AIBO and the Emergence of the Robosphere A Self-Organizational Framework for Sustainable Human-Robot Ecosystems

Antonio Fleres[1[0000-0002-6108-9067]] and Luisa Damiano[1[0000-0003-4786-524X]]

[1] IULM University, Carlo Bo. 1, 20143 Milan, Italy
antonio.fleres@iulm.it; luisa.damiano@iulm.it

Abstract. Sony's AIBO — a robotic dog designed for social companionship — has generated not only widespread adoption but also a distinctive socio-robotic community involving owners, repair specialists, and ritual practices that persisted after the robot's discontinuation. Previous studies have examined AIBO mainly from anthropo-social, ethnographic, psychological, and technical perspectives. This paper, by contrast, develops an epistemological analysis within the framework of self-organization, focusing on how such a socio-robotic community can be modelled as a sustainability-oriented system. We argue that the AIBO case exhibits emergent properties — ritualized recognition of end-of-life, community-driven repair economies, and affectively sustained stewardship — that distinguish socio-robotic communities from generic device-repair cultures. These features make it a paradigmatic instance of sustainability-oriented human–robot organization. Our contribution is conceptual and theoretical: we apply Varelian notions of closure, autonomy, and co-evolution to the AIBO case, yielding testable hypotheses on how socio-robotic communities sustain themselves beyond manufacturer support. In doing so, we reframe the robosphere as a domain where hybrid human–robot systems generate sustainability-oriented practices. The paper aims to contribute to social robotics and cognitive science by highlighting both the theoretical relevance and the practical implications of interpreting human–robot communities as self-organizing systems, and by outlining preliminary design guidelines that can inform the development of sustainable social robotics.*

Keywords: AIBO, Robosphere, Self-organization, Socio-robotic communities, Sustainable social robotics.

1 Introduction

The increasing diffusion of robotics across therapeutic, industrial, artistic, military, urban, and domestic domains is reshaping not only technological infrastructures but also

* A preliminary reflection on social robotics and sustainability was presented at CIFMA 2022 (Fleres, 2022), where AIBO was mentioned among illustrative cases, in a preparatory phase that did not yet involve theoretical modeling. The present paper, co-authored by Fleres and Damiano, is submitted to CIFMA 2025 as a mature development of this line of research, modeling the AIBO socio-robotic community in self-organizational terms, formulating exploratory design guidelines, and outlining directions for future applications.

human social environments. Developments in multi-agent systems illustrate a tendency to connect artificial agents in decentered and distributed ways, reinforcing the view of robotics as a technically networked domain—a perspective captured by the notion of "networkism" (Novikov, 2015). Yet the rise of service and social robots shows that artificial agents are not confined to technical interconnections: through their interactive and relational capacities, they increasingly participate in social networks alongside human agents. In this sense, hybrid human–robot ecologies emerge as sites where technological, human, and social systems become entangled, extending networked logics into genuinely socio-technical domains. Building on this background, recent theoretical work has used the term "robosphere" — originally introduced by Humberto Maturana (1998) — to describe a newly emerging complex system composed of interrelated human and robotic agents (e.g., Colombano, 2003; Lamola, 2022; Fleres, 2025).

Different philosophical perspectives have engaged with this notion, from post-phenomenological interpretations focused on meaning-making (Lamola, 2022) to systemic interpretations grounded in complex systems theory (Fleres, 2025), which emphasize the dynamics of interaction, closure, and homeostasis. In this paper, we adopt the latter perspective, viewing the robosphere as an evolving network of self-organizing hybrid ecosystems that can sustain themselves over time. Previous studies on AIBO have examined the phenomenon mainly from anthropo-social and ethnographic perspectives, highlighting ritual practices and cultural meanings (Knox & Watanabe, 2018; White & Katsuno, 2021), as well as from psychological and human–robot interaction perspectives, focusing on attachment, social presence, and therapeutic use (Kahn et al., 2002; Melson et al., 2009; Weiss et al., 2009). Technical accounts have also analyzed the robot's interactive architectures and embodied functions (Pfeifer & Bongard, 2006; Kanamori et al., 2002). Yet, the AIBO case has never been investigated from an epistemological standpoint, and in particular by means of self-organizational modelling oriented toward sustainability.

It is precisely this gap that motivates our contribution: to frame the AIBO socio-robotic community as a paradigmatic case of hybrid self-organizing system, offering conceptual insights into the design of sustainable human–robot communities. Specifically, we take the case of AIBO, SONY's iconic robotic pet, to illustrate how such systems can sustain their coherence and continuity through spontaneous coordination and organizational dynamics. This work aims to contribute not only to the field of social robotics — by offering insights into the design of robots as relational nodes rather than isolated devices — but also to cognitive science, where it seeks to extend self-organization models beyond classical biological or computational domains, toward hybrid human–robot systems. Our conceptual framework is intended to inspire future synthetic modelling and empirical inquiry into sustainable artificial ecologies, opening potential directions for research at the intersection of robotics, cognition, and sustainability. While repair practices can also be observed around non-social devices, the AIBO case illustrates emergent properties that are specifically socio-robotic. These include ritualized practices of end-of-life recognition, affectively modulated human–robot co-adaptation, and the rise of third-party institutional actors that integrate technical repair with symbolic care. Taken together, these features situate the AIBO community beyond the scope of ordinary device-repair cultures, and justify its analysis through the theoretical lens of self-organization and autonomy. The paper is structured as follows. Section 2 outlines the research questions and methodology. Section 3 presents the AIBO case and the socio-robotic community that emerged around it. Section 4 introduces the theoretical model of self-organization, while Section 5 applies it to the AIBO ecosystem. Section 6 discusses sustainability implications, Section 7 proposes preliminary design guidelines, and Section 8 concludes by outlining future research directions.

2 Research Questions and Methodology

In this paper we undertake a conceptual and theoretical study by applying the notion of the robosphere— analyzed within the theoretical framework of self-organization and organizational closure (Varela,1979; Damiano, 2009, 2012) — to the interpretation of the hybrid socio-robotic system that has emerged around Sony's AIBO robot in Japan. There are two central research questions guiding this study:
(1) Can the hybrid system formed around AIBO be meaningfully understood as an element of the robosphere when analyzed through the theoretical framework of self-organization?
(2) If so, what underlying dynamics can be identified that might inform the design of more sustainable and resilient robotic systems in the future?
To address these questions, the paper adopts a theoretical and analytical approach that combines:
– a detailed analysis of AIBO's lifecycle, focusing on its discontinuation and the subsequent emergence of community-driven repair and reuse practices;
– a conceptual application of the generic model of self-organizing systems, as articulated by Varela
and further developed by Damiano, to the AIBO case, identifying organizational characteristics such as closure, emergence, autonomy, and co-evolution;
– a theoretical elaboration on how this interpretation of the AIBO case offers insights into the sustainability potential of human–robot ecosystems, contributing to an expanded understanding of the robosphere as not only a socio-technical but also a sustainability-oriented system. This contribution is theoretical and conceptual in nature. Rather than presenting empirical experiments or computational simulations, it develops a philosophical and analytical framework that can guide future empirical research, synthetic modelling, or simulation efforts within the cognitive science community and related interdisciplinary fields. By focusing on the organizational principles underlying hybrid socio-robotic communities, and particularly on their emergent properties, the study provides a conceptual basis for subsequent operational hypotheses and design explorations. In this way, the AIBO case is not treated as a generic example of repair culture, but as a socio-robotic community exhibiting distinctive organizational properties that justify its modelling within the framework of autonomy and self-organization. Although this study is primarily conceptual, the analysis of the AIBO case is grounded in publicly documented sources, including ethnographic studies, academic literature (e.g. Knox & Watanabe 2018; White & Katsuno 2021), and media documentation of post-production repair and ritual practices. These materials were systematically

reviewed to identify organizational patterns consistent with the theoretical model. The study therefore combines conceptual modelling with qualitative synthesis of existing empirical evidence.

3 The case of AIBO

3.1 AIBO: A Robot Profile

AIBO is a robotic dog, designed to function as a companion, which was developed, produced, and manufactured by SONY between 1999 and 2006. More than 150,000 units were sold worldwide during this period. The name “AIBO” is an acronym for “Autonomous Intelligent Robot” and it resembles the Japanese word aibō, meaning “friend” or “companion”, in line with its intended role as a robotic pet destined to social interaction with its owners (Kahn et al., 2002). AIBO is a robotic companion equipped with a range of sensors—including tactile and environmental sensors—that enable both verbal and physical interaction with users. It can express up to six distinct emotions through its embodied behaviour, allowing it to engage with humans in ways reminiscent of a domestic pet (Pfeifer & Bongard, 2002; Sharkey & Sharkey, 2012).
These features support AIBO’s use in various contexts, notably as a social companion, and in therapeutic settings, particularly among elderly individuals and children (Weiss et al., 2009; Kanamori et al., 2002; Kertéz & Turunen, 2019). Some AIBO models also support the installation of a software package called AIBOLife, which allows the robot to develop a unique personality over time, shaped by its interactions with the user.

3.2 Post-Production Stewardship: Repair, Recycling and Rituals

On January 2006, SONY announced its decision to discontinue the production of AIBO. Support for the robot was progressively reduced over the following years, culminating in its complete termination in 2013. In 2014, SONY formally terminated all official replacement and repair services for AIBO, resulting in a complete inability for the user community to access authorized means of maintenance or restoration. In 2011, in response to the increasing demand for technical support, repairs, and replacements, Norimatsu Nobuyuki, a former SONY employee, founded a company called A-Fun, which, recognizing the owners’ emotional attachment towards their AIBO robotic companions, aimed at addressing related specific needs (Burch, 2018).
Specifically, A-Fun tackled the challenge of a shortage of spare parts, as original components were no longer available on the market. To address this issue, the company adopted a strategy of salvaging usable parts from AIBO units donated by users. Indeed, a repairability assessment was carried out for each individual unit. If an AIBO was deemed beyond repair, the owner would formally declare its "death," enabling the robot to be dismantled and its components reused for future repairs. Acknowledging the profound sense of grief and attachment experienced by AIBO owners, A-Fun also established a collaboration with Buddhist monk Ōi Bungen, who conducted memorial services for the donated AIBO units designated for dismantling (White & Katsuno, 2021). These ceremonies served as a gesture of respect and recognition for the emotional loss

felt by the owners. Between 2015 and 2018, approximately 700 funeral rites for AIBO were officiated by Ōi Bungen. The practice of holding funerals for robotic companions has attracted academic interest, particularly regarding its social and cultural implications (Knox & Watanabe, 2018).

3.3 End-of-Life Rituals and Resources Circularity in the AIBO Community

Another important element to consider is the response to the "death" of an AIBO, as it gives rise to socially and environmentally significant behaviors. Both the AIBO's owner and the A-Fun company participate in evaluating each individual case. If the robot is deemed too old or damaged to be repaired, AIBO must be disassembled, prompting the owner to officially declare the "death" of their AIBO and potentially join a waiting list for a funeral ceremony. The components from disassembled units are donated to the company to be reused in the repair of other AIBOs, thereby contributing to a sustainable maintenance cycle. The organization of a mortuary ritual serves as an acknowledgment of the owner's grief and a gesture of respect. The experience of mourning decommissioned AIBOs reveals a meaningful emotional connection between humans and robots. Research has shown that human reactions to the "death" of robots are not significantly different from responses to the death of people or animals, indicating a level of personification that can lead to genuine grief (Carter et al., 2020). The donation of a "dead" AIBO can thus be interpreted both as an act of solidarity and as a contribution to a circular economy model, wherein obsolete devices are not discarded as waste but repurposed as valuable resources for sustaining other units.

3.4 AIBO Socio-Robotics Community as a Research Object

This virtuous dynamic of life-cycle extension can be understood through two key factors. The first concerns the emotional bonds that social robots, like AIBO, can create with their human users. Literature in Social Robotics highlights that the interactive effectiveness of social robots — that is, their ability to give users the impression of being with someone, a quality referred to as social presence (Biocca et al., 2003; Dumouchel & Damiano, 2017)— is largely achieved through their capacity to communicate via affective signals, particularly emotions (e.g., Baumgaertner & Weiss, 2014). This capacity is often described as "artificial empathy", which — when framed within a systemic view of sociality and affect — can be understood as a specific form of "affective coordination" that humans establish with robots through mutual interaction and the exchange of emotional signals (Damiano & Dumouchel, 2020). In the case of AIBO, this capacity played a decisive role. The robot's ability to adapt its "personality" in response to human interactions, and to recognize and react to users' emotions, enabled a co-evolutionary relationship that transformed AIBO from a mere technological object into an "affective member of the family" (e.g., Melson et al., 2009). This emotional attachment strongly motivated owners to choose repair over replacement, significantly extending the operational lifespan of their devices.

Secondly, the rise of specialized repair companies, particularly A-Fun, played a crucial role. A-Fun assumed a fundamental position in providing ongoing technical support to the AIBO user community. Robots are technologically dependent on the availability of technical support, meaning that the decision to continue operating a robot is not solely in the hands of the user but also contingent on the willingness and capacity of technical service providers. Without such support, users would be forced to abandon their robotic companions, often against their wishes. The fact that a new company could assume the role previously held by SONY was thus critical for maintaining the continuity of the socio-robotic community.

Taken together, these factors illustrate the emergence of properties that cannot be reduced to either the robots, the users, or the company alone, but that characterize the socio-robotic community as a self-organizing system.

3.5 Framing the AIBO Socio-Robotic Community within a Theoretical Perspective

The hypothesis driving the work presented here is that the interdependent network formed by owners, robots, and A-Fun can be described as a self-organized system that is not only resilient but also oriented towards sustainability. Specifically, it resists the dominant models of rapid technological consumption by promoting practices of reuse and resource valorization. In this sense, the combined actions of the user community and A-Fun, working together with their robots, constitute a valuable resource for maintaining the system's long-term stability, pointing to a potential model for future human–robot socio-technical communities.

Indeed, the AIBO case does not merely offer an example of affective human–robot interaction or community-driven repair practices, but rather exemplifies the interconnection of heterogeneous elements — owners, robots, and the company — whose collective dynamics are best described within conceptual frameworks focused on emergent forms of autonomy (e.g., autonomous constitution, regulation, and maintenance). These observations raise the question of how such a socio-robotic community can be meaningfully framed as a self-organizing system and understood within a broader theoretical context capable of engaging with sustainability across domains. To address this, the following section introduces the theoretical reference model that guides our interpretation: the generic model of self-organizing systems, originally developed by Varela (1979) based on earlier pioneering works, and subsequently elaborated by Damiano (2009, 2012) and Fleres (2025). This model provides the conceptual framework through which we analyze the AIBO case, allowing us to situate its dynamics within a wider discussion on the sustainability potential of emerging autonomous human–robot systems.

3.6 Outlook: From Repair Culture to Socio-Robotic Community

Unlike ordinary repair cultures around non-social devices, the AIBO case demonstrates socio-robotic specificities: ritualized end-of-life recognition, affective bonds that sustain repair beyond functional value, and third-party institutional actors that integrate technical maintenance with symbolic care. These features qualify the AIBO case as a socio-robotic community proper and anticipate the organizational analysis developed in the next section.

4 Theoretical Reference Model: The Autonomous or Self-Organizing System

The theoretical reference model guiding our interpretation of the system that has formed around AIBO is the one presented in Damiano (2009, 2012) as a generic theoretical model of a self-organizing system — constructed by identifying conceptual convergences among pioneering approaches to self-organization. In this context, "generic" indicates that the model is independent of specific levels or domains of application, while "pioneering approaches" refers to the foundational scientific frameworks that first introduced the notion of self-organization into scientific discourse, as identified in Stengers (1985).

It is important to note that the specificity of this model lies in its conceptual lineage: it inherits from Varela's approach the idea that self-organization explains how systems—biological, social, or technical—maintain their identity through internal networks of mutual dependence. In this sense, self-organization does not refer to spontaneous order in general, but to the recursive maintenance of a system's own organization. This clarification helps situate the following five notions—organization, emergence, autonomy, co-evolution, and closure—within a broader understanding of how self-organizing systems sustain coherence across domains.

Building on this conceptual background, the model is articulated through the following five key theoretical notions.

I. ***Organization.*** The notion that a self-organizing system is constituted through the structuring of relationships among components, producing an integrated whole of interacting parts.

II. ***Emergence.*** The notion that self-organizing systems exhibit novel qualities or properties at the system level that are irreducible to the properties of individual components; it refers to the presence, within these systems, of qualitatively distinct organizational levels, at minimum: (a) the level of the parts as isolated elements, and (b) the level of the whole as the organized concatenation of those parts. According to this notion, parts and wholes interact within a stratified system, where higher-order levels impose organizational constraints that shape the behavior of components.

III. ***Autonomy.*** The notion that a self-organizing system exhibits a degree of independence from its environment, broadly expressed as the emergent capacity to self-determine its own dynamics and structure, as well as to respond to external events through internal self-regulation.

IV. ***Co-evolution.*** The notion that a self-organizing system and its environment engage in a symmetric dynamic of reciprocal perturbations, within which each adjusts its dynamics through self-regulation, leading to coupled behaviours — that is, the emergence, on both the side of the self-organizing system and the side of its environment, of reciprocally compatible patterns of activity.

V. ***Closure.*** The notion that a self-organizing system is defined by a closed network of relations among components, which underlies the system's emergent properties – particularly its autonomy and co-evolutionary dynamics. Based on this notion, the self-organizing system is understood as an integrative unit formed by reticular connections among elementary operations, potentially open to the development of higher-level reticular connections, via co-evolutionary dynamics with other self-organizing systems, that allow it to participate in increasingly complex self-organizational units.

According to Damiano (2009, 2012), this model aligns with the autonomous system model proposed by Francisco Varela in Principles of Biological Autonomy (1979) based on extensive, in-depth studies on scientific research concerning natural self-organization. In that work, Varela addressed the challenge of developing a theory capable of treating the heterogeneous plurality of autonomous systems (e.g., families, ecosystems, managerial complexes, nations, clubs) in a unified manner. Specifically, Varela focused on identifying and explaining the organizational features that render systems autonomous, independently of their specific domain — whether biological, social, technical, or ecological. Varela's solution was to propose a notion of closure that generalizes the Piagetian one (Piaget, 1967; Ceruti, 1989; Damiano, 2012), capturing the circular interdependence of components that defines autonomous or self-organizing systems. This allowed him to articulate a general framework for describing such systems across multiple levels of scientific inquiry.
As Varela writes:
"Autonomous systems are organizationally closed, that is, their organization is characterized by processes such that (1) the processes are related into a network, so that they depend recursively on each other in the generation and implementation of the processes themselves; and (2) constitute the system as a recognizable unit in the space (domain) in which the process exists. [...] The processes that specify a closed organization can be of any type and take place in any space defined by the properties of the components that constitute the process." (Varela, 1979, p. 55)
This notion is the core of the generic model of the autonomous or self-organizing system that we adopt here. In this framework, the AIBO community is not treated as a generic repair culture but as a socio-robotic community, whose organization can be described in terms of closure, autonomy, co-evolution, and emergent properties. These notions allow us to identify system-level features — ritualized recognition of end-of-life, affectively sustained stewardship, and resource circularity — that arise from the interplay among owners, robots, and repair institutions. Moreover, because the model highlights criteria such as closure and resilience, it provides a basis for formulating operational hypotheses that can be tested in future empirical or simulation-based studies. In what follows, we apply this model to the system that has constituted itself around AIBO. Our ambition is to do so in line with Varela's 1979 descriptive approach: extending the exploration of autonomy beyond the biological domain and addressing the

description of autonomous systems by focusing on their organizational features rather than on their material substrate.

5 AIBO's Socio-Robotic Community

To clarify how the theoretical framework operates in practice, in *Table 1* we summarize the mapping of each key notion of the generic self-organizing system model onto the empirical dynamics of the AIBO socio-robotic community.

While Table 1 provides a conceptual overview of how the theoretical principles apply to the AIBO community, we next examine the specific components and relationships that constitute this socio-robotic system. Our analysis focuses on the specific closure forming the community — that is, the concrete interdependencies between the system's key elements: AIBO robots, human users, and technical support providers — to show how these connections sustain the system's coherence and resilience over time.

The core elements of this network — the robots, their human companions, and specialized repair services — are engaged in a web of mutual dependencies. AIBO relies on its human owner for two main reasons: first, to ensure access to electricity and routine maintenance; second, to receive the social interactions required for the optimal performance of the AIBOLife software, in models equipped to run it. In parallel, AIBO depends on technical service providers for extraordinary maintenance and component replacement, tasks that require the expertise of trained technicians.

Human users, on the other hand, develop strong emotional bonds with their robots – in some cases enhanced by the presence of the AIBOLife software – leading them to prefer repairing their existing AIBO units rather than replacing them with newer models. Consequently, users come to rely on technical support companies for maintenance services and access to spare parts no longer easily found on the market. In the specific case of A-Fun, this dependency is further deepened by the company's additional service of conducting funerary rites for AIBO units, a gesture aimed at honouring the users' experiences of grief. This practice establishes a new social bond between A-Fun and its clients, reinforcing the interdependence within the system.

Furthermore, A-Fun itself is situated within a relationship of double dependency. The company relies on AIBO robots, donated by users whose units have reached the end of their operational lives, as a critical source of spare parts; at the same time, it depends on the user base to sustain a market demand for its services.

It is important to highlight that this network of interdependent relationships organized following the withdrawal of technical support by SONY. Our interpretation reads this event as the system's response to this loss: a spontaneous restructuring through the formation of A-Fun as a new node, assuming the role previously occupied by SONY. This reorganization led to the development of new practices aimed at maintaining the stability of the community, particularly through the extension of AIBO's lifespan and the preservation of the bond between the robots and their human owners.

Besides, it is worth noting that similar initiatives have emerged in other regions, including North America and Europe, where companies now offer services analogous to those provided by A-Fun. The rise of companies in different geographical markets fulfilling similar roles can be interpreted as another instance of distributed self-organization, suggesting the presence of a global socio-robotic ecosystem that has emerged from the wider AIBO community.

Theoretical Notion	Definition	Manifestation in the AIBO Community
Organization	Structuring of relationships among components to form an integrated system.	Coordinated interactions between AIBO units, human owners, and A-Fun create a functional, interdependent network that maintains system coherence.
Emergence	Appearance of novel properties at the system level, irreducible to the individual parts.	Practices such as part salvaging, repair networks, and Buddhist memorial rituals generate emergent social and cultural phenomena — including ritualized recognition of end-of-life and collective stewardship — that go beyond technical maintenance.
Autonomy	System's capacity to self-regulate and maintain coherence independently of external control.	After Sony's withdrawal, the community organizes itself to continue AIBO lifecycles without corporate oversight, relying on local initiatives and shared knowledge.
Co-evolution	Dynamic, reciprocal adaptation between the autonomous system and its external environment.	The AIBO community interacts continuously with broader social, technological, and cultural contexts: adapting to shifts in market conditions, public perceptions of robots, and available resources, while also influencing societal understandings of robotic companionship and sustainability.
Closure	Internal network of operations that sustain the system's identity and stability over time.	The recursive loop of emotional attachment, third-party repair (A-Fun), reuse of donated parts, and shared ritual practices sustains the identity and resilience of the AIBO socio-robotic community over time.

Table 1. Mapping of key self-organization concepts onto the AIBO socio-robotic community.

To better visualize the closure and interdependencies discussed above, Figure A presents a schematic overview of the key relational dynamics shaping the AIBO socio-robotic community.

6 Toward a Self-Organizational Approach to Sustainable Social Robotics

The self-organizational model we propose for the AIBO case (Table 1, Figure A) develops the application of autonomous system modelling beyond its more classical domains — prebiotic, biological, metabiological, or technical — emphasizing how socio-robotic communities, such as the AIBO community, can also display recognizable patterns of self-organization. This extension opens the door to a broader discussion on how such frameworks may inform sustainability strategies for social robots and, more generally, for emerging human–robot ecosystems.

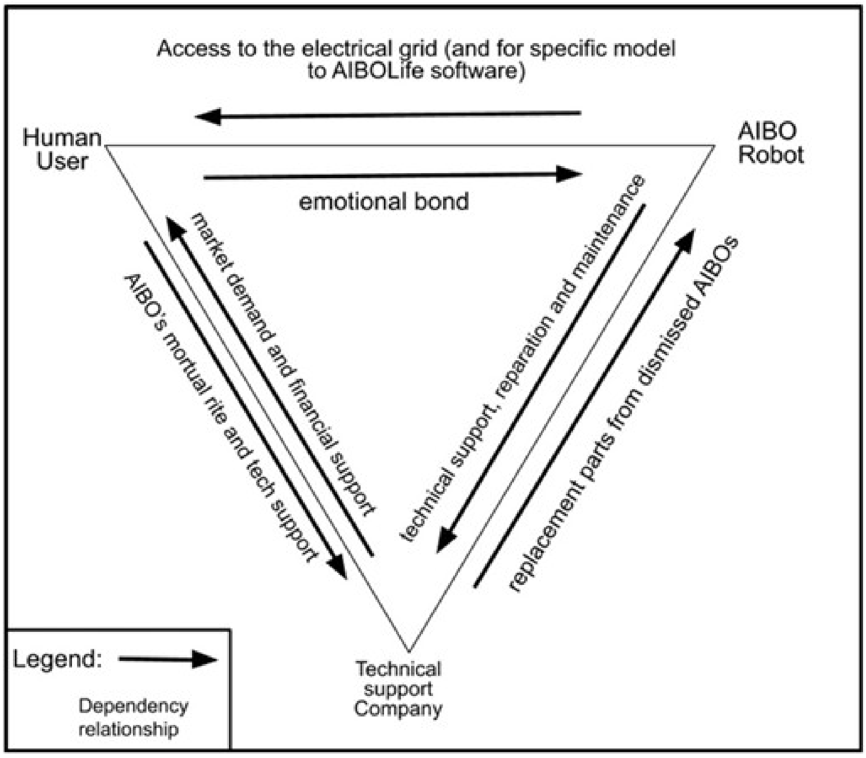

Fig. A. Overview of the interdependent relationships sustaining the AIBO socio-robotic ecosystem as a self-organizing system. Building on this systemic overview, we now turn to the broader implications of interpreting the AIBO case through a self-organizational modeling.

While the literature on ecological robotics and sustainable AI has primarily addressed the material and energetic dimensions of sustainability (e.g., Shintake, 2022; Nagai et al., 2021; Chen et al., 2024; Murakami et al., 2024), the present work extends this debate to the organizational and relational levels. By focusing on the emergent dynamics of socio-robotic communities, it complements technical approaches with an epistemological perspective on sustainability as a self-organizing process.

In particular, the self-organizational interpretation of the AIBO user community highlights a key aspect emerging from the analysis: the sustainability implications of self-organized socio-robotic systems. In stark contrast to the dominant paradigm of technological consumption — marked by rapid obsolescence — AIBO users have shown a marked inclination toward preserving and extending the lifespan of their robots. Notably, this virtuous dynamic has been driven not by commercial incentives, but by social, emotional, and affective values, demonstrating how socio-robotic communities can sustain practices that promote long-term resilience and resource conservation.

This observation suggests that it is possible for sustainable practices to emerge organically from within user communities themselves, offering a crucial insight for the future design of social robots: rather than focusing solely on individual human–robot interactions or market dynamics, designers and engineers might look to embed sustainability-enhancing protocols within the broader socio-robotic ecosystems in which robots are situated — including mechanisms for repair, reuse, and collective stewardship.

This perspective not only informs the design of sustainability-oriented strategies but also extends and actualizes the foundational theoretical contributions of pioneers such as Heinz von Foerster (1960), Jean Piaget (1967), Humberto Maturana and Francisco Varela (Maturana & Varela, 1980; Varela, 1979, 1991), and Erich Jantsch (1980). Their work on biological and cognitive autonomy laid the groundwork for understanding how complex systems achieve self-maintenance and resilience — insights that, as we show here, can be meaningfully applied to socio-robotic ecosystems such as the AIBO community. This theoretical grounding naturally raises the question of how such a perspective can inform the sustainability strategies of future social robots. We believe that the proposed framework provides a theoretical platform for developing new design protocols to strengthen emerging sustainable practices and promote socially and environmentally positive values. It is essential to consider, in the design of next-generation robots, the role of the broader techno-social systems in which these embodied agents are embedded. Robots are not isolated devices; rather, they function as integral components of a network of technological and social interactions. As such, it is necessary to reflect on the potential roles a robot may play within this ecosystem—not only in terms of human–robot interaction, but also in relation to the robot's end-of-life phase and the possible reuse of its components by other members of the user community. This shift in perspective implies that the robot should no longer be viewed merely as a consumable product destined for disposal, but rather as a node within a broader relational network. In this light, the robot becomes a catalyst for social interaction and a resource to be sustained, repaired, and reintegrated, rather than discarded.

Due to this, it is crucial to highlight that the concept of the robosphere, when developed within the theoretical framework of self-organization, offers significant potential from a sustainability perspective. The idea of sustainability was already implicitly embedded in Colombano's conceptualization of the robosphere, as it acknowledged the possibility of self-repair and self-maintenance within robotic ecosystems. However, this dimension has remained a relatively marginal aspect in Colombano's framework and in other approaches to the robosphere, such as Lamola's (Fleres, 2025). Our self-organizing interpretation of the robosphere — particularly through the Varelian notion of organizational closure — brings this dimension into sharper focus. It illustrates how human–robot ecosystems can generate new constraints and interdependencies aimed at the recovery and reuse of components, thereby fostering dynamics that enhance the stability and resilience of the system as a whole.

Approaching the robosphere through the perspective of self-organization theory allows for meaningful parallels to be drawn with other natural self-organizing systems. The innovative contribution of this perspective lies in its framing of socio-robotic ecosystems as resources for enhancing robotic sustainability — where both robots and human communities co-evolve, forming relational networks oriented toward the self-maintenance of the entire system. This approach can serve as the foundation for a generative paradigm of robotics-related practices aimed at sustainability.

Furthermore, this research trajectory may contribute to the dissemination of a culture of self-organization, which could support the development of sustainable practices within human communities. Natural self-organizing systems tend toward homeostasis — the ability to maintain equilibrium over time — by employing a range of strategies, including material recycling. Embracing a culture of self-organization can thus help propagate values essential to sustainability, such as circularity, interconnectivity, and co-evolution with the environment.
We propose that interpreting the AIBO case through the lens of self-organization theory is not only valuable for advancing theoretical developments — particularly those linking self-organization to the concept of the robosphere via Varela's work — but also offers an innovative perspective on human–robot relationships. This research represents a first step toward a global vision of sustainability in social robotics. By examining how complex, self-maintaining systems can emerge through human–robot interaction, we begin to outline a path toward sustainable socio-robotic futures. We are thus currently exploring a promising avenue for further research, focusing on the use of synthetic methodologies to model natural sustainability processes and deliberately apply them to the development of robospheric technologies and communities oriented toward sustainability goals — encompassing not only environmental, but also social and affective dimensions. Such synthetic approaches could provide new insights into how the principles of self-organization can be harnessed not just to describe, but to actively design sustainable socio-robotic ecosystems. While the AIBO community provides an exemplary case of socio-robotic self-organization, its cultural specificity — rooted in Japanese ritual practices and collective attitudes toward technology — calls for comparative analyses. Future research should test whether similar self-sustaining dynamics can emerge in different cultural and technological contexts, and under what organizational conditions.

7 Preliminary Design Guidelines for Sustainable Social Robotics

Drawing on the analysis of the AIBO case and the theoretical framework of self-organization, we propose the following preliminary guidelines for the design of socially and environmentally sustainable social robots.

A. Support repairability and reuse: embed protocols that facilitate maintenance, part replacement, and resource circulation.
B. Foster socio-robotic communities: design robots as nodes in networks of human–robot relations, rather than as disposable products.
C. Acknowledge symbolic and affective practices: integrate awareness of ritual and affective dimensions that sustain long-term stewardship.
D. Promote distributed resilience: encourage architectures and ecosystems that can reorganize after corporate withdrawal or market shifts.

These guidelines are not intended as definitive prescriptions, but as an invitation to consider how design choices can align with the emergent dynamics of socio-robotic communities.
These principles can be operationalized in multiple ways. For example: point A may correspond to open-source maintenance platforms and modular component design; point B to online and local communities that coordinate updates and repairs; point C to participatory rituals of robot care and decommissioning; and point D to distributed technical infrastructures enabling independent service providers to ensure continuity beyond the manufacturer.

8 Conclusion and Future Work

In this work, we have explored the AIBO case within the theoretical framework of self-organization, offering a conceptual analysis of how socio-robotic communities can exhibit emergent, resilient, and sustainability-oriented dynamics. By applying the generic model of autonomous systems to the AIBO user community, we have shown how practices of repair, reuse, and collective stewardship can arise spontaneously within human–robot ecosystems, challenging dominant paradigms of technological consumption and obsolescence.
We believe these insights are relevant not only to the field of social robotics — where they highlight the importance of designing robots as nodes within broader relational networks — but also to cognitive science and interdisciplinary cognition research, where they can enrich theoretical models of emergent adaptive systems and suggest new directions for synthetic modelling and experimental inquiry.
Indeed, while this study is primarily conceptual, it provides a foundational framework that can guide future empirical research, computational simulations, and synthetic explorations. By focusing on the organizational principles underlying socio-robotic communities, we open the door to operationalizing these concepts and testing them in diverse contexts, including the design of next-generation robots and their socio-technical environments.
Future research — building on ongoing work in this direction — could leverage synthetic methodologies to model natural sustainability processes and deliberately apply them to the development of robospheric communities, integrating environmental, social, and affective dimensions into the design of human–robot ecosystems. Such an approach has the potential to generate not only new technological practices but also a broader cultural shift toward the adoption of sustainability-oriented values within human societies.
We believe that this work could inspire further transdisciplinary dialogue on the role of self-organization in shaping the future of sustainable human–robot ecologies, helping to chart a path toward robotic futures that are resilient, responsible, and ethically attuned to the complex systems in which they are embedded.

Acknowledgements. This research has been developed within the PRIN 2022 project Org(SB-EAI) (n. 20222HHXAX, CUP F53D23004560006), funded by the Italian

Ministry of University and Research under the European Union's NextGeneration EU, Mission 4, Component 1. The authors thank P. Stano and A. Roli for the fruitful scientific discussions on these topics within the ongoing collaboration in the Org(SB-EAI) project, with particular reference to WP3 and WP4.

References

1. Asada, M.: Towards artificial empathy: how can artificial empathy follow the developmental pathway of natural empathy?. In: International Journal of Social Robotics, vol. 7(19)– 33 (2015)
2. Baumgaertner, B. and Weiss, A.: Do emotions matter in the ethics of human–robot interaction? Artificial empathy and companion robots. In: International symposium on new frontiers in human–robot interaction (2014)
3. Biocca, F., Harms, C., & Burgoon, J. K.: Toward a more robust theory and measure of social presence: Review and suggested criteria. In: Presence: Teleoperators & virtual environments, vol 12(5):456–480 (2003)
4. In Japan, a Buddhist Funeral Service for Robot Dogs. National Geographic, https://www.nationalgeographic.com/travel/article/in-japan-a-buddhist-funeral-service-for-robot-dogs, last accessed 2025/05/09
5. Carter, E.J., Reig, S., Tan, X.Z., Laput, G., Rosenthal, S. and Steinfeld, A.: Death of a robot: Social media reactions and language usage when a robot stops operating. In Proceedings of the 2020 ACM/IEEE international conference on human-robot interaction, pages 589–597. (2020)
6. Chen, S.C., Pamungkas, R.S. and Schmidt, D.: The role of machine learning in improving robotic perception and decision making. In International Transactions on Artificial Intelligence, vol. *3*(1), pp. 32-43 (2024)
7. Ceruti, M.: La danza che crea. Feltrinelli, Milan (1989)
8. Colombano, S.: Robosphere: Self-sustaining robotic ecologies as precursors to human planetary exploration. In: AIAA Space 2003 Conference & Exposition, pp. 62–78 (2003)
9. Damiano, L.: Co-emergences in life and science. In: Synthese, vol. 185(2), pp. 273–294 (2012)
10. Damiano, L.: Unità in dialogo, Mondadori, Milan (2009)
11. Damiano, L., & Dumouchel, P. G.: Emotions in relation. Epistemological and ethical scaffolding for mixed human-robot social ecologies. In: HUMANA.MENTE Journal of Philosophical Studies, 13(37):181–206 (2020)
12. Dumouchel, P. and Damiano, L.: Living with robots, Harvard University Press. Cambridge (2017)
13. Fleres, A.: Robotica (sociale) e sostenibilità. Impalcature teoriche della robosfera (PhD thesis), IULM University (2025)
14. Fleres, A.: The relationship between social robotics and unsustainability: thinking about the future of human–robot interaction. In: 4th International Workshop on Cognition: Interdisciplinary Foundations, Models and Applications (CIFMA 2022), Berlin, Germany (2022) Available at: https://cifma.github.io/Papers-2022/CIFMA_2022_paper_Fleres.pdf
15. Hartmann, F., Baumgartner, M. and Kaltenbrunner, M.: Becoming sustainable, the new frontier in soft robotics. In Advanced Materials, vol. 33(19), p.2004413 (2021)
16. Jantsch, E.: The self-organizing universe: Scientific and human implications of the emerging paradigm of evolution. Pergamon Press, Oxford (1980)

17. Kahn Jr, P.H., Friedman, B. and Hagman, J.: "I care about him as a pal" conceptions of robotic pets in online AIBO discussion forums. In: CHI'02 Extended Abstracts on Human Factors in Computing Systems, pp 632–633 (2002).
18. Kanamori, M., Suzuki, M. and Tanaka, M.: Maintenance and improvement of quality of life among elderly patients using a pet-type robot. In Nihon Ronen Igakkai zasshi. Japanese journal of geriatrics, vol. 39(2), pp 214–218 (2002)
19. Kertész, C. and Turunen, M.: Exploratory analysis of Sony AIBO users. In Ai & Society, vol 34, pp 625–638 (2019).
20. Knox, E. and Watanabe, K.: AIBO robot mortuary rites in the Japanese cultural context. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS), pages 2020–2025, IEEE (2018)
21. Lamola, M.J.: On the Robosphere: A Philosophical Explication of the Socio-technical Status of Social Robots. In: International Journal of Social Robotics, vol 14(5), pp. 1199– 1209 (2022)
22. Maturana H. R., Bunnell P.: Biosphere, Homosphere, and Robosphere: What has that to do with Business. Society for Organizational Learning, pp 1–28 (1998).
23. Maturana, H. R., and Varela, F. J.: Autopoiesis and cognition: The realization of the living, 42. Springer Science & Business Media (1980/2012).
24. Melson, G.F., Kahn, Jr, P.H., Beck, A. and Friedman, B.: Robotic pets in human lives: Implications for the human– animal bond and for human relationships with personified technologies. In: Journal of Social Issues, vol. 65(3), pp. 545–567 (2009)
25. Murakami, K., Sato, M., Kubota, M. and Shintake, J.: Plant robots: Harnessing growth actuation of plants for locomotion and object manipulation. Advanced Science, vol. 11(43), p.2405549 (2024)
26. Nagai, T., Kurita, A. and Shintake, J.: Characterization of sustainable robotic materials and finite element analysis of soft actuators under biodegradation. In Frontiers in Robotics and AI, vol 8, p. 760485 (2021)
27. Novikov, D.A.: Cybernetics: from past to future. Springer (2015)
28. Pfeifer, R. and Bongard, J.: How the body shapes the way we think: a new view of intelligence. MIT press, Cambridge (2006)
29. Piaget, J.: Biologie et connaissance. Gallimard, Paris (1967)
30. Sharkey A. and Sharkey N.: Granny and the robots: ethical issues in robot care for the elderly. In Ethics and information technology, vol 14, pp. 27–40 (2012)
31. Shintake, J.: Green robotics: Toward realization of environmentally friendly soft robots. In Journal of Robotics and Mechatronics, vol. 34(2), pp.270-272 (2022)
32. Sarc, R., Curtis, A., Kandlbauer, L., Khodier, K., Lorber, K.E. and Pomberger, R.: Digitalisation and intelligent robotics in value chain of circular economy oriented waste management–A review. In Waste Management, *95*, pp.476-492 (2019)
33. Stengers, I.: Les généalogies de l'auto-organisation. In : Dupuy J.-P (Ed), Généalogies de l'auto-organisation, Cahiers du CREA, vol. 8, pp. 7–104 (1985)
34. Sugano S., Shirai Y. and Chae S.: Environment design for human-robot symbiosis - Introduction of wabot-house project. In 2006 Proceedings of the 23rd International Symposium on Robotics and Automation in Construction, ISARC 2006, pp. 152–157 (2006)
35. Varela, F.J.: Principles of biological autonomy. MIT Press, Cambridge, MA (1979)
36. Varela, F. J.: Organism: A meshwork of selfless selves. In Organism and the Origins of Self, Dordrecht: Springer Netherlands (1991)
37. von Foerster, H.: On self-organizing systems and their environments. In Understanding understanding: Essays on cybernetics and cognition, pp 1–19 (1960/2003).