append(site1)
    count_c=0
    row=linecache.getline(filename, r)
    lst=(row.split(" "))
    for c in range(0,len(lst)-1):
        count_c=count_c+1
        if count_c<=nOperators*2:
            x2=math.ceil(count_c/2)
            if (count_c % 2) == 0:
                y2="e"
            else:
                y2="b"
            site2="o"+str(x2)+str(y2)
        else:
            site2="p"+str(count_c-2*nOperators)
        tt=float(lst[c])
        dctSitesTt[(site1,site2)]=tt

lstProjects1=dctProjectRevenue.keys()
lstProjects=[]
for p in lstProjects1:
    lstProjects.append(p)

lstRequests1=dctRequestsAttributes.keys()
lstRequests=[]
for r in lstRequests1:
    lstRequests.append(r)

lstOperators1=dctOperatorsDays.keys()
lstOperators=[]
for o in lstOperators1:
    lstOperators.append(o)

lstDays=list(range(1,nDays+1))

lstTimeSessions=[1,2]

lstSkills=list(range(1,nSkills+1))

dctDaysOperators={}
for o in dctOperatorsDays.keys():
    lstD= dctOperatorsDays[o]
    for d in lstD:
        dctDaysOperators.setdefault(d,[]).append(o)
dctDaysRequests={}
dctRequestsDays={}
for d in lstDays:
    for r in dctRequestsAttributes.keys():
        lst=dctRequestsAttributes[r]
        day=int(lst[1])
```

```
        if (day==d):
            dctDaysRequests.setdefault(d,[]).append(r)
            dctRequestsDays[r]=d


dctRequestRefProject={}
dctRequestSkill={}
dctRequestNOp={}
dctRequestServiceTime={}
dctRequestStartingTime={}
dctRequestEndingTime={}
dctRequestMain={}
dctRequestAlternatives={}

for r in lstRequests:
    lst=dctRequestsAttributes[r]
    ReqProject=int(lst[0])
    ReqSkill=int(lst[2])
    ReqNOp=int(lst[3])
    ServiceTime=float(lst[4])
    StartingTime=float(lst[5])
    EndingTime=float(lst[6])
    dctRequestRefProject[r]="p"+str(ReqProject)
    dctRequestSkill[r]=ReqSkill
    dctRequestNOp[r]=ReqNOp
    dctRequestServiceTime[r]=ServiceTime
    dctRequestStartingTime[r]=StartingTime
    dctRequestEndingTime[r]=EndingTime
    if float(lst[7]) > 0:
        dctRequestMain[r]='r'+str(int(lst[7]))
    if float(lst[8])>0:
        x = str(lst[8]).split('.')
        x1 = x[0]
        x2 = (x[1])
        dctRequestAlternatives.setdefault(r,[]).append('r'+str(x1))
        dctRequestAlternatives.setdefault(r,[]).append('r'+str(x2))

lstRequestPure=[]
lstRequestMain=[]
lstRequestAlternative=[]
for r in lstRequests:
    if float(dctRequestsAttributes[r][7]) ==0 and float(dctRequestsAttributes[r][8]) == 0:
        lstRequestPure.append(r)
    if float(dctRequestsAttributes[r][7]) == 0 and float(dctRequestsAttributes[r][8]) > 0:
        lstRequestMain.append(r)
    if float(dctRequestsAttributes[r][7]) > 0 and float(dctRequestsAttributes[r][8]) == 0:
        lstRequestAlternative.append(r)

lstBeginNodes=[]
lstEndNodes=[]
lstOperatorsHome=[]
for o in lstOperators:
    lstOperatorsHome.append("o"+str(o)+"b")
    lstOperatorsHome.append("o"+str(o)+"e")
    lstBeginNodes.append("o"+str(o)+"b")
```

```
        lstEndNodes.append("o"+str(o)+"e")

lstV=lstOperatorsHome+lstRequests

lstOperatorsHomeEndBegin=[]
for o in lstOperators:
    lstOperatorsHomeEndBegin.append(("o"+str(o)+"b","o"+str(o)+"e"))

dctOperatorsHome={}
for o in lstOperators:
    dctOperatorsHome.setdefault(o,[]).append("o"+str(o)+"b")
    dctOperatorsHome.setdefault(o,[]).append("o"+str(o)+"e")

lstOperatorsHomeEnd=[]
lstOperatorsHomeBegin=[]
dctOperatorsHomeEnd={}
dctOperatorsHomeBegin={}
for o in lstOperators:
    dctOperatorsHomeBegin[o]=("o"+str(o)+"b")
    lstOperatorsHomeBegin.append("o"+str(o)+"b")
    dctOperatorsHomeEnd[o]=("o"+str(o)+"e")
    lstOperatorsHomeEnd.append("o"+str(o)+"e")

dctDaysSessions={}
for d in lstDays:
    for s in lstTimeSessions:
        dctDaysSessions.setdefault(d,[]).append(s)

dctRequestDaySession={}
for r in lstRequests:
    d=dctRequestsDays[r]
    if dctRequestStartingTime[r] <= 12 :
        dctRequestDaySession[r]=(d,1)
    else:
        dctRequestDaySession[r]=(d,2)

dctDaysSessionsRequests={}
for d in lstDays:
    lst=dctDaysRequests[d]
    for r in lst:
        x=dctRequestDaySession[r][1]
        dctDaysSessionsRequests.setdefault((d,x),[]).append(r)

dctDaysSessionsOperators={}
for d in lstDays:
    for s in dctDaysSessions[d]:
        for o in dctDaysOperators[d]:
            dctDaysSessionsOperators.setdefault((d,s),[]).append(o)

dctOperatorsDaysArcs={}
for d in lstDays:
    for o in dctDaysOperators[d]:
        begin=dctOperatorsHomeBegin[o]
        end=dctOperatorsHomeEnd[o]
        for s in dctDaysSessions[d]:
```

```
            if(d,s) in dctDaysSessionsRequests.keys():
                requests=dctDaysSessionsRequests[d,s]

                for r in requests:
                    dctOperatorsDaysArcs.setdefault((o,d),[]).append((begin,r))
                    dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,end))

                    if r in lstRequestPure:
                        for x in lstRequestMain:
                            if x in requests:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))
                        for x in lstRequestPure:
                            if x in requests and r!=x:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))

                    if r in lstRequestMain:
                        for x in lstRequestPure:
                            if x in requests:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))
                        for x in lstRequestMain:
                            if x in requests and r!=x:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))

                    if r in lstRequestAlternative:
                        for x in lstRequestPure:
                            if x in requests:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))
                        for x in lstRequestAlternative:
                            if x in requests and r!=x:
                                dctOperatorsDaysArcs.setdefault((o,d),[]).append((r,x))

dctOperatorsDaysArcsMatch={}
lstOperatorsDaysArcsMatch=[]
lstOperatorsDaysRequestsArcsMatch=[]
for o in lstOperators:
    for d in dctOperatorsDays[o]:
        lst=dctOperatorsDaysArcs[o,d]
        for a in lst:
            skillo=dctOperatorsSkills[o]
            if a[0]=="o"+str(o)+"b":
                skilli=dctOperatorsSkills[o]
                skillj=dctRequestSkill[a[1]]
                for si in skilli:
                    if skillj==si:
                        dctOperatorsDaysArcsMatch.setdefault((o,d),[]).append(a)
                        lstOperatorsDaysArcsMatch.append((o,d,a[0],a[1]))
            else:
                skilli=dctRequestSkill[a[0]]
                if a[1]=="o"+str(o)+"e" or a[1]=="o"+str(o)+"b":
                    skillj=dctOperatorsSkills[o]
                    for s in skillj:
                        for so in skillo:
                            if skilli==s:
                                if a not in dctOperatorsDaysArcsMatch[(o,d)]:
                                    dctOperatorsDaysArcsMatch.setdefault((o,d),[]).append(a)
```

```
                        lstOperatorsDaysArcsMatch.append((o,d,a[0],a[1]))
            else:
                skillj=dctRequestSkill[a[1]]
                if skillj in skillo:
                    if skilli in skillo:
                        if a not in dctOperatorsDaysArcsMatch[(o,d)]:
                          dctOperatorsDaysArcsMatch.setdefault((o,d),[]).append(a)
                          lstOperatorsDaysArcsMatch.append((o,d,a[0],a[1]))
                          lstOperatorsDaysRequestsArcsMatch.append((o,d,a[0],a[1]))

lstOperatorsDaysSessions=[]
for o in dctOperatorsDays:
    lst1=dctOperatorsDays[o]
    lstOperatorsDaysSessions1= list(it.product(lst1 , lstTimeSessions))
    for dpl in lstOperatorsDaysSessions1:
      d=dpl[0]
      s=dpl[1]
      lstOperatorsDaysSessions.append((o,d,s))

lstRequestsDaysOperatorsMatch=[]
dctRequestsOperatorsMatch={}
dctOperatorsRequestsMatch={}
lstRequestsOperatorsMatch=[]
for r in lstRequests:
    d=dctRequestsDays[r]
    lst=dctDaysOperators[d]
    for o in lst:
        skills=dctOperatorsSkills[o]
        if dctRequestSkill[r] in skills:
            dctOperatorsRequestsMatch.setdefault(o,[]).append(r)
            dctRequestsOperatorsMatch.setdefault(r,[]).append(o)
            lstRequestsOperatorsMatch.append((r,o))
            lstRequestsDaysOperatorsMatch.append((r,d,o))

lstOperatorsDaysSessionHome=[]
for o in lstOperators:
    lstd=dctOperatorsDays[o]
    lsth=dctOperatorsHome[o]
    prod=list(it.product(lstd,lstTimeSessions,lsth))
    for x in prod:
        d=x[0]
        s=x[1]
        i=x[2]
        lstOperatorsDaysSessionHome.append((o,d,s,i))

lstOperatorDaySessionRequests=[]
for r in lstRequests:
    d=dctRequestDaySession[r][0]
    s=dctRequestDaySession[r][1]
    lsto=dctRequestsOperatorsMatch[r]
    for o in lsto:
        lstOperatorDaySessionRequests.append((o,d,s,r))

dctDaySessionOperatorRequests={}
for d in lstDays:
```

```
        for s in dctDaysSessions[d]:
            if (d,s) in dctDaysSessionsRequests.keys():
              req=dctDaysSessionsRequests[d,s]
              for o in dctDaysSessionsOperators[d,s]:
                  for r in req:
                      if r in dctOperatorsRequestsMatch[o]:
                          dctDaySessionOperatorRequests.setdefault((d,s,o),[]).append(r)

dctOperatorsDaysExist={}
lstOperatorsDaysExist=[]
for (o,d) in dctOperatorsDaysArcsMatch.keys():
    dctOperatorsDaysExist.setdefault(o,[]).append(d)
    lstOperatorsDaysExist.append((o,d))


lstOperatorsDaysSessionsExist=[]
dctOperatorsDaysSessionsExist={}
for (d,s,o) in dctDaySessionOperatorRequests.keys():
    lstOperatorsDaysSessionsExist.append((o,d,s))
    dctOperatorsDaysSessionsExist.setdefault((o,d),[]).append(s)

lstOperatorsDaysArcsBegin=[]
for x in lstOperatorsDaysArcsMatch:
    for o in lstOperators:
      if x[2]== 'o'+ str(o) + 'b':
          lstOperatorsDaysArcsBegin.append(x)

dctOperatorsDaysArcsBegin={}
for x in lstOperatorsDaysArcsBegin:
    o,d,i,j= x
    dctOperatorsDaysArcsBegin.setdefault((o,d),[]).append((i,j))

dctOperatorsDaysSessions={}
for x in lstOperatorsDaysSessionsExist:
    o,d,s=x
    dctOperatorsDaysSessions.setdefault((o,d),[]).append(s)

lstOperatorsDays=[]
for o in dctOperatorsDays.keys():
    lst=dctOperatorsDays[o]
    for d in lst:
       lstOperatorsDays.append((o,d))

dctOperatorsDaysRequestsOut={}
dctOperatorsDaysRequestsIn={}

for o in lstOperators:
    for d in dctOperatorsDays[o]:
        for j in dctDaysRequests[d]:
          if (o,d) in dctOperatorsDaysArcsMatch.keys():
              for x in dctOperatorsDaysArcsMatch[o,d]:
                  if x[0]==j:
                      dctOperatorsDaysRequestsOut.setdefault((o,d,j),[]).append(x[1])

for o in lstOperators:
```

```
    for d in dctOperatorsDays[o]:
        for j in dctDaysRequests[d]:
          if (o,d) in dctOperatorsDaysArcsMatch.keys():
                for x in dctOperatorsDaysArcsMatch[o,d]:
                    if x[1]==j:
                        dctOperatorsDaysRequestsIn.setdefault((o,d,j),[]).append(x[0])

lstOperatorsDaysArcsEnd=[]
for x in lstOperatorsDaysArcsMatch:
    for o in lstOperators:
      if x[3]== 'o'+ str(o) + 'e':
         lstOperatorsDaysArcsEnd.append(x)

dctOperatorsDaysArcsEnd={}
for x in lstOperatorsDaysArcsEnd:
    o,d,i,j= x
    dctOperatorsDaysArcsEnd.setdefault((o,d),[]).append((i,j))

dctProjectRequests={}
for r in lstRequests:
    p=dctRequestRefProject[r]
    dctProjectRequests.setdefault(p,[]).append(r)

lstProjectsPure=[]
for r in lstRequestPure:
    p=dctRequestRefProject[r]
    if p not in lstProjectsPure:
      lstProjectsPure.append(p)


lstProjectPureRequestOperator=[]
for p in lstProjectsPure:
    lst=dctProjectRequests[p]
    for r in lst:
        lst1=dctRequestsOperatorsMatch[r]
        for o in lst1:
            lstProjectPureRequestOperator.append((p,r,o))


dctOperatorsDaysRequestsArcs={}
for o in lstOperators:
    for d in dctOperatorsDays[o]:
        for j in dctDaysRequests[d]:
            if (o,d) in dctOperatorsDaysArcsMatch.keys():
              for x in dctOperatorsDaysArcsMatch[o,d]:
                    if x[0]==j:
                        dctOperatorsDaysRequestsArcs.setdefault((o,d,j),[]).append(x)

lstProjectRequests=[]
for r in lstRequests:
    lst=dctRequestsAttributes[r]
    p=lst[0]
    lstProjectRequests.append((p,r))

lstDaysOperators=[]
```

```
for d in lstDays:
    lst=dctDaysOperators[d]
    for o in lst:
        lstDaysOperators.append((d,o))

lstOperatorsDaysMorning=[]
for x in lstOperatorsDaysSessionsExist:
    if x[2]==1:
        lstOperatorsDaysMorning.append((x[0],x[1]))

lstOperatorsDaysMorningAfternoon=[]
for o in lstOperators:
    for d in dctOperatorsDaysExist[o]:
       x=dctOperatorsDaysSessionsExist[o,d]
       if 1 in x and 2 in x:
        lstOperatorsDaysMorningAfternoon.append((o,d))

lstOperatorsDaysAfternoon=[]
for x in lstOperatorsDaysSessionsExist:
    if x[2]==2:
      lstOperatorsDaysAfternoon.append((x[0],x[1]))

dctNodesTt={}
for i in lstV:
    if i[0]=="o":
        x=i
    else:
        x=dctRequestRefProject[i]
    for j in lstV:
        if j[0]=="o":
            y=j
        else:
            y=dctRequestRefProject[j]
        dctNodesTt[i,j]=dctSitesTt[x,y]

lstArcs=[]
lstArcs=list(it.product(lstV , lstV))

lstRequestOperatorOperator=[]
for i in lstRequests:
    if dctRequestNOp[i]==2:
        skill=dctRequestSkill[i]
        for o1 in lstOperators:
            if skill in dctOperatorsSkills[o1] and i in dctOperatorsRequestsMatch[o1]:
               for o2 in lstOperators:
                   if o1!=o2:
                       if skill in dctOperatorsSkills[o2] and i in
dctOperatorsRequestsMatch[o2]:
                            lstRequestOperatorOperator.append((i,o1,o2))

lstMainAlternative=[]
for r in lstRequestMain:
    altern=dctRequestAlternatives[r]
    for a in altern:
        lstMainAlternative.append((r,a))
```

```
lstOperatorsSkill3=[]
for o in lstOperators:
    skills=dctOperatorsSkills[o]
    skill3=3
    if skill3 in skills:
        lstOperatorsSkill3.append(o)

lstAlternAltern=[]
for r in lstRequestMain:
    altern=dctRequestAlternatives[r]
    a1=altern[0]
    a2=altern[1]
    lstAlternAltern.append((a1,a2))

lstOperatorDaySessionAlternPure=[]
for x in lstOperatorsDaysArcsMatch:
    if x[2] in lstRequestAlternative:
        if x[3] in lstRequestPure:
            o=x[0]
            d=x[1]
            a=x[2]
            p=x[3]
            s=dctRequestDaySession[a][1]
            lstOperatorDaySessionAlternPure.append((o,d,s,a,p))

lstOperatorDayAlternPure=[]
for x in lstOperatorsDaysArcsMatch:
    if x[2] in lstRequestAlternative:
        if x[3] in lstRequestPure:
            o=x[0]
            d=x[1]
            a=x[2]
            p=x[3]
            lstOperatorDayAlternPure.append((o,d,a,p))

lstMainAlternativeProject=[]
for r in lstRequestMain:
    altern=dctRequestAlternatives[r]
    p=dctRequestRefProject[r]
    for a in altern:
        lstMainAlternativeProject.append((r,a,p))

lstProjectRequestPure=[]
for r in lstRequestPure:
    p=dctRequestRefProject[r]
    lstProjectRequestPure.append((p,r))

lstProjectRequestAltern=[]
for r in lstRequestAlternative:
    p=dctRequestRefProject[r]
    lstProjectRequestAltern.append((r,p))

dctOperatorsDaysArcsMatchNoAltern={}
lstOperatorsNoAltern=[]
```

```
for o in lstOperators:
    for d in dctOperatorsDays[o]:
      if (o,d) in dctOperatorsDaysArcsMatch.keys():
        lst=dctOperatorsDaysArcsMatch[o,d]
        for l in lst:
            if l[0] not in lstRequestAlternative and l[1] not in lstRequestAlternative:
               dctOperatorsDaysArcsMatchNoAltern.setdefault((o,d),[]).append(l)
               if o not in lstOperatorsNoAltern:
                   lstOperatorsNoAltern.append(o)

dctOperatorsDaysNoAltern={}
for (o,d) in dctOperatorsDaysArcsMatchNoAltern.keys():
     dctOperatorsDaysNoAltern.setdefault(o,[]).append(d)

dctOperatorsDaysArcsMatchAltern={}
lstOperatorsAltern=[]
for o in lstOperators:
    for d in dctOperatorsDays[o]:
      if (o,d) in dctOperatorsDaysArcsMatch.keys():
         lst=dctOperatorsDaysArcsMatch[o,d]
         for l in lst:
             if (l[0] in lstRequestAlternative and l[1] in lstRequestAlternative) or (l[0] in
lstOperatorsHomeBegin and l[1] in lstRequestAlternative) or    (l[0] in lstRequestAlternative and
l[1] in lstOperatorsHomeEnd):
                 dctOperatorsDaysArcsMatchAltern.setdefault((o,d),[]).append(l)
                 if o not in lstOperatorsAltern:
                     lstOperatorsAltern.append(o)

dctOperatorsDaysAltern={}
for (o,d) in dctOperatorsDaysArcsMatchAltern.keys():
     dctOperatorsDaysAltern.setdefault(o,[]).append(d)

dctOperatorsDaysArcsMatchAlternPure={}
lstOperatorsAlternPure=[]
for o in lstOperators:
    for d in dctOperatorsDays[o]:
      if (o,d) in dctOperatorsDaysArcsMatch.keys():
        lst=dctOperatorsDaysArcsMatch[o,d]
        for l in lst:
            if l[0] in lstRequestAlternative and l[1] in lstRequestPure:
               if o not in lstOperatorsAlternPure:
                   dctOperatorsDaysArcsMatchAlternPure.setdefault((o,d),[]).append(l)
                   lstOperatorsAlternPure.append(o)

dctOperatorsDaysAlternPure={}
for (o,d) in dctOperatorsDaysArcsMatchAlternPure.keys():
     dctOperatorsDaysAlternPure.setdefault(o,[]).append(d)

dctRequestAlternOperator={}
for i in lstRequestAlternative:
    lstOp=dctRequestsOperatorsMatch[i]
    for o in lstOp:
        dctRequestAlternOperator.setdefault(i,[]).append(o)
```

```
dctProjectAlternRequests={}
for i in lstRequestAlternative:
    p=dctRequestRefProject[i]
    dctProjectAlternRequests.setdefault(p,[]).append(i)

lstProjectsNotPure=[]
for r in lstRequestAlternative:
    p=dctRequestRefProject[r]
    if p not in lstProjectsNotPure:
        lstProjectsNotPure.append(p)

model=AbstractModel()

model.Projects= Set(dimen=1,initialize=lstProjects)
model.ProjectsNotPure= Set(dimen=1, initialize=lstProjectsNotPure)
model.ProjectsPure=Set(dimen=1, initialize=lstProjectsPure)
model.Requests= Set(dimen=1,initialize=lstRequests)
model.Days= Set(dimen=1,initialize=lstDays)
model.TimeSessions= Set(dimen=1,initialize=lstTimeSessions)
model.Operators= Set(dimen=1,initialize=lstOperators)
model.A=Set(dimen=4, initialize=lstOperatorsDaysArcsMatch)
model.Ods=Set(dimen=3, initialize=lstOperatorsDaysSessionsExist)
model.Io=Set(dimen=2, initialize=lstRequestsOperatorsMatch)
model.OperatorsDays=Set(dimen=2, initialize=lstOperatorsDaysExist)
model.RequestsDaysOperators=Set(dimen=3, initialize=lstRequestsDaysOperatorsMatch)
model.ProjectPureRequestOperator=Set(dimen=3, initialize=lstProjectPureRequestOperator)
model.ProjectRequests=Set(dimen=2, initialize=lstProjectRequests)
model.OperatorsDaysSessionHome=Set(dimen=4, initialize=lstOperatorsDaysSessionHome)
model.DaysOperators=Set(dimen=2, initialize=lstDaysOperators)
model.Odij=Set(dimen=4, initialize=lstOperatorsDaysRequestsArcsMatch)
model.Odsj=Set(dimen=4, initialize=lstOperatorDaySessionRequests)
model.Arcs=Set(dimen=2, initialize=lstArcs)
model.OperatorsDaysMorning=Set(dimen=2, initialize=lstOperatorsDaysMorning)
model.OperatorsDaysAfternoon=Set(dimen=2, initialize=lstOperatorsDaysAfternoon)
model.OperatorsDaysMorningAfternoon=Set(dimen=2,
initialize=lstOperatorsDaysMorningAfternoon)
model.RequestOperatorOperator=Set(dimen=3, initialize= lstRequestOperatorOperator)

model.MainAlternative=Set(dimen=2, initialize=lstMainAlternative)
model.AlternAltern=Set(dimen=2, initialize=lstAlternAltern)
model.OperatorDaySessionAlternPure=Set(dimen=5, initialize=lstOperatorDaySessionAlternPure)
model.ProjectRequestsPure=Set(dimen=2, initialize=lstProjectRequestPure)
model.MainAlternativeProject=Set(dimen=3, initialize=lstMainAlternativeProject)
model.OperatorDayAlternPure=Set(dimen=4, initialize=lstOperatorDayAlternPure)
model.RequestAlternProject=Set(dimen=2, initialize=lstProjectRequestAltern)

model.MaxWeeklyHours= Param(model.Operators, initialize=dctOperatorsMaxHours, within=Any)
model.ReqnOperators= Param(model.Requests, initialize=dctRequestNOp, within=Any)
model.ServiceTime= Param(model.Requests, initialize= dctRequestServiceTime, within=Any)
model.StartingTime=Param(model.Requests, initialize= dctRequestStartingTime, within=Any)
model.EndingTime=Param(model.Requests, initialize= dctRequestEndingTime, within=Any)
model.TravelTime= Param(model.Arcs, initialize=dctNodesTt, within=Any)
model.HourlyCost= Param(model.Operators, initialize=dctOperatorsHCost, within=Any)
model.RevenueProj= Param(model.Projects, initialize=dctProjectRevenue, within=Any)
model.OperatorsDaysAvailability=Param(model.Operators, initialize=dctOperatorsDays,
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within=Any)
model.ProjectNumberRequests=Param(model.Projects, initialize=dctProjectNRequests,
within=Any)

model.z= Var(model.Projects, within =Binary)
model.r= Var(model.ProjectsNotPure, within =Binary)
model.x= Var(model.A, within=Binary)
model.y= Var(model.Ods, within=Binary)
model.u= Var(model.Io, within=Binary)
model.w= Var(model.Io, within=NonNegativeReals)
model.f= Var(model.OperatorsDaysSessionHome, within=NonNegativeReals)

def OBJ_rule(model):
    return sum(model.RevenueProj[p]*model.z[p] for p in model.Projects) -
(sum((model.HourlyCost[o])*((model.f[o,d,s,dctOperatorsHomeEnd[o]]) -
(model.f[o,d,s,dctOperatorsHomeBegin[o]])) for o in lstOperators for d in dctOperatorsDaysExist[o]
for s in dctOperatorsDaysSessions[o,d])) - (sum (22*model.TravelTime[i,j]*model.x[o,d,i,j] for o in
lstOperatorsNoAltern for d in dctOperatorsDaysNoAltern[o] for (i,j) in
dctOperatorsDaysArcsMatchNoAltern[o,d])) - sum
(22*model.TravelTime[dctOperatorsHomeBegin[o],j]*model.x[o,d,i,j] for o in
lstOperatorsAlternPure for d in dctOperatorsDaysAlternPure[o] for (i,j) in
dctOperatorsDaysArcsMatchAlternPure[o,d])
model.OBJ=Objective(rule=OBJ_rule, sense=maximize)

def CONS2_rule(model,o,d):
    return sum(model.x[o, d, i, j] for (i,j) in dctOperatorsDaysArcsBegin[o,d]) ==
sum(model.y[o,d,s] for s in dctOperatorsDaysSessionsExist[o,d])
model.CONS2=Constraint(model.OperatorsDays, rule=CONS2_rule)

def CONS3_rule(model,j,d,o):
    return sum(model.x[o,d,i,j] for i in dctOperatorsDaysRequestsIn[o,d,j]) == sum(model.x[o,d,j,i]
for i in dctOperatorsDaysRequestsOut[o,d,j])
model.CONS3=Constraint(model.RequestsDaysOperators, rule=CONS3_rule)

def CONS4_rule(model,o,d):
    return sum (model.x[o,d,i,j] for (i,j) in dctOperatorsDaysArcsEnd[o,d]) == sum (model.y[o,d,s]
for s in dctOperatorsDaysSessions[o,d])
model.CONS4=Constraint(model.OperatorsDays, rule= CONS4_rule)

def CONS5_rule(model,i,d,o):
        return sum (model.x[o,d,i,j] for (i,j) in dctOperatorsDaysRequestsArcs[o,d,i]) ==
model.u[i,o]
model.CONS5=Constraint(model.RequestsDaysOperators, rule=CONS5_rule)

def CONS6_rule(model,p,i,o):
        return model.u[i,o]<=model.z[p]
model.CONS6=Constraint(model.ProjectPureRequestOperator, rule=CONS6_rule)

def CONS7_rule(model, p,i):
    return sum(model.u[i,o] for o in dctRequestsOperatorsMatch[i]) >=
model.ReqnOperators[i]*model.z[p]
model.CONS7=Constraint(model.ProjectRequestsPure, rule=CONS7_rule)

def CONS8_rule(model,o,d):
    return model.f[o,d,1,dctOperatorsHomeBegin[o]] >= 7*model.y[o,d,1]
```

```
model.CONS8=Constraint(model.OperatorsDaysMorning, rule=CONS8_rule)

def CONS9_rule(model, o,d):
    return model.f[o,d,1,dctOperatorsHomeEnd[o]] <= (11*model.y[o,d,1]) - model.y[o,d,2]+1
model.CONS9=Constraint(model.OperatorsDaysMorningAfternoon, rule=CONS9_rule)

def CONS10_rule(model, o,d):
    return model.f[o,d,2,dctOperatorsHomeBegin[o]] >= 18*model.y[o,d,2] + (2*model.y[o,d,1]) - 2
model.CONS10=Constraint(model.OperatorsDaysMorningAfternoon, rule=CONS10_rule)

def CONS11_rule(model,o,d):
    return model.f[o,d,2,dctOperatorsHomeEnd[o]] <= 21.5*model.y[o,d,2]
model.CONS11=Constraint(model.OperatorsDaysAfternoon, rule=CONS11_rule)

def CONS12_rule(model,o,d,i,j):
    if i in lstRequestAlternative and j in lstRequestAlternative:
        return model.w[i,o] + model.ServiceTime[i] <= model.w[j,o] +21.5*(1-model.x[o,d,i,j])
    if i in lstRequestAlternative and j in lstRequestPure:
        return model.w[i,o] + model.ServiceTime[i] +
model.TravelTime[dctOperatorsHomeBegin[o],j]<= model.w[j,o] +21.5*(1-model.x[o,d,i,j])
    else:
        return model.w[i,o] + model.ServiceTime[i] + model.TravelTime[i,j]<= model.w[j,o]
+21.5*(1-model.x[o,d,i,j])
model.CONS12=Constraint(model.Odij, rule=CONS12_rule)

def CONS13_rule(model, o,d,s,j):
    if j in lstRequestAlternative:
        return model.f[o,d,s,dctOperatorsHomeBegin[o]] <= model.w[j,o] + 21.5*(1-
model.x[o,d,dctOperatorsHomeBegin[o],j])
    else:
        return model.f[o,d,s,dctOperatorsHomeBegin[o]] +
model.TravelTime[dctOperatorsHomeBegin[o],j] <= model.w[j,o] + 21.5*(1-
model.x[o,d,dctOperatorsHomeBegin[o],j])
model.CONS13=Constraint(model.Odsj, rule=CONS13_rule)

def CONS14_rule(model, o,d,s,i):
    if i in lstRequestAlternative:
        return model.w[i,o] + model.ServiceTime[i] <= model.f[o,d,s,dctOperatorsHomeEnd[o]] +
21.5*(1-model.x[o,d,i,dctOperatorsHomeEnd[o]])
    else:
      return model.w[i,o] + model.ServiceTime[i] +
model.TravelTime[i,dctOperatorsHomeEnd[o]]<= model.f[o,d,s,dctOperatorsHomeEnd[o]] +
21.5*(1-model.x[o,d,i,dctOperatorsHomeEnd[o]])
model.CONS14=Constraint(model.Odsj, rule=CONS14_rule)

def CONS15_rule(model, i,o):
    return model.StartingTime[i]*model.u[i,o] <= model.w[i,o]
model.CONS15=Constraint(model.Io, rule=CONS15_rule)

def CONS15b_rule(model, i,o):
    return model.w[i,o] <= model.EndingTime[i]*model.u[i,o]
model.CONS15b=Constraint(model.Io, rule=CONS15b_rule)

def CONS16_rule(model,o):
    return sum((model.f[o,d,s,dctOperatorsHomeEnd[o]]) -
```

```
(model.f[o,d,s,dctOperatorsHomeBegin[o]]) for d in model.OperatorsDaysAvailability[o] for s in
model.TimeSessions) <= model.MaxWeeklyHours[o]
model.CONS16=Constraint(model.Operators, rule=CONS16_rule)

def CONS17_rule(model,o,d,s):
    return model.y[o,d,s] <= sum (model.u[i,o] for i in dctDaySessionOperatorRequests[d,s,o])
model.CONS17=Constraint(model.Ods, rule=CONS17_rule)

def CONS18_rule(model,o,d,s):
    return model.f[o,d,s,dctOperatorsHomeBegin[o]] <= 22*model.y[o,d,s]
model.CONS18=Constraint(model.Ods, rule=CONS18_rule)

def CONS19_rule(model,i,o1,o2):
    return model.w[i,o1] <= model.w[i,o2] - 22*(model.u[i,o1] + model.u[i,o2]-2)
model.CONS19=Constraint(model.RequestOperatorOperator, rule=CONS19_rule)

def CONS20_rule(model,i,o1,o2):
    return model.w[i,o1] >= model.w[i,o2] + 22*(model.u[i,o1] + model.u[i,o2]-2)
model.CONS20=Constraint(model.RequestOperatorOperator, rule=CONS20_rule)

def CONS21_rule(model,o,d,s):
    return model.f[o,d,s,dctOperatorsHomeEnd[o]] - model.f[o,d,s,dctOperatorsHomeBegin[o]] >=
sum(model.ServiceTime[i]*model.u[i,o] for i in dctDaySessionOperatorRequests[d,s,o])
model.CONS21=Constraint(model.Ods, rule=CONS21_rule)

def CONS22_rule(model,im,ia,p):
    return sum((model.u[im,o] + model.u[ia,o]) for o in dctRequestAlternOperator[ia]) ==
model.z[p]
model.CONS22=Constraint(model.MainAlternativeProject, rule=CONS22_rule)

def CONS23_rule(model, ia1, ia2):
    return sum(model.u[ia1,o] for o in dctRequestsOperatorsMatch[ia1]) == sum(model.u[ia2,o]
for o in dctRequestsOperatorsMatch[ia2])
model.CONS23=Constraint(model.AlternAltern, rule=CONS23_rule)

def CONS24_rule(model,o,d,ia,j):
    return model.w[ia,o]+ model.ServiceTime[ia]*model.u[ia,o] +
model.TravelTime[dctOperatorsHomeBegin[o],j]*model.x[o,d,ia,j] <= model.w[j,o]
model.CONS24=Constraint(model.OperatorDayAlternPure, rule=CONS24_rule)

def CONS25_rule(model):
    return sum(model.r[p] for p in lstProjectsNotPure) <= 5
model.CONS25=Constraint(rule=CONS25_rule)

def CONS26_rule(model, p):
    return model.r[p] <= model.z[p]
model.CONS26=Constraint(model.ProjectsNotPure, rule=CONS26_rule)

def CONS27_rule(model, p):
    return 2*model.ProjectNumberRequests[p]*model.r[p] >= sum(model.u[i,o] for i in
dctProjectAlternRequests[p] for o in dctRequestAlternOperator[i])
model.CONS27=Constraint(model.ProjectsNotPure, rule=CONS27_rule)

def CONS28_rule(model,p):
    return model.r[p] <= sum(model.u[i,o] for i in dctProjectAlternRequests[p] for o in
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dctRequestAlternOperator[i] )
model.CONS28=Constraint(model.ProjectsNotPure, rule=CONS28_rule)

projectFolderPath= os.path.dirname(os.path.realpath("__file__"))

logPath=(projectFolderPath+"\\logs\\log.txt")
outPath=(projectFolderPath+"\\logs\\out.txt")
executableCplexPath = projectFolderPath + "\\solver\\cplex.exe"

instance=model.create_instance()
dateTimeObj = datetime.now()
timeStampInstanceCreated = dateTimeObj.strftime("%Y-%m-%d %H:%M:%S")
print("Instance created=" +str(timeStampInstanceCreated))

opt = SolverFactory("cplex", solver_io="lp", executable=executableCplexPath)
gaplimit=0.01

opt.options['mipgap']=gaplimit
opt.options['emphasis mip'] = 2
opt.options['mip display'] = 2

with Redirect(logPath, 'w'):
        results = opt.solve(instance, tee=True)
        model.solutions.load_from(results)

dctSol_y={}
dctSol_x={}
dctSol_u={}
dctSol_w={}
dctSol_f={}
dctSol_z={}
dctSol_r={}

exprobject=getattr(instance,'y')
for index in exprobject:
    dctSol_y.setdefault((index[0],index[1],index[2]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'x')
for index in exprobject:
    dctSol_x.setdefault((index[0],index[1],index[2],index[3]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'u')
for index in exprobject:
    dctSol_u.setdefault((index[0],index[1]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'w')
for index in exprobject:
        dctSol_w.setdefault((index[0],index[1]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'f')
for index in exprobject:
    dctSol_f.setdefault((index[0],index[1],index[2],index[3]),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'z')
for index in exprobject:
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        dctSol_z.setdefault((index),[]).append(value(exprobject[index]))

exprobject=getattr(instance,'r')
for index in exprobject:
        dctSol_r.setdefault((index),[]).append(value(exprobject[index]))

lstSol_y=[]
for k in dctSol_y.keys():
        if dctSol_y[k][0]>0.1:
            lstSol_y.append([k[0],k[1],k[2], dctSol_y[k][0]])
lstHeader_y=["o","d","s","y"]
dfSol_y=pd.DataFrame(lstSol_y, columns=lstHeader_y)
dfSol_y=dfSol_y.sort_values(['o', 'd', 's', 'y'], ascending=[True,True, True, True])
dfSol_y.to_csv(projectFolderPath+"\\logs\\dfSol_y.csv", header=True, index=None, sep='|',
mode='w')

lstSol_x=[]
for k in dctSol_x.keys():
        if dctSol_x[k][0]>0.1:
            lstSol_x.append([k[0],k[1],k[2],k[3],dctSol_x[k][0]])
lstHeader_x=["o","d","i","j", "x"]
dfSol_x=pd.DataFrame(lstSol_x, columns=lstHeader_x)
dfSol_x=dfSol_x.sort_values(['o', 'd', 'i','j', 'x'], ascending=[True,True, True, True, True])
dfSol_x.to_csv(projectFolderPath+"\\logs\\dfSol_x.csv", header=True, index=None, sep='|',
mode='w')

lstSol_u=[]
for k in dctSol_u.keys():
        if dctSol_u[k][0]>0.1:
            lstSol_u.append([k[0],k[1], dctSol_u[k][0]])
lstHeader_u=["i" ,"o", "u"]
dfSol_u=pd.DataFrame(lstSol_u, columns=lstHeader_u)
dfSol_u=dfSol_u.sort_values(['i','o', 'u'], ascending=[True,True, True])
dfSol_u.to_csv(projectFolderPath+"\\logs\\dfSol_u.csv", header=True, index=None, sep='|',
mode='w')

lstSol_f=[]
for k in dctSol_f.keys():
        if dctSol_f[k][0]>0.1:
            lstSol_f.append([k[0],k[1],k[2],k[3],dctSol_f[k][0]])
lstHeader_f=["o","d","s","i","t",]
dfSol_f=pd.DataFrame(lstSol_f, columns=lstHeader_f)
dfSol_f=dfSol_f.sort_values(['o', 'd', 's','i','t'], ascending=[True,True, True, True, True])
dfSol_f.to_csv(projectFolderPath+"\\logs\\dfSol_f.csv", header=True, index=None, sep='|',
mode='w'

lstSol_w=[]
for k in dctSol_w.keys():
        if dctSol_w[k][0]>0.1:
            lstSol_w.append([k[0],k[1],dctSol_w[k][0]])
lstHeader_w=["i","o","w"]
dfSol_w=pd.DataFrame(lstSol_w, columns=lstHeader_w)
dfSol_w=dfSol_w.sort_values(['o','i','w'], ascending=[True,True, True])
dfSol_w.to_csv(projectFolderPath+"\\logs\\dfSol_w.csv", header=True, index=None, sep='|',
mode='w')
```

```
lstSol_z=[]
for k in dctSol_z.keys():
    if dctSol_z[k][0]>0.1:
        lstSol_z.append([k,dctSol_z[k][0]])
lstHeader_z=["p","z"]
dfSol_z=pd.DataFrame(lstSol_z, columns=lstHeader_z)
dfSol_z=dfSol_z.sort_values(['p','z'], ascending=[True,True])
dfSol_z.to_csv(projectFolderPath+"\\logs\\dfSol_z.csv", header=True, index=None, sep='|',
mode='w')

lstSol_r=[]
for k in dctSol_r.keys():
    if dctSol_r[k][0]>0.1:
        lstSol_r.append([k,dctSol_r[k][0]])
lstHeader_r=["p","r"]
dfSol_r=pd.DataFrame(lstSol_r, columns=lstHeader_r)
dfSol_r=dfSol_r.sort_values(['p','r'], ascending=[True,True])
dfSol_r.to_csv(projectFolderPath+"\\logs\\dfSol_r.csv", header=True, index=None, sep='|', mode='w')
```