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Digital health for environmentally sustainable cancer screening

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This study explores the role of digital health in promoting environmental sustainability through a pilot study performed in rural areas in Tuscany (Italy). A multi-screening model, based on a mobile multi-screening unit (MMSU) and digital health tools, was deployed to reduce the travelled distances required for cancer screening. Serving 19 municipalities in a mountainous area, the MMSU reduced patient and caregivers' travel, cutting CO_2-equivalent emissions by over 90% compared to conventional healthcare models. The project demonstrates how integrating digital health technologies, such as telemedicine for data transmission and centralised reporting, can enhance healthcare accessibility and environmental sustainability. By consolidating multiple screenings into one visit, the MMSU model offers a scalable solution for reducing healthcare's carbon footprint while addressing barriers to care in underserved areas. This pilot study highlights the potential of digital health to align service delivery with environmental objectives, contributing to the broader discourse on sustainable healthcare innovation.

Digital health has emerged as a transformative driver in healthcare, offering unprecedented opportunities to improve the efficiency and accessibility of services through innovative technologies[1,2]. These developments have significantly contributed to universal healthcare service delivery, streamlining management processes, and enhancing patient access to care. From telemedicine to health data management systems, digital health has rapidly evolved[3], particularly in response to the COVID-19 pandemic, which accelerated the adoption of digital tools across healthcare sectors globally[4–6]. Hence, in the wake of the pandemic emergency, the European Union and single-member states have funded substantial projects at both the infrastructure and organisational and training levels to increase the digitisation of public services[7].

While the healthcare sector has leveraged digital transformation to improve service delivery[8], its potential to drive sustainable healthcare practices, particularly in strengthening climate resilience, remains largely unexplored[9], leaving a critical dimension of healthcare innovation insufficiently addressed. Recognised as a significant contributor to global greenhouse gas emissions[10–12], the healthcare sector faces increasing pressure to adopt more sustainable practices. Within the European context, the European Green Deal aims to make Europe the first climate-neutral continent by 2050[13], in line with the Paris Agreement on climate change[14], placing additional emphasis on the need for healthcare systems to contribute to these sustainability goals. Environmental sustainability in healthcare involves strategies to reduce the sector's environmental impact by lowering carbon emissions, optimising resource use, and enhancing system resilience to the challenges of climate change while ensuring the continued delivery of healthcare services and the improvement of population health outcomes[15]. These approaches align closely with the broader objectives of climate action and sustainable development, underscoring their growing importance in rethinking healthcare delivery models.

Among the various initiatives promoting digital health in Europe, environmental sustainability is rarely treated as a primary objective. An exploratory analysis of the EU Funding & Tenders Portal reveals that out of 60 projects related to digital health, only two explicitly mention environmental sustainability, and even in these cases, sustainability is positioned as a secondary goal rather than being on equal footing with digital health innovation[16]. More specifically, Italy lags in integrating sustainability considerations into its health policy frameworks, such as the National Recovery and Resilience Plan (PNRR), which heavily focuses on digital health yet pays insufficient attention to the environmental ramifications of healthcare[17]. This underscores a significant gap in European healthcare policy, where the intersection of digital health and environmental sustainability still needs to be developed and funded. This disparity highlights the need to rethink how digital health projects can be designed to address climate resilience and environmental sustainability as integral, rather than ancillary, objectives of healthcare delivery.

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One key element in delivering sustainable and equitable healthcare is the concept of proximity care. Reducing the distance that citizens must travel to access healthcare services improves access and health outcomes[18] and reduces the environmental burden associated with long-distance travel and associated CO_2-equivalent emissions (CO_2-eq). According to the sustainable healthcare framework proposed by MacNeill et al.[19], proximity care aligns with principles aimed at minimising emissions and optimising the efficiency and environmental performance of care delivery. This framework emphasises three core strategies: reducing the demand for health services, aligning the supply of services with demand, and minimising emissions from service delivery. To operationalise these principles, this article presents a pilot project conducted in rural areas of Italy, which integrates digital health tools with proximity care to deliver a more environmentally and socially sustainable provision of preventive services. This model addresses the dual challenges of geographical barriers and environmental impact by bringing healthcare services closer to the population using digital health tools, particularly in rural and mountainous areas. Aligned with two core principles of MacNeill et al.'s framework, the project promotes health and prevents disease, thereby reducing the demand for healthcare services while simultaneously decarbonising healthcare operations. Indeed, by leveraging digital tools, the model enhances accessibility and equity, demonstrating a practical application of proximity care that reduces patient travel and its associated environmental footprint, fostering a more sustainable and inclusive healthcare model.

This pilot project is conducted in the mountainous health district of Valle del Serchio, located in the Province of Lucca, Italy. The district spans 390.68 km² and includes 19 municipalities with approximately 59,000 residents. Notably, this area exhibits Tuscany's highest cancer mortality rate, recorded at 276 per 100,000 inhabitants, significantly surpassing the regional average of 245 per 100,000 in 2020[20,21] Due to its geographic isolation and economic decline, including a significant outflow of younger populations[22] the region faces barriers to healthcare access, resulting in lower participation in screening programmes compared to the Tuscan average[23].

To address these challenges, the new scalable screening model aims to reduce the distance residents must travel for access to cancer screenings, thereby lowering CO_2-eq emissions and increasing participation rates by providing multiple services at a single location thereby saving both time and costs[17]. Moreover, this model consolidates several screening procedures into a single visit by adopting a screening invitation manager, an algorithm for organising invitation letters. This pilot study is developed in a specific area of Italy and the findings are intended to be generalised, extending beyond local implications to provide insights applicable to similar contexts in other regions.

Implementing the new screening model involved two groups of professionals: (1) medical professionals operating on the mobile unit and (2) administrative staff responsible for managing the invitation process. The screening invitation manager was implemented as a technological innovation within the workflow of the administrative offices. As part of the programme, citizens are invited via letter and are not required to collect data at home or interact with digital tools. This approach ensures inclusivity and accessibility for all demographic groups, particularly those less familiar with digital health technologies. Hence, administrative staff and healthcare professionals primarily use the digital component to manage data and optimise workflows. During the visit, based on the individual's age, breast (mammography), colorectal (immuno-chemical faecal occult blood test), and cervical cancer screenings (Pap test or HPV test) are offered along with early melanoma detection through a digital video dermoscopy. The service is provided as close as possible to patients' homes using a mobile multi-screening unit (MMSU). This unit is staffed by a radiologic technologist, an obstetrician, and a nurse, who perform the tests and collect screening data for both conventional screenings and early diagnosis programmes, e.g., dermoscopy. With the new service provision, the composition of the healthcare team remains the same as in the traditional programme of screening.

As illustrated in a previous study, integrating compact, advanced diagnostic tools—comparable to hospital standards—with efficient data management and transmission systems ensures citizen privacy and seamless sharing of health information with hospital networks[24]. In addition, the centralised management of appointments through a dedicated application and the ability to conduct multiple screenings in a single visit highlight the direct impact of digital health on environmental, social, economic and organisational aspects.

The MMSU visits each municipality, ensuring screenings occur as close as possible to residents' homes. Data acquisition (mammography images, dermoscopy images, etc.) is performed onsite. At the same time, medical reporting and analysis are centralised at the Local Health Authority (LHA), leveraging telemedicine to transfer patient information efficiently. This separation of diagnostic data acquisition and reporting allows for economies of scale and more specialised interpretation of results, enhancing the quality of care.

Behavioural and social levers, combined with digital health tools, form the project's foundation. Beyond the multi-service approach—where multiple screenings are performed in a single visit—a robust communication and promotion campaign led by local mayors, general practitioners (GP), and third-sector organisations has also supported the initiative. Moreover, invited citizens may find reassurance in the continuity of care, as the same healthcare professionals—often those they have previously encountered during screenings at the LHA facilities—will be delivering the service at the MMSU. This familiarity and the *me-too* processes can enhance trust and comfort, potentially increasing participation rates. The MMSU travels to central locations within municipalities, such as local town squares, further enhancing accessibility. Beyond digital health integration, these strategies have been integral to the model as mechanisms to "push" participation and increase adherence to preventive screening programmes over time.

Results

Environmental impact assessment

We assessed the environmental impact of the mobile healthcare unit by comparing pre-pilot and pilot scenarios. The comparison was made between traditional health centre attendance and MMSU usage, focusing on the reduction of CO_2-eq emissions and distance travelled by participants and by the MMSU.

Pre-pilot scenario

A baseline estimate was established from a previous study on the possible implementation of the MMSU, which served to support the initiation of the

Table 1 | Summary of emission reduction linked to the environmental costs for screening

YEAR 2020	Traditional delivery of screenings	MMSU model	Annual emission reduction
Total travel emissions linked to cancer-screening programmes—women (kgCO_2-eq)	31,721.12	656.38	−31,428.72
Total travel emissions linked to cancer-screening programmes—men (kgCO_2-eq)	3785.25	148.18	−3637.06
Total emissions (kgCO_2-eq)	35,870.36	804.57	−35,065.79

Comparison between the current and future MMSU model, year 2020.

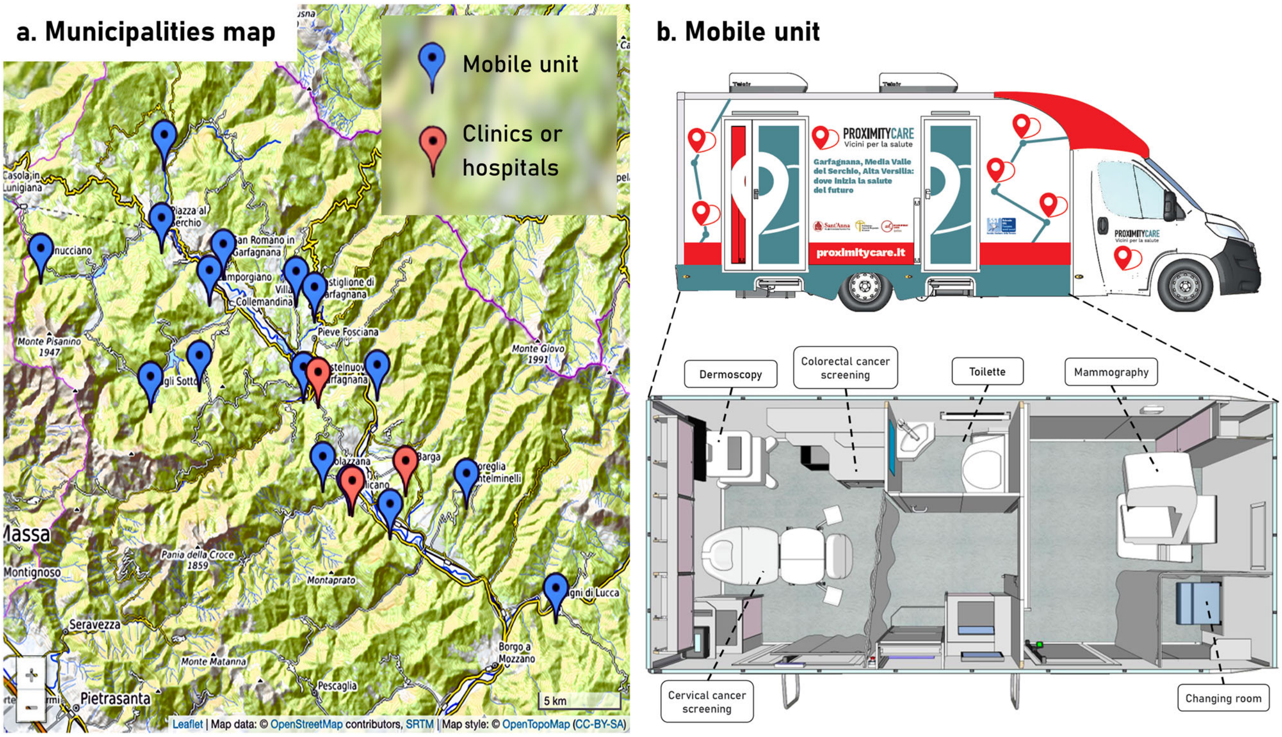

Fig. 1 | Geographic distribution of municipalities visited by the MMSU and MMSU overview. **a** The map illustrates the MMSU's travel destinations across the Valle del Serchio health district (Tuscany, Italy) from October 2023 to July 2024. Blue pins mark 16 of the district's 19 municipalities reached by the MMSU for preventive screening services. Red pins represent the locations of the three fixed healthcare facilities traditionally used for these services. **b** MMSU overview—outside and inside. The MMSU has an entrance for each of the two rooms. The unit is equipped to provide multiple preventive services, including dermoscopy, colorectal cancer screening, mammography, and cervical cancer screening, with dedicated spaces for each. Additionally, the layout includes a changing room and a toilette, ensuring comfort and privacy for patients.

Table 2 | Environmental impact of travel emissions for traditional screenings versus the MMSU during the pilot phase

PILOT PHASE (October 2023–July 2024)	Adhesion rate	Travel emissions traditional delivery of screenings (kgCO_2-eq)	Travel emissions MMSU model (kgCO_2-eq)	Emission reduction (kgCO_2-eq)
Multi-screening programmes	66%	8334	357	
Single-screening programmes	54%	5074		
Total	60%	13,408	357	13,051

The table compares kgCO_2-eq travel emissions between traditional health centre delivery of screenings and the MMSU model. Emission reductions are presented for both multi-screening and single-screening programmes.

pilot[17]. Table 1 presents the key environmental metrics before introducing the current pilot project. As shown in Table 1, the possible implementation of the MMSU would lead to a reduction of roughly 35 tons of CO_2-eq emissions compared to traditional fixed health centres.

Pilot project results

During two pilot phases (2023 and 2024), 2668 residents from 16 out of the 19 municipalities (Fig. 1a) of the Valle del Serchio health district were invited to participate in cancer screenings via the MMSU (Fig. 1b). The 2023 pilot involved 5 municipalities over 16 days, with a total of 96 h dedicated to screenings, operating 6-h shifts each day from 8 a.m. to 2 p.m. A total of 1033 residents were

invited, and the healthcare and supporting personnel included 4 radiologic technologists, 2 obstetricians, 3 nurses, and 3 drivers. The medical staff worked on a rotational basis in the most efficient combination, ensuring that only one professional from each role (e.g., one radiologic technologist, one obstetrician, one nurse) was present at any given time. In 2024, the pilot expanded to 11 municipalities over 34 days, totalling 204 h, with the same 6-h daily schedule. A larger group of 1635 residents was invited to participate. The personnel involved increased to include 4 radiologic technologists, 3 obstetricians, 6 nurses, and 3 drivers, continuing the rotation system to maintain efficiency with one professional from each category on duty at a time.

Of all multi-screening invitees of both pilot phases, 66% (502 out of 756) attended their appointment, while 54% (1032 out of 1912) of single-screening invitees participated. The data also show an upward trend in attendance over time, with approximately 20% of individuals attending a traditional screening also participating in the melanoma early diagnosis programme offered through video dermoscopy. Table 2 summarises a reduction of 97% in CO_2-eq emissions and travel distances resulting from the implementation of the MMSU, compared to traditional health centre attendance.

The data are broken down by multi-screening and single-screening services, highlighting the environmental impact reductions achieved through the MMSU model. Both multi-screening and single-screening participation rates have increased over time, with further improvements anticipated as the project consolidates. As the mobile screening initiative becomes more established, single-screening attendance is expected to gradually align with the higher participation seen in multi-screening services. For colorectal cancer screening, in particular, results are already positive, having maximised the possibility of collecting samples as close to residents' homes as possible, ensuring broader coverage and strong participation rates.

Table 3 | The environmental impact of travel emissions for traditional screenings, divided by invitation types

PILOT PHASE (October 2023–July 2024)	Adhesion rate	Travel emissions traditional delivery of screenings ($kgCO_2$-eq)
Cervical screening	60%	797
Cervical and breast cancer screening	74%	627
Cervical, colorectal, and breast cancer screening	43%	777
Cervical and colorectal screening	62%	980
Colorectal and breast cancer screening	71%	5950
Breast cancer screening	66%	2220
Colorectal screening	55%	2057
Total	61%	13,408

The table illustrates the projected travel emissions linked to conventional health centre delivery of screenings had the mobile MMSU not been introduced. It details travel emissions for multi-screening and single-screening programmes, categorised by invitation type.

This highlights the potential for further growth in engagement across all screening services as the project matures.

Table 3 illustrates the travel emissions that would have occurred with conventional health centre delivery of screenings had the mobile MMSU not been introduced. Specifically, it details the emissions and adherence associated with traditional screening delivery, categorised by invitation type. The adhesion rate across various invitation types averaged 61%. This indicates a relatively strong engagement, particularly in screenings with higher rates, such as cervical and breast cancer screenings (74% and 66%, respectively). Traditional delivery methods resulted in a total travel emission of 13,408 kgCO2-eq, contrasting sharply with the 357 kgCO2-eq emissions recorded for the MMSU model. This reduction underscores the environmental advantages of the mobile unit. Notably, the highest reduction in CO2 emissions was observed in the colorectal and breast cancer screening category. This reduction can be linked to the higher number of invited participants and the elevated adhesion rates for this screening type. Furthermore, this category also involved longer travel distances, as mammography services are centralised at a single fixed location. In contrast, the other screenings allow citizens to choose from multiple nearby healthcare facilities—two for cervical screenings and four for colorectal screenings.

Discussion

The proposed mobile multi-screening model, tested in the Valle del Serchio health district, demonstrates how innovative, scalable and digitalised healthcare delivery models can contribute to both Sustainable Development Goal 13 (Climate Action) and Sustainable Development Goal 10 (Reduced Inequalities), while directly addressing Sustainable Development Goal 3 (Good Health and Well-being)[25]. By employing an MMSU equipped with digital health tools, the model reduces the environmental impact of healthcare services while also mitigating geographic and socio-economic barriers to healthcare access, thus improving health and well-being of individuals and communities.

The MMSU significantly reduces patient travel distances, critical in rural and remote areas where residents often need to travel long distances to reach healthcare facilities and take care of themselves. This reduction in travel directly supports SDG 13 by lowering CO_2-eq emissions associated with healthcare access. Digital technologies within the unit enhance efficiency and sustainability, allowing for the remote transmission of health data and reducing the need for repeated visits to healthcare centres. By providing a compact yet comprehensive set of screening services, the MMSU minimises the environmental footprint of healthcare delivery and enhances the healthcare system's overall resilience to climate-related disruptions.

The model actively addresses SDG 10 by delivering healthcare services directly to underserved populations, reducing disparities and promoting equity. In regions such as Valle del Serchio, where geographic isolation often limits access to preventive services, the MMSU serves as a critical resource, particularly for elderly individuals and those with mobility challenges. By adopting a proactive approach that brings the healthcare system closer to people, this model bridges the gap between rural and urban healthcare access. It ensures that individuals in remote areas are not excluded from essential services, such as cancer screenings[26]. Additionally, the model lowers travel costs for the population, enhancing social sustainability and increasing participation in preventive programmes.

The mobile healthcare unit also offers advantages in terms of economic sustainability. Unlike fixed healthcare facilities, the MMSU can be shared across multiple geographical areas, reducing operational and maintenance costs while maximising the efficient use of resources. This healthcare delivery model can be more cost-effective and flexible, allowing it to reach populations in different geographic locations without requiring extensive infrastructure. Regarding resource optimisation, by grouping screenings into one appointment and using an algorithm to optimise scheduling, the MMSU model reduces unnecessary trips and resource consumption, also promoting adhesion.

As the project progresses and the appropriate amount of data is collected, a long-term sustainability perspective is incorporated, with emphasis not only on immediate outcomes but also on the project's potential for enduring impact and scalability. This involves evaluating its capacity to enhance adherence to preventative healthcare programmes, thereby reducing reliance on hospital-based services and lowering the environmental footprint of such services. The evaluation framework aligns with the triple bottom line (TBL) approach, integrating environmental, social, and economic sustainability metrics. Key indicators, such as reductions in travel distances and improvements in adherence rates, will be closely monitored. These metrics have considerable implications for environmental outcomes and social benefits, including reduced travel expenses, minimised disruption to the working time of informal carers, and lower opportunity costs associated with time spent attending screenings. Furthermore, data collection on the reported experience and social impacts for those participating in screenings on the mobile unit is currently underway. After completing their screening, participants are invited to voluntarily complete a questionnaire assessing their experience with the service provided. To conclude, focused analyses will assess the project's scalability, evaluating its potential to maintain both environmental and economic benefits as participation increases.

This study serves as an initial step toward understanding the integration of environmental sustainability in healthcare. While it establishes a foundation, further research is required to explore additional environmental sustainability measures, including energy consumption, resource use, and waste management. These aspects will be addressed in future investigations, aiming to provide a more comprehensive assessment and deepen our understanding of the environmental impacts of digital health solutions within healthcare systems.

Implementing this model has been challenging, particularly regarding organisational and cultural adaptation. While the technical solutions—such as the MMSU and digital health technologies—were relatively straightforward to implement, the *organisational changes* required proved more complex[27]. Adapting the workforce to new workflows, training staff to use new technologies, and altering the *organisational culture* within the healthcare system have been significant barriers to smooth implementation. For instance, one of the barriers that were faced during the implementation phase was shifting the mindset of the administrative staff, who were accustomed to working in *silos*, where each person managed a single-screening programme from start to finish. The introduction of the screening invitation manager to guarantee multi-screening activities disrupted this system, requiring a more collaborative, integrated, and proactive approach, which proved challenging to align with the organisational and institutional culture. Indeed, resistance to the adoption of the invitation manager was driven by psychological concerns about changes to well-established workflows and fears that technology might replace their roles, leading to a perceived loss of control and authority. To address this issue, targeted training sessions were organised to reduce mistrust and build confidence in the new technology. Regarding the medical professionals working on the mobile unit, measures were introduced to ensure a smooth technological transition. All screenings were conducted using the same data collection platforms employed at the hospital level, ensuring continuity in workflows and minimising resistance to digital health innovations. For dermoscopy, being a newly introduced service, the same information system used for mammography was employed, ensuring consistency and ease in the collection of images. Additionally, the medical professionals working at the MMSU were actively involved in citizen outreach efforts and public presentations of the project. This approach not only highlighted their pivotal role as "pioneers" in this initiative but also leveraged their professional reputation to build trust among patients and peers.

As other healthcare organisations consider similar projects, it is essential to acknowledge that organisational inertia can be a significant barrier. The cultural resistance encountered in this project is a common feature of anthropological organisations, particularly healthcare systems[28]. This resistance can be attributed to both individual psychological factors and the collective influence of social norms, as well as established roles and statuses within professional bureaucracies that often hinder the adoption of innovation[29–32].

In healthcare, the characteristics of professional bureaucracies, particularly their well-established structures, often resist change due to their reliance on standardisation and the strong professional autonomy of healthcare workers[33]. These forces—more vital than in many other sectors—can create even more significant resistance to adopting new technologies and maintain the change over time. As a matter of fact, change in healthcare needs a peculiar focus to ensure success[28,34].

Therefore, implementing innovation in healthcare requires technical expertise and a deep understanding of the organisational culture, with particular attention to overcoming the inherent resistance that professional autonomy often fosters. Moreover, ensuring the ongoing maintenance and support of these innovations remains critical to long-term success.

The MMSU model's objective extends beyond mere implementation; it aims to drive change proactively. This model impacts healthcare delivery and encourages healthcare professionals to adopt a more proactive approach. It emphasises the importance of extending preventative services closer to the citizens rather than waiting for individuals to seek care. Such an approach is essential, as merely relying on individuals to pursue preventive care is often insufficient and sometimes difficult. In many cases, such an approach is not feasible due to the significant distances and high costs associated with accessing preventive healthcare facilities. The effort and expense required to access these services can be a substantial barrier for individuals who consider themselves healthy. Additionally, this issue can exacerbate inequalities in healthcare access, as those living in mountainous or remote areas face greater distances and logistical challenges than their urban counterparts. This disparity underscores the need for more equitable, community-oriented solutions that bridge the accessibility gap, especially in universal health coverage systems.

Ongoing research is focused on addressing the psychological and social barriers that might affect population acceptance of services provided by the mobile unit. During the 2023 pilot phase, events were organised to introduce the project to the municipalities ahead of the mobile unit's arrival. During these sessions, citizens frequently sought clarification about the initiative, revealing certain perceptions. Some individuals expressed uncertainty, likely due to unfamiliarity with the purpose of the mobile unit and doubts about the quality of care compared to traditional settings. Others regarded the screenings provided by the MMSU as complementary rather than equivalent to those available in hospital facilities, which contributed to lower levels of trust and engagement. A comprehensive communication campaign, led by local mayors and general practitioners, proved instrumental in building trust and significantly increasing adherence during the 2024 pilot phase compared to the previous one. Overcoming psychological barriers, including privacy concerns and perceptions of lower care quality in non-traditional settings, is essential for the model's long-term success and scalability; future studies using focus groups or surveys are needed to investigate and address all drivers of non-adherence.

As expected, initial results suggest that multi-screening, as offered by the mobile unit, could act as a leverage point to increase participation compared to single-disease screenings. The multi-screening approach appears to provide added value for the population by reducing travel distances and related emissions, and capitalising on the perceived efficiency of consolidating multiple preventive services into a single session. Further investigation is warranted to understand better how this perception of value, alongside economic and environmental benefits, can enhance participation and contribute to improved public health outcomes. As for invitations to individual screenings, initial results indicate that the adhesion rate is potentially in line with the traditional delivery model. For example, adherence to mammography screening remains around 70%, consistent with the rates observed prior to the two pilots. Although the current data are insufficient to confirm this trend across all single-screening types, at this stage, it is essential to focus on further increasing adherence to individual screening programmes within the multi-screening framework to ensure the MMSU model becomes a sustainable and systematic component of healthcare delivery.

In considering the broader implications of our findings, it is essential to examine the policy dimensions of integrating environmental sustainability into healthcare systems. Traditionally, universal healthcare system planning has focused on three core objectives: quality, equity, and financial sustainability. This study proposes a crucial expansion of this framework by expanding the concept of sustainability according to the Triple Bottom Line claim, introducing environmental sustainability as a core objective. It is essential to move beyond viewing environmental sustainability as a secondary benefit and instead integrate it as a primary objective within the healthcare policy landscape.

Digital health is central to this shift. Digital innovations have the potential to drive sustainability within healthcare systems by improving efficiency and reducing the environmental footprint of healthcare delivery. To facilitate this transition, national health strategies could benefit from incorporating environmental impact assessments, ensuring that healthcare systems align with broader European climate goals and the Sustainable Development Goals (SDGs). In doing so, digital health technologies would be positioned as key enablers of environmental sustainability, contributing meaningfully to systemic environmental targets. As illustrated, cultural and behavioural challenges are significant barriers to the successful implementation of such innovations. In the case of the MMSU model, strategies that utilise behaviour change, and social influence were critical in overcoming resistance and promoting adoption. These approaches should be further integrated into healthcare change management processes, providing practical tools to foster acceptance and long-term sustainability of innovative healthcare delivery models. Addressing these behavioural and social factors is essential for ensuring the broad acceptance of sustainability-driven healthcare innovations, thereby aligning environmental, social, and financial sustainability within healthcare systems.

Methods

The software and the digital data management system of the MMSU play crucial roles in optimising its operation, addressing both social and environmental aspects.

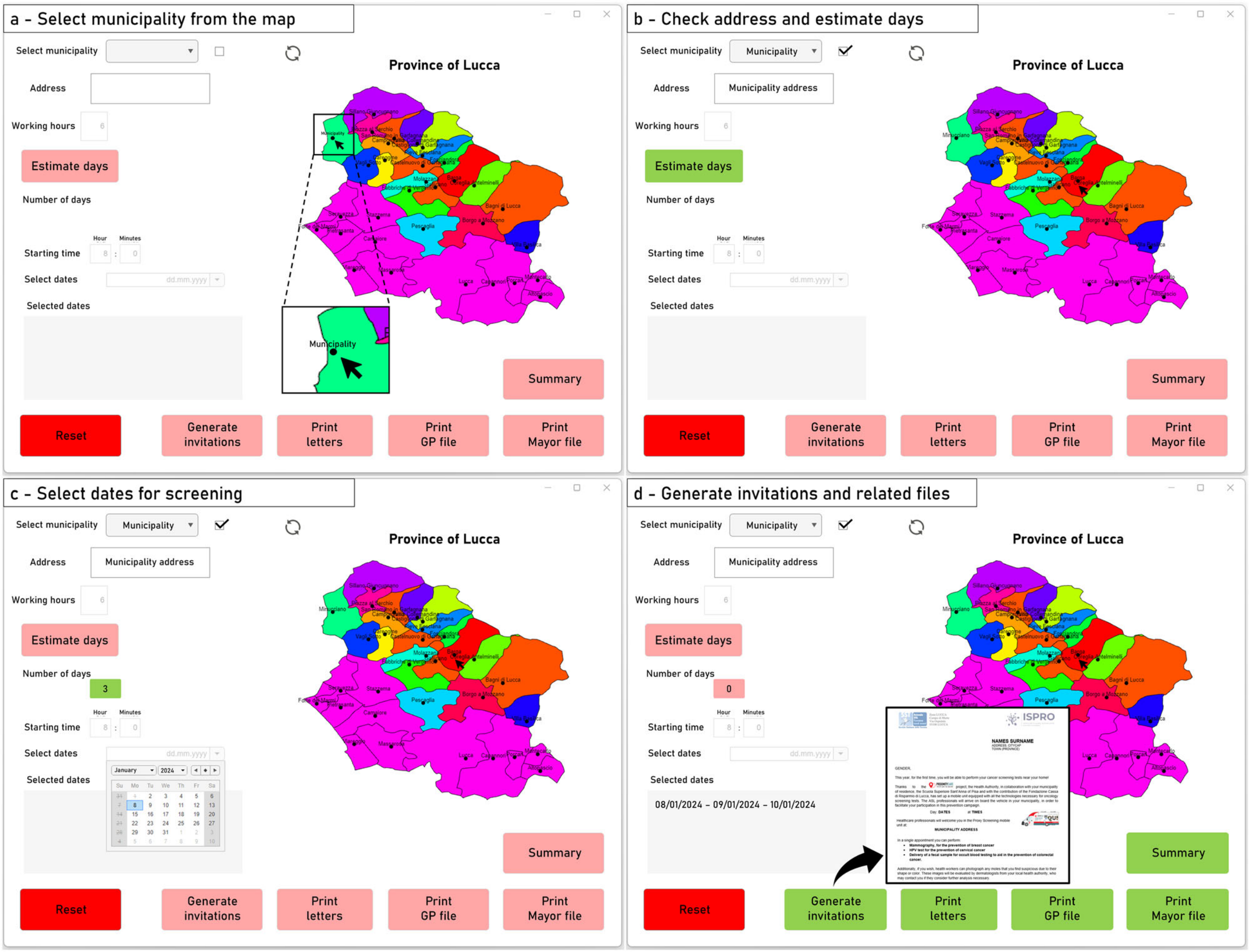

Fig. 2 | Software application workflow for cancer screening invitations. The healthcare worker can (**a**) select the municipality from the map, (**b**) estimate required days, (**c**) schedule the calendar, and (**d**) print letters for the citizens and other documents for general practitioners (GP) and mayors.

Digital health integration

The system's ability to combine screening services and use digital tools for data transmission enables remote consultations and diagnosis, significantly reducing patients' need to travel long distances to specialist clinics or hospitals. The application allows single or multi-screening appointments based on citizens' needs, ensuring seamless coordination between people and the healthcare system. The ability to combine different screenings in a single appointment reduces both social and environmental costs.

The MMSU provides mammography, cervical (Pap test or HPV test), colorectal screenings (immuno-chemical faecal occult blood test), and dermatoscopic evaluations. Three software systems—handling mammography, cervical, and colorectal screenings, along with dermoscopy—securely transmit patient data to clinical experts for analysis. Privacy is safeguarded through secure connections, protecting sensitive medical information while enabling remote monitoring of health conditions.

Remote clinical experts can analyse the transmitted screening data offline or offer real-time consultations. This approach promotes health equity and citizen empowerment while protecting the environment and facilitating early diagnosis and follow-up care.

Screening invitation manager

The software application manages invitations for cancer screenings by integrating information from multiple healthcare management systems. The healthcare workers extract from three independent management systems, following the regional clinical guidelines, the lists of citizens to be screened, and upload them in a dedicated folder. The application processes the data and organises the screening calendar for individual municipalities or groups of municipalities based on the healthcare workers' selections, working hours, and screening protocols (i.e., single or multi-screening) needed by citizens. According to the application workflow shown in Fig. 2, the user selects

the municipality or group of municipalities (Fig. 2a), estimates the required days (Fig. 2b), chooses the dates and times (Fig. 2c), and finally generates the list of invitees and related files. The final aim is to optimise the mobile unit's movement to cover all the involved municipalities and the presence of healthcare workers on board. Furthermore, the application automatically generates a letter for each citizen, inviting them to perform a specific screening protocol (i.e., single or multi-screening), thus significantly facilitating the work and reducing the effort of the screening secretariat staff (Fig. 2d).

Telemedicine and remote consultations

Telemedicine and remote consultations have been significantly enhanced by integrating a well-coordinated data management process with advanced communication and security technologies (Fig. 3). The screening process begins with the generation of a citizen worklist based on the calendar provided by the application. This worklist guides the management of screenings using three specific systems: the Radiology Information System-Picture Archiving and Communications System (RIS-PACS) for mammography and dermoscopic evaluation, WINSAP 2.0 for cervical screening, and the Laboratory Information System (LIS) for colorectal screening. Mammography and dermoscopic data are transmitted in DICOM image format via

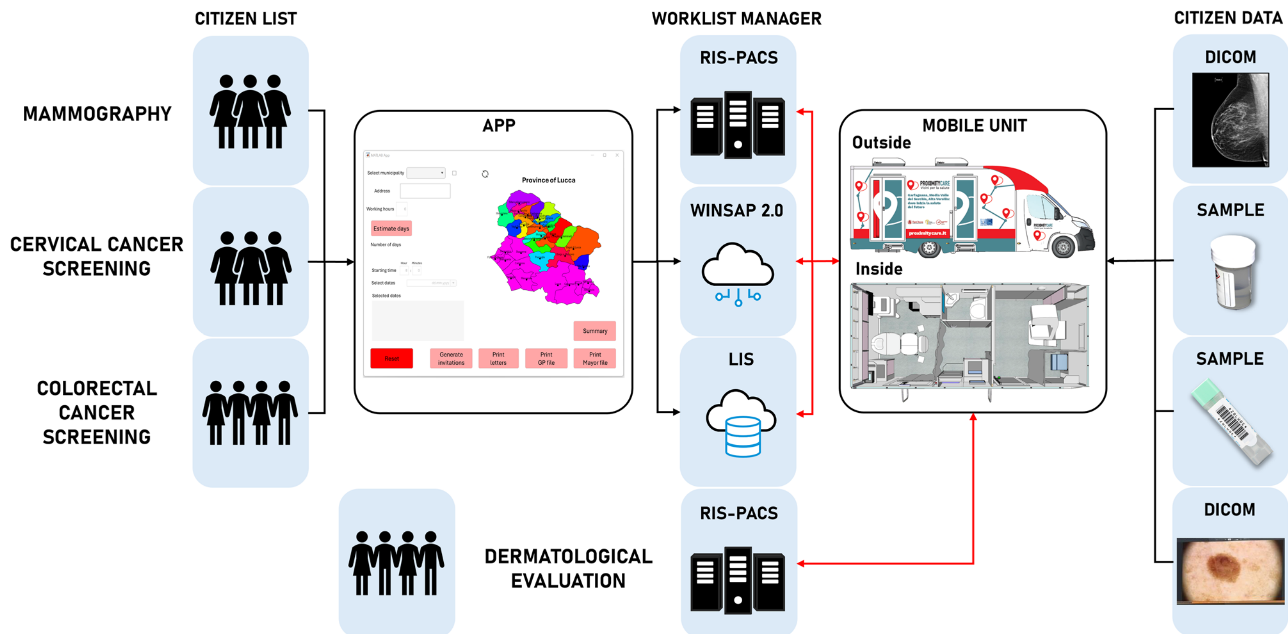

Fig. 3 | Screening process and data management. Monodirectional data communication is in black, and bidirectional communication is in red.

RIS-PACS. At the same time, cervical and colorectal screening samples are collected, labelled with the citizen's information, and transmitted via WINSAP 2.0 and LIS, respectively. These samples are then delivered to the hospital on the same day or when the mobile unit returns to its central management station. The process is not limited to sending data for reporting but also includes receiving updates from the centralised screening office, such as the daily worklist of scheduled citizens, ensuring a continuous and seamless flow of information between all parties involved.

The medical data transmission initiates using a Global System for Mobile Communications (GSM) modem, i.e., the TP-Link® TL-MR6400, with 4 G LTE capabilities and a SIM card. Once this GSM connection is established, the data is routed through a secondary modem, the FortiGate/FortiWifi® 60 F Series, which features a high-performance firewall, and an integrated VPN managed by Fortinet®. The data flow is protected across the Wireless Area Network (WAN) through Advanced Encryption Standard 256 (AES256) encryption. This encrypted signal provides secure connections to all necessary devices and computers for citizen data management and reporting. This protocol ensures that essential data is securely stored locally and, in the event of network failure, ready for immediate transmission once connectivity is restored, safeguarding sensitive citizen information and minimising delays in the screening programme, even during connectivity issues.

Data collection

To evaluate the environmental impact of the screening programme, the CO_2-eq emissions associated with travel from each municipality of residence to the nearest screening location were computed. These emissions were determined using emission factors from the Department for Energy Security and Net Zero 2024 conversion factors[35]. Following the guidelines of the Greenhouse Gas Protocol[36], direct and indirect emissions of an average car size and unknown fuel type were considered. Indirect emissions are defined in category three as fuel and energy unrelated to scopes 1 and 2, namely wheel-to-tank (WTT) emissions.

Travel distances were calculated using Google Maps, and the fastest route option for automobile travel was selected from each resident's address to the nearest screening facility. Emissions calculations also accounted for the travel of the MMSU from one municipality to the other, according to its itinerary and healthcare personnel. It was assumed that the healthcare staff travelled from the reference hospital of the area (Castelnuovo di Garfagnana) to the municipality where the MMSU was operating. Due to privacy constraints, only the municipality of residence for each invitee was accessible, rather than their specific address. As a result, a travel distance of zero kilometres is assumed for individuals residing within the same municipality as the nearest healthcare facility.

Population adherence was assessed by comparing the number of individuals invited to the mobile unit screenings with the actual number of participants who attended (as indicated by the exam registration from Tuscany's regional administrative databases). This measure provides insight into the effectiveness of the mobile unit in increasing participation compared to traditional screening locations.

Data availability

The data analysed are available from the corresponding author upon request.

Code availability

Information about the code and ad hoc customisations is available upon request.

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V.B.: data collection, data curation, methodology, writing—original draft. V.M.: data collection, data curation, methodology, writing—original draft. F.P.: methodology, writing—original draft. A.D.: co-implementation of software tools and data analysis. G.C.: supervision, conceptualisation, investigation, research design, methodology, writing review & editing. S.N.: supervision, conceptualisation, investigation, research design, writing review & editing. All authors read, reviewed and approved the manuscript.

Competing interests

The authors declare no competing interests.

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