From Machine Health to Elderly Health: A Sustainability-oriented Elderly-centric Social Robot System enabled by PHM

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ABSTRACT

The purpose of designing machines is to serve humans and assist them in completing their work on time. A machine, such as a social robot, can be particularly supportive for older individuals who may have reduced strength and be more susceptible to various health issues. The present paper proposes a scenario in which elderly health is monitored by a social robot. As an observer, a social robot, through perceiving its environment, can capture several moments (including daily activities or falls) of an older adult and can provide timely reminders and alerts to the elderly and their caregivers, ensuring the elderly's well-being. Therefore, validation of the machine's health (functioning) is necessary. To accomplish this, the current paper suggests utilization of Prognosis and Health Management (PHM) for the elderly-centric robot system. Furthermore, a PHM-enabled elderly-centric robot system has two main entities: an older adult and a robot, hence it is important to analyze the sustainability dimensions from various perspectives. There are two main objectives of this paper: (i) to develop a comprehensive list of sustainability topics under various dimensions achieved from the examination of three sustainable frameworks: the Triple Bottom Line, Responsible Research and Innovation, Sustainable Assessment and Sustainability Awareness Framework (SuSAF). (ii) to apply the comprehensive list of sustainability dimensions to the proposed case of PHM-enabled elderly-centric social robot system. The results suggest that SuSAF is the most comprehensive and suitable framework for the sustainability assessment of the proposed system. Furthermore, the use of sustainable dimensions can ensure improved robot health and, hence, the health of the elderly.

1. INTRODUCTION

The need of the hour is to develop an effective support system for older adults amid the growing population of older adults. The social robot, with an embodied form and equipped with multiple sensors, is well-suited to serve as part of this system for various purposes. The robot can play several roles, such as a health-status observer and data collector (e.g., audio and video), by monitoring older adults' physical health (Abdollahi, Mahoor et al. 2023). This paper examines scenarios related to the elderly, related to their daily activities, declines in activity, mobility, and fall risk. It is assumed that these factors are monitored by a social robot; however, it is important to note that a human-in-the-loop is essential for all decision-making processes. Furthermore, it is essential to evaluate the health of machine components to ensure they operate accurately and extend the machine's lifespan. In this regard, Prognosis and Health Management (PHM) can be used to assess machine health.

Currently, PHM is focused mainly on cyber-physical systems, such as wind turbines, requiring knowledge of electrical, electronic, mechanical, and computer science disciplines. To the best of our knowledge, PHM is not discussed in the context of health monitoring systems for the elderly. However, similar to other cyber-physical systems, a social robot-based health monitoring system for the elderly also requires the integration of interdisciplinary fields, and therefore necessitates the application of PHM to such systems, as shown in Figure 1.

The present study discusses the application of PHM on an elderly-centric robotic system. The system consists of two main entities: the elderly and the social robot. The robot uses its sensors, speakers and motors. Using its sensor such as cameras, it can capture and store video recordings of the elderly's movements and daily activities. This will help in analyzing the change in gait and progression of risk of falls. The application of PHM functions will ensure that the sensors used to observe older adults are functioning properly.

Additionally, the health of other robot components, such as speakers and motors, is also evaluated by employing PHM.

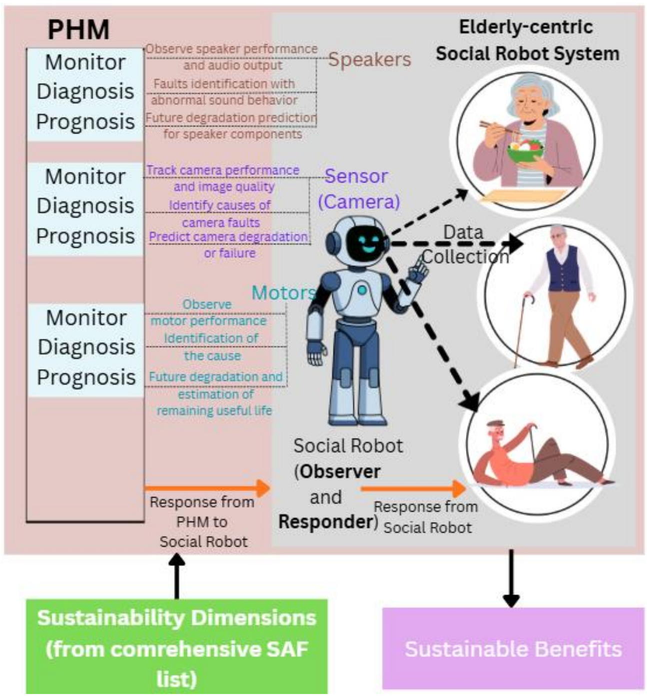

Figure 1. A sustainability-oriented elderly-centric social robot system for health monitoring enabled by PHM.

The main objective is to explore sustainability assessment frameworks suitable for an elderly-centric robotic healthcare system enabled by PHM. Since this system consists of both the human and the technical components; therefore, a comprehensive framework for sustainability is required which covers different aspects, such as environmental, technical including reuse/recycling of material, human perspective, including individual, social perspectives from all stakeholders, as well as the need for such a framework to be ethical, inclusive, and socially acceptable. Furthermore, the comprehensive Sustainability Assessment Framework (SAF) will be applied to the PHM-enabled elderly-centric robotic system to assess its impact.

The structure of this paper is as follows: Section 2 reviews related work, the methodology is presented in Section 3, PHM insights and sustainability dimensions for the proposed case are discussed in Section 4, and finally, the conclusion is provided in Section 5.

2. RELATED WORK

PHM is a technology that ensures reliable, efficient, economical, and safe operation of engineering systems (Hu, Miao et al. 2022). With the rapid advances in sensing and communication technologies, PHM has evolved into an enabling discipline that provides methods and technologies to ensure reliable operations under real conditions (Liu, Jia et al. 2018). To achieve this, PHM continuously monitors a system's environmental, operational, and performance using various sensors (Cheng, Azarian et al. 2010) in order to detect deviations from normal operations, indicating potential problems. When an anomaly is detected, the diagnostic phase of PHM determines the failure type along with its root causes, and finally, prognosis forecasts the future health of a system or predicts its remaining useful life, thereby facilitating proactive maintenance planning (Su and Lee 2023).

2.1. Health Monitoring Systems for the Elderly

Many different health monitoring systems have been presented in existing studies. Pantelopoulos and Bourbakis (2010) presented a physiological data fusion model for multi-sensor wearable health monitoring systems (WHMS) for the elderly, along with the definition of a Prognosis formal language to follow the progression of health symptoms. On the other hand, a wireless physical health monitoring system based on smart sensor technology was implemented to provide the essential freedom and convenience of use for continuous health monitoring and diagnostic process for older patients, allowing for immediate intervention and personalized care (Yang 2023). Further, Cantone, Esposito et al. (2023) presented a four-actor system (comprising a stationary humanoid robot, elderly individuals, medical personnel, and caregivers) that enables continuous monitoring of the physical and emotional well-being of the elderly through specific sensors that measure vital signs, with real-time updates relayed to physicians and assistants, thereby ensuring timely and appropriate care.

However, several technological issues still need to be resolved in order to make these systems more applicable in real-world scenarios. Technology acceptance, power consumption, bioeffects of wireless technology on the elderly health, privacy and security, mobility and portability, availability and reliable communication, and scalability are some of the challenges that still need to be addressed (Mardini, Iraqi et al. 2019). Therefore, there is a need to address and resolve these issues for the long-term sustainability of such systems.

2.2. Sustainability Frameworks

The Brundtland report (Brundtland, Khalid et al. 1987) stated that 'Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.' Kates et al. (Robert, Parris et al. 2005) clearly illustrated sustainable development, focusing on what to sustain (Nature, life support, community) and what to develop (people, economy, society). To evaluate sustainability across categories such as social, economic, and environmental, various approaches were considered in sustainability frameworks (Serrano-Arcos, Payán-Sánchez et al. 2021). One such framework is the Triple Bottom Line (TBL), also known as the Three Pillars of Sustainability (TPS), which focuses on the social, environmental, and economic dimensions (Kusmendar, Asih et al. 2025). It is important to consider Responsible Research and Innovation (RRI) to ensure that technology behaves ethically and adheres to privacy protection rules. In this regard, Ehlers et al. (Ehlers, El Benni et al. 2025) proposed a framework that combines RRI and sustainable assessment (SA), called the RRI-SA framework. The Sustainability Awareness Framework (SuSAF) supports software engineers during software development by helping them assess the potential impacts of the system on sustainability and address related problems (Duboc, Betz et al. 2019).

3. METHODOLOGY

A case is proposed in Figure 1, which comprises three major parts: an elderly-centric social robot system, PHM system, and the application of sustainability framework. In an elderly-centric social robot system, the social robot can play the role of observer and responder. As an observer, a robot, using its camera, can monitor the daily activities of older adults, including eating, walking, and falls. The social robot, as a responder, can respond to older adults. These responses can be spread as information by utilizing robot's speakers, which are useful for giving reminders or alerts to older adults. Similarly, a robot can respond with gestures. Robot motors can help enable gestures and aid navigation.

This system is enabled by PHM, which, through three functions (monitor, diagnosis, and prognosis), can assess the performance of various parts of the social robot, identify faults and their causes, and predict future degradation or maintenance needs. This information can initiate appropriate actions for the proper functioning, hence increasing the lifespan of robot.

This study explores existing sustainability frameworks that can be applied to an elderly-centric social robot-based system enabled by PHM. The identified frameworks will be compared to create a comprehensive list of sustainability topics across various dimensions (environmental, technical, social, individual, economical). Subsequently, this comprehensive list will be applied to the selected scenarios of an elderly-centric social robot-based system enabled by PHM.

4. PHM INSIGHTS AND SUSTAINABILITY DIMENSIONS

This section includes details of the PHM-enabled elderly-centric social robot system, the development of a comprehensive SAF list, and the application of sustainability dimensions to this system.

4.1. PHM-enabled Elderly-centric Social Robot System

A social robot is an entity that perceives its environment using sensors and responds to the individual verbally (speech) and non-verbally (gestures). It is essential to determine if the robot is functioning correctly. To achieve this, PHM can play an important role in monitoring various robot components and providing diagnosis as well as prognosis. In this paper, the proposed case considers four robot components (speaker, camera, motor, and battery). Using a camera, the robot can monitor older adults' daily activities. Robot's speakers are helpful in establishing communication and providing reminders. With motors, a robot can communicate non-verbally through gestures. A battery is important since it provides power to the robot system. Furthermore, PHM functions (Monitoring, Diagnosis, and Prognosis) can be applied to the robot's components. The data collected by these components can be monitored by PHM to identify early faults, determine their causes, and enable predictions regarding failure or degradation. The role of PHM, including its functions, is illustrated in Table 2 for the considered robot components. Moreover, different actions related to maintenance are also suggested in Table 1. It is expected that a PHM-enabled elderly-centric social robot system will benefit older adults, as it ensures the proper functioning of technical components and thus improves their safety.

Table 1. Role of PHM in the selected scenario of an elderly-centric social robot system

Robot Component	**PHM**			**Actions**
	Monitor (*What it Monitors?*)	**Diagnosis** (*What is the Cause?*)	**Prognosis** (*What it Predicts?*)	
Speakers	Sound; volume; Distorted voice; Intermittent sound; No sound	Amplifier problem; Damaged speaker; Wiring problem; Hardware failure	Amplifier wear; Remaining Useful Life (RUL) of the speaker; Probability of hardware failure	Repair of the amplifier; Replacement of speakers
Camera	Camera performance; Image quality (blur, noise etc.); Missing frames	Sensor problem; Lens obstruction; sensor-related Hardware failure	RUL of the sensor; Probability of failure of the camera; To anticipate degradation in image quality in future	Recalibration of the camera; Cleaning the lens; Replacement of the camera
Motors	Motor performance;	Motor inefficiency or gear degradation;	RUL of motor bearings; Probabilit	Repairing gears; Motor replacement

	Overheating of motor; Irregular Posture; High current	Excessive load; Malfunctioning of the control system; Electrical Fault	y of failure of actuators; Prediction of motor failure within a certain time	; Scheduling the maintenance
Battery	Voltage; Temperature; Power consumption	Degradation of the battery; Overheating	Prediction of remaining battery life	Battery replacement

4.2. Development of a Comprehensive SAF

Three SAFs TBL, RRI-SA and SuSAF, are utilized to create a comprehensive list. The aims of the particular framework, the domain where the framework can be applied, the sustainability dimensions involved, what topics it covers, and the order of impact are incorporated in this list (Table 2). This list suggests the major sustainability dimensions as social, economic, environmental, individual and technical. It should be noted that social, economic and environmental dimensions are present in all the SAFs.

Table 2. Comprehensive list of SAF

	TBL (Slaper and Hall 2011, Tavanti 2025)	**RRI-SA (Ehlers, El Benni et al. 2025)**	**SuSAF (Duboc, Betz et al. 2019)**
Main Aim	To assess the impact of an organization on sustainability.	To assess the impact of technology development on sustainability (at an early stage of development)	To assess the potential effects of software systems on sustainability (at an early stage of development)
Focus	Organization	Technology development	Software product
Dimensions addressed	Social	Social	Social
	Economic	Economic	Economic
	Environmental	Environmental	Environmental
			Individual
			Technical
Topics covered	Social: education; equity & access to social resources; social equity; labor practices; community engagement; health & well-being; quality of life; social capital	Social: using topics covered in Social-LCA assessment **(UNEP 2020),** including technology being responsible, ethical and acceptable.	Social: Sense of Community; Trust, Inclusiveness & Diversity; Equality; Participation & Communication;
	Economic: job creation, community development, and economic resilience.	Economic: using topics covered in LCC assessment (Swarr, Hunkeler et al. 2011)	Economic: Value; Customer Relationship Management; Supply chain, Governance & processes; Innovation and R&D
	Environmental: minimizing ecological footprints; using resources efficiently; reducing emissions, and adopting sustainable practices; air & water quality; energy consumption, natural resources; solid and toxic waste; land use/land cover;	Environmental: using topics covered in LCA assessment (Finkbeiner, Inaba et al. 2006)	Environmental: Material & Resources; Soil, Atmospheric & water pollution; Energy; Biodiversity & Land use; Logistics & Transportation
			Individual: Health; Lifelong learning; Privacy; Safety; Agency
			Technical: Maintainability; Usability; Extensibility & Adaptability; Security; Scalability
Order of impact	-	-	Immediate; Enabling; Structural

It is evident from Table 2 that SuSAF is the most comprehensive framework covering five dimensions and related topics to assess the direct, indirect and structural impact of a system. However, there are additional topics from TBL (e.g. quality of life) and RRI-SA (such as technology being responsible, ethical, and acceptable) which can enrich dimensions mentioned in SuSAF even further.

An overall structure of sustainability-oriented elderly-centric social robot system enabled by PHM is illustrated in Figure 2. The innermost part of Figure 2 depicts the elderly-centric social robot system, in which the social robot monitors the elderly's health and responds accordingly. In a way, a robot is taking care of the elderly's health. The PHM is applied to this system to evaluate the health of the machine, i.e. robot, which means that PHM is indirectly involved in assessing the well-being of the elderly. Lastly, various sustainability dimensions are applied to this PHM-enabled system to assess its sustainability impact.

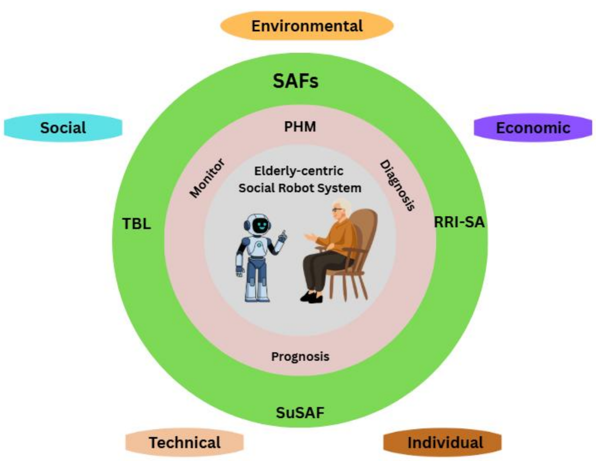

Figure 2. A Sustainability-oriented Elderly-centric Social Robot System enabled by PHM

4.3. Application of sustainability dimensions on PHM-enabled elderly-centric robot system

The details of the employment of sustainability dimensions, obtained from the development of a comprehensive SAF list for a PHM-enabled elderly-centric social robot system, are shown in Table 3. The environmental dimension concerns about the impact of a robot on the environment and natural resources. The social dimension ensures the improvement of society's well-being. The focus of the economic dimension is related to cost efficiency. The technical dimension assesses various factors of the system, including maintainability, usability and security. The individual dimension evaluates the system's influence at the individual level, such as privacy, safety and agency, which in the proposed case is to assess the impact on an older adult.

Table 3. Application of sustainability dimensions, achieved from a comprehensive SAF list, to a PHM-enabled elderly-centric social robot system

Sustainability Dimensions	PHM application to robot system helps in	Sustainability Benefits
Environmental	Anticipating the degradation of components and effectively scheduling their maintenance.	The lifespan of robot components will be increased, thus reducing electronic waste and resource consumption.
Social	Ensures that the robot is functioning correctly by accurately monitoring elderly activities and providing timely reminders.	This will enhance the support for the elderly by increasing their safety, independence, social participation and inclusiveness. Furthermore, it will also reduce the burden of caregivers.
Economic	Predicting the maintenance requirements of robot components in advance to prevent any sudden failures.	This will reduce the cost of maintenance or emergency repairs.
Technical	PHM, through diagnosis and prognosis, can predict the failure of robot components (including hardware and software).	It will ensure more reliable operations and reduce the likelihood of unexpected component failures.
Individual	Ensures the trustworthiness of social robot towards increased use of this system.	The quality of life of elderly will be improved by receiving uninterrupted services for a longer time. It will ensure the privacy and safety of elderly.

5. CONCLUSION

This study presents the application of PHM, the exploration of SAFs, and the application of key sustainability dimensions for the proposed case. The paper revolves around the health of an elderly person who is being monitored and supported by a social robot. Therefore, it is important to ensure that the robot's components function properly and predict their degradation or failure in advance. For this purpose, PHM functions should be utilized for various components of the robotic system. This integration will lead to a PHM-enabled elderly-centric robot system that indirectly addresses the health of older adults by maintaining the robot's health. Furthermore, the sustainability dimensions can be applied to the developed system to observe the impact of system operation on sustainability. The findings suggest SuSAF is the most comprehensive framework covering five major sustainable dimensions, i.e., environmental, social, economic, technical, and individual. At the same time, SuSAF is the most relevant framework for technical systems. By continousl health monitoring of elderly-centric robot system will help to identify the issues at early stage for accurate functioning and extension of machine lifespan, thereby increasing the trust and satisfaction of the elderly.

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BIOGRAPHIES

Deepti M. has expertise in Human-Robot Interaction, Artificial Intelligence and Software Engineering. She has been actively involved in teaching and research for more than 25 years. She has been mentoring students at all levels (bachelor, Master, PhD, postdoc).

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