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Advancing sociotechnical systems theory: New principles for human-robot team design and development

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ABSTRACT

This paper reviews and adapts sociotechnical systems (STS) principles for the design and development of Human-Robot Teams (HRTs). Through a collaborative review process, the authors identify existing STS principles relevant to HRTs, suggest modifications, and introduce new ones to address the unique challenges of designing and developing human-robot teams. A framework of 34 STS principles grouped into seven themes is presented: Systems Design and Adaptation, Human-centered Approach, Integration and Optimization, Collaboration and Participation, Information and Communication, Organizational Alignment and Process Management, and Trust and Reliability. To address the dynamic nature of HRTs incorporating mutual understanding between humans and intelligent robots, eight new principles are introduced: Adaptive Autonomy, Agility and Responsiveness (future thinking), Cognitive Workload Management, Ethical Considerations, Transparency and Explainability, Collaborative Sensemaking, Trustworthiness and Unpredictability Management.

This STS framework bridges traditional STS theory and AI-enhanced HRTs, guiding developers in creating effective, trustworthy, and ethical HRTs. The paper benefits researchers, developers, and organizations by addressing sociotechnical complexities and upholding a more balanced, ethical, and human-centered collaboration in HRT development.

1. Introduction

Sociotechnical systems (STS) theory posits that organizational and work effectiveness is optimized when social and technical systems are designed to work in harmony. The recent rapid advancement of Artificial Intelligence (AI) and robotics has introduced new complexities to sociotechnical system design, particularly in the context of Human-Robot Teams (HRTs) working together.

We define Human-Robot Teams (HRTs) as a system or team of humans and intelligent robots, who interact socially and collaboratively to perform tasks interdependently in a joint workspace and engage with the same objects to achieve common goals. In HRTs, the robots are assumed to have appropriate intelligence empowered by AI. The complex and dynamic interactions and communication between humans and robots in HRTs is enabled by AI such as large language models (LLMs) (Makarius et al., 2020; Wolf and Stock-Homburg, 2023).

The integration of intelligent robots into teams with human workers presents both opportunities and challenges, necessitating a careful consideration of socio-technical factors to ensure optimal and functional HRTs. STS thinking is particularly crucial in the design and development of HRTs for several reasons. First, it ensures a balanced focus on both the technological capabilities of robotic team members and the social dynamics of human-robot collaboration. Second, it encourages a holistic approach to system design, considering the broader organizational context and potential impacts on work processes. Third, STS principles show how STS theory can be converted into practical interventions. Adapting these guiding principles enables designers and developers to appreciate the importance of human factors, user-centered design and ergonomics in developing effective HRT systems.

While current STS principles offer a valuable foundation for understanding complex human-machine systems, this article reviews the existing STS principles and introduces new principles with the focus on HRT designers and developers.

This article suggests that the unique characteristics of HRTs require adaptations to existing principles and introduction of new ones in the context of HRT design and development. It aims to provide a comprehensive framework that aligns with STS theory. This article will review and explore these modified and new principles in detail, discussing their

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theoretical basis founded in STS and practical implications for the design and development of effective human-robot teaming systems.

This article begins with a literature review of STS principles'' background and evolution, followed by the research approach. It then presents findings and discussion of STS principles for HRT design and development, introduces a framework with adapted and new STS principles for HRTs, and concludes with future research directions.

1.1. Literature review: background and evolution of STS principles

Sociotechnical Systems (STS) theory emerged during the 1950s as a result of studying the impact of technological changes on work (Trist and Bamforth, 1951). These studies showed technology interventions led to decreased job satisfaction and productivity. It was also found that workers organized their work to adopt technology while meeting their social needs.

These observations led to the core principles for STS theory that addressed the interrelatedness and interdependencies of social and technical systems (Clegg, 2000; Emery and Trist, 1972; Klein, 2014; Trist and Bamforth, 1951). The technical system includes the technology, tools, techniques, and associated work structures and processes used to transform inputs into outputs while the social system comprises the people in the organization, their skills, attitudes, values, and relationships. The social system also includes the grouping of individuals in different roles into teams, coordination, control, boundary management, delegation of responsibility to the work group and reliance on its judgment for operational decisions (Klein, 2014).

The two deeply intertwined and mutually influential systems led to the principle of "joint optimization" where both social and technical systems need to be designed for the overall optimal system performance. Subsequently these ideas were extended to the concept of "open sociotechnical systems" that interact with their environments (Emery and Trist, 1972; Trist, 1981), closely followed by the demonstration that participative design could lead to more effective work systems (Emery and Thorsrud, 1976).

Cherns (1976, 1987) further articulated a set of nine principles for sociotechnical design, including concepts like minimal critical specification and the need for congruence between social and technical systems. Clegg (2000) provided a modern reformulation of STS principles, adapting them to contemporary work environments and technologies, particularly with the rapid technological changes of the late 20th century. Clegg's reformulation includes 19 sub-principles clustered into three groups – meta, content, and process principles. Clegg's pivotal work highlights certain foci: information technology, cognitive work, flexibility, user-centered design, iterativeness, broader scope, and integration with other disciplines. In technology, Clegg addresses the role of information technology in modern work systems, which was less prominent in earlier STS formulations. His emphasis on cognitive work and knowledge management follows the shift towards knowledge-based work in many industries. His principles include inclusion of flexible and adaptable systems that can respond to changing environments and technologies. Clegg emphasizes designing systems that balance human and technical needs, viewing design as an adaptive process in rapidly changing environments (Clegg, 2000, Clegg et al., 2017).

A comprehensive synthesis of STS principles was conducted by Imanghaliyeva et al. (2020), providing a thorough review of STS principles up to 2019. Their work serves as a valuable foundation for understanding the evolution of STS theory.

1.2. STS in the 21st century

Modern STS researchers emphasize that 'sociotechnical' means more than just examining social and technical factors in isolation. Contemporary STS principles have evolved to address the complex challenges of today's technological landscape to lend importance to.

- Continuous Adaptation (Bednar and Welch, 2020; Pasmore et al., 2019)
- Human-Centered Automation (Clegg, 2000; Maguire, 2014)
- Rapid Technological Advancements (Karwowski, 2006; Pasmore et al., 2019)
- Organizational Ecosystems (Mohrman and Winby, 2018)
- Boundary Management (Klein, 2014)
- Language and Concept Clarity (Klein, 2014)
- Values and Organizational Boundaries (Klein, 2014)

While STS principles are important overall, not all of them are relevant for different stages and processes. That is, some principles lend stronger relevance at the macro or organizational levels e.g., interactions with senior management, governance, steering board, policy makers, clients, consultants. Others are critical at the meso (e.g., HRT team interacting with other systems at the mid-level like line management, engineers, project managers, contractors, other sub-contractors, supervisors, safety unit) and micro levels (e.g., HRT unit at the base level comprising a team of human operators (workers, engineers), intelligent robot and other related tools and technologies) in the organizational system (Ang et al., 2024a; Ang et al., 2023). Additionally, the principles could have different relevance across the process lifecycle, for instance, during ideation, planning, design, development or implementation or operational and maintenance levels (Ang et al., 2024a; Ang et al., 2023).

In this article, we will be focusing on the design and development stages of HRT systems. Design is the phase where the detailed specifications, features, and architecture of the HRT solution are conceived and documented, while development is the stage where the designed HRT solution is built, tested, and brought into functional existence. These two phases are interactive processes. These stages are likely to work more closely with the micro and meso levels of the organization. Design requires user involvement to ensure that it meets the users'' needs within the capabilities of the robot systems. The design of a HRT requires a multidisciplinary team, while during development, it is important to keep in focus the engineering solution and human factors.

A unique aspect of HRTs is the mutual learning between the human and the robot, whereby the human can learn from the robot, and conversely, the robot can learn from the human, known as 'collaborative intelligence' (Ang et al., 2024b). This bidirectional learning represents a fundamental shift from traditional sociotechnical systems where technology served as a relatively static tool or interface. In conventional STS frameworks, the 'technical' component appeared mostly predictable and unchanging within operational contexts, with adaptation primarily occurring through human adjustment to technological constraints. However, AI-driven HRTs are dynamic where both human and intelligent robots continuously modify their behaviours, capabilities, and decision-making processes based on interaction experiences. This creates unprecedented challenges for traditional STS principles, which were conceptualised for systems with relatively stable technical components and predictable human-technology interfaces. Thus, the HRT design needs to be intuitive enough for both the human and robot to learn from each other.

In this article, we refer to the processes of HRT design and development as 'HRT development', and 'designers and developers' as 'developers'. Our review aims to address the emerging gaps and necessary modifications considering recent advancements in AI and robotics technologies, particularly in the context of developing human-robot teams (HRTs).

1.3. Human-robot teams

Human-robot teams (HRTs) involve multiple humans and multiple robots working interdependently on joint tasks, interacting socially to achieve common goals (van Diggelen et al., 2018). Hoffman and Breazeal (2004) described them as collaborating in shared spaces and interacting with common objects. Key aspects include joint tasks, interdependence, interaction, and shared workspaces. Advances in AI such as large language models enable robots to learn, make decisions and adapt creating a more dynamic relationship (Wolf and Stock-Homburg, 2023).

1.4. Gaps in existing STS principles

The co-evolutionary dynamic characteristics of HRTs identified in the previous section raise fundamental questions about the applicability of existing STS principles. Traditional STS design principles assume relatively stable technical capabilities and focus primarily on optimizing human adaptation to technological systems. However, when both human and intelligent robotic technologies are simultaneously learning and adapting, several critical gaps emerge.

First, traditional STS principles were developed for systems where the technical component remained relatively constant during operations. The mutual learning aspect of HRTs means that system capabilities, interfaces, and even fundamental operational logic can evolve continuously. This raises the question of whether principles designed for static sociotechnical relationships can adequately guide the design of dynamic, co-evolutionary systems. The gap questions the applicability of previously formed principles under dynamic conditions.

Second, traditional STS frameworks primarily address human adaptation to technology, with limited consideration of technology adapting to humans beyond initial design phases. HRTs require continuous bidirectional adaptation, where design principles must account for ongoing mutual modifications of both human and robot behaviours (whether directed or non-directed), preferences, and capabilities. The gap identified questions whether the existing principles allow for bidirectional adaptation requirements.

Third, the literature shows that the collaborative intelligence emerging from human-robot mutual learning can produce behaviours and capabilities that might not be explicitly designed or anticipated. Traditional STS principles may be insufficient for managing these emergent properties, which can fundamentally alter HRT performance, safety, and user experience.

These theoretical gaps directly informed our research approach, leading to two research questions designed to systematically evaluate and address these challenges.

1.5. Methodology and analysis

The purpose of the research approach is to collaboratively discuss and identify STS-HRT gaps, and justifications for modified or new principles in the context of the design and development of HRTs (where the robot is assumed as a peer and intelligent member of the team).

Given that existing STS principles were developed for different technological contexts, it is essential to systematically evaluate their relevance and effectiveness when applied to co-evolutionary human-robot teaming systems. This first question fills the gap to provide a foundation for understanding where traditional principles succeed and where they fall short in guiding HRT development.

Research question 1. How well do the current STS principles fit with the design and development of human-robot teams?

Next, we address the adaptation gap by seeking to identify specific theoretical and practical enhancements needed to accommodate mutual learning dynamics. The second question acknowledges that rather than completely replacing existing STS theory, we may need to modify these principles to address the unique challenges posed by intelligent, adaptive artificial agents functioning as team members rather than as tools.

Research question 2. What modifications or additions do we need (if any) for STS principles to fit in the context of HRT design and development?

The authors used a multimethod approach (Kasirye, 2024) using two qualitative approaches underpinned by an interpretivist paradigm to review existing STS principles and to propose new principles that are relevant in the HRT context. To evaluate how well current STS principles fit HRT design and development, we employed a collaborative expert evaluation approach with a multidisciplinary team comprising the three authors as STS theorists and HRT practitioners. Our evaluation team included two STS experts specialising in HRT design, HRT robotics experts with over 20 years' experience, and system designers with over 10 years robotics experience. This team collectively observed HRT design processes over three years and then conducted structured in-depth discussions to assess principle relevance, identify gaps, and determine necessary modifications of STS principles. The multidisciplinary profile of this team can be found in Supplementary File 10.

The evaluation methodology involved: (1) systematic literature review of existing STS principles; (2) individual expert assessment of principle applicability to HRT contexts; (3) collaborative face-to-face sessions to discuss, debate, and justify principle relevance; and (4) iterative refinement through multiple validation sessions. This approach leveraged both theoretical expertise in STS and practical experience in HRT design to ensure comprehensive evaluation of principle fit within intelligent human-robot team contexts. The cumulative expertise of the team provided robust validation of a principle's applicability, with detailed process documentation provided as supplementary material.

Fig. 1 illustrates the four-step process used to address RQ1.

The evaluation team then identified existing principles that were still relevant either directly or with some modifications (Research Question 2). Extracts of the Excel spreadsheet used to provide instructions, structure and iterative ideas for the discussions are attached as supplementary files. Supplementary File 4 provides an example of the principles reviewed. The comprehensive review (Supplementary File 4) examined STS principles from diverse disciplinary perspectives, including management scholars (Trist and Bamforth, 1951; Emery, 1980; Clegg, 2000; Griffith and Dougherty, 2001; Davis, 2019), social scientists (Cherns, 1976, 1987; Eason, 2013; Klein, 2014), engineering researchers (Carayon, 2006; Mariani, 2019), organizational behaviour experts (Pasmore et al., 1986, 2019), design theorists (Maguire, 2014), infrastructure and environment specialists (Imanghaliyeva et al., 2020), and computing researchers (Waterson and Eason, 2019; Rücker et al., 2019).

1.6. Direction of modifications

While most existing literature did not focus specifically on robotics contexts except for Rücker et al.'s (2019) work, we identified several critical modification pathways that fit within a HRT design context as follows.

Traditional STS principles assumed unidirectional human adaptation to technology. We modified these to accommodate mutual learning between humans and robots, incorporating insights from co-generative learning (Griffith and Dougherty, 2001), mutual learning frameworks (Levin, 1997), and collaborative intelligence concepts (Ang et al., 2024a, 2024b). This demonstrates bidirectional learning enhancements that are not explicit in traditional STS principles. Next, we found that existing trust principles required expansion to address the complex ethical dimensions of AI-driven teams, integrating work on ethical frameworks (Vermaas et al., 2011; Nagbøl et al., 2021; Wolf and Stock-Homburg, 2023; Love et al., 2023) and dynamic trust mechanisms (Onososen and Musonda, 2022). Further, traditional principles needed to be enhanced to address the emergent and cognitive complexity of human-robot sensemaking, drawing from sensemaking literature (Klein, 2014; Reymondet, 2016; van Diggelen et al., 2018; Makarius et al., 2020; Wolf and Stock-Homburg, 2023) and cognitive frameworks (Karakikes and Nathanael, 2023).

Table 1 summarises 26 STS principles that were eventually selected

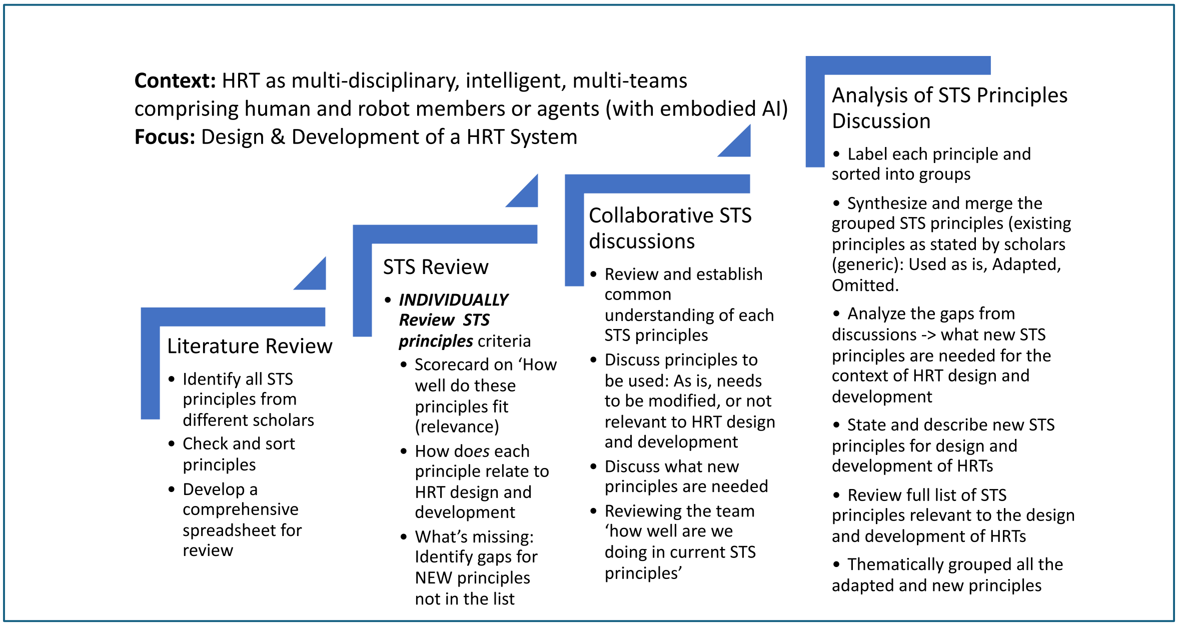

Fig. 1. Collaborative review approach.

as relevant for the HRT context.

1.7. Findings

STS principles for HRT development.

The review identifies 26 existing STS principles (Table 1) that are relevant to HRT design and development. Following (Table 1), each principle is explained in terms of how it is adapted to accommodate the unique characteristics of HRT design.

1.8. Adaptability

This key principle emphasizes the need for adaptability in responding to changes over time, both internally and externally (Cherns, 1987; Trist and Bamforth, 1951; Waterson and Eason, 2019), including continuous system improvements (Carayon, 2006). Davis (2019) addresses the adaptability of physical workspaces while Klein (2014) discusses adaptive strategic planning in alignment with organizational goals. Adaptability, though often emphasized at the organizational or macro domains, is critical for HRT development, while recognizing that certain external variances are beyond the designers' control. HRT adaptability refers to the system's ability to respond to variances including dynamic workspaces, diverse human and robot participants, cultural differences, goal alignment and continuous system improvement to manage changes over time.

1.9. Autonomy

Autonomy relates to the ability to control and take responsibility for one's tasks and outcomes. This means allowing individuals or groups to have decision-making power and self-regulation (Cherns, 1987; Emery and Thorsrud, 1976; Maguire, 2014; Pasmore et al., 2019; Trist and Bamforth, 1951).

In HRT development, autonomy includes those designing and developing the systems, and those involved in implementation and operations. Therefore, autonomy here refers to the self-regulation and decision-making power of individuals and workgroups in a HRT system, and how they are developing the system for self-regulated human-robot teams.

1.10. Boundary controls

Technological systems emphasize the need for careful analysis and design of boundaries and interdependencies between system components (Eason, 2013; Trist and Bamforth, 1951). System boundaries can impact design objectives like usability and personal development (Klein, 2014); therefore, understanding the impact of cross-boundary work on sociotechnical systems and their implications for ergonomics is important (Carayon, 2006).

In HRT development, boundary controls involve carefully identifying, analyzing and defining the interfaces between humans and robots. These boundaries should be designed to facilitate knowledge sharing, monitoring, and information flow. The placement of boundaries impacts design objectives with implications for physical, cognitive, and psychosocial ergonomics. Developers should consider how technological boundaries influence and create demands for the social system as an integrated whole while respecting necessary divisions.

1.11. Co-generative learning

Co-generative learning as a principle is closely related to the principles of 'Participation and co-design' and 'Learning opportunities'. Several authors (Ang et al., 2024b; Elden and Levin, 1991; Levin, 1997) discuss co-generative learning as a sociotechnical aspect involving various stakeholder groups.

HRT developers and users can co-generatively learn alongside the AI-driven technologies to ensure understanding of the technological and social aspects and impacts.

At the operations stage, we expect that humans and robots in an HRT system can learn from and teach each other (e.g. skills transfer), working co-generatively to define, learn and understand the interdependent sociotechnical systems'' impact on each other, and reiterates the need for continuous learning in HRTs, particularly since HRTs evolve over time.

1.12. Compatibility

Cherns (1976, 1987) emphasizes that the design process must be compatible with its objectives, stressing the importance of collaborative effort. In HRT development, compatibility ensures alignment between

Table 1
Existing STS Principles for HRT design and development.

	STS Principle	Brief Description
1	Adaptability	Capacity to adapt and manage changes or variances
2	Autonomy	Self-regulation, decision-making power, responsibility for outcomes.
3	Boundary Controls	Define interfaces, manage knowledge and information flow.
4	Co-generative learning	Learn and teach each other, generated collaboratively with the various stakeholders.
5	Compatibility	Align design process with objectives, participatory, consensus.
6	Congruence	Reinforce behaviours, align authority with resources, create harmony.
7	Continuous	Dynamic systems, ongoing redesign, continual negotiation of goals.
8	Incompletion	Flexible design, iterative process
9	Information Management	Efficient information flow, collaborative design, timely access.
10	Integrative	Holistic approach, multidisciplinary collaboration.
11	Joint Optimization	Balance social and technical elements, synergistic, mutual adaptation.
12	Learning Opportunities (continuous)	Continuous learning, varied experiences, knowledge sharing, co-generative learning
13	Minimal Critical Specifications	Define essentials, flexible, promote adaptation.
14	Multidisciplinarity	Diverse expertise, cross-disciplinary collaboration
15	Multifunctionality	Versatile team structures, flexible roles, overlapping skill sets.
16	Open Systems	Environmental influence, holistic view, real-world evaluation.
17	Participation/Co-design	Stakeholder engagement, collaborative creation, ongoing involvement.
18	Self-managing	Autonomy, self-regulation, balanced decision-making.
19	Simplicity and Transparency	Clear interactions, feedback-oriented, problem visibility.
20	Socially Shaped	Influenced by social factors, inclusive design, context-specific.
21	Support Structures	Resources, training, consideration of social/ psychological aspects.
22	Task interdependencies	Tasks are shared, coordinated and accomplished. Sequential, reciprocal or parallel tasks to achieve shared goals.
23	Transitional	Evolving systems, built-in flexibility, continuous learning mechanisms.
24	Values and Mindset	Ethical, human-centric values, balanced approach.
25	Variance Control	Detect, respond and manage deviations/ variances, maintain stability.
26	Work Roles/Job Design	Meaningful roles, complementary tasks, shared responsibility.

the design process and intended objectives of the HRT system. This principle involves a participatory approach where stakeholders, including human team members and robot designers, collaboratively reveal assumptions and reach decisions by consensus. The design process should reflect the readiness of the organization to deal with conflicts, and to consult with and inform team members to foster shared understanding and commitment to the HRT system's goals.

1.13. Congruence

Clegg (2000) states that system components should be congruent. Social support structures need to be designed to reinforce desired work behaviours, for instance, aligning work authority with access to necessary resources, linking reward systems to knowledge rather than just actions (Cherns, 1976, 1987).

In developing HRTs, congruence involves creating support structures that reinforce desired behaviours and interactions within the HRT. This means aligning authority with access to resources for developers of HRTs, and for humans and robots to have the necessary tools and permissions to perform their roles effectively. Reward systems should be designed to value knowledge and expertise, recognizing the unique contributions of HRT developers, and HRT human and robot members.

1.14. Continuous

Socio-technical change must be continuous and requires the continuous redesign of work systems (Pasmore et al., 2019), including continual negotiation of goals, values, and meaning with stakeholders (Winter et al., 2014).

In HRT development, this principle emphasizes that these systems should be viewed as dynamic, evolving entities rather than static design constructs. This involves ongoing negotiation of goals and meanings among team members, redesign, adaptation, and upgrade of the HRT system in response to performance feedback, changing needs, technologies, and team dynamics.

1.15. Incompletion

Incompletion implies that designs are incomplete and unfinished, requiring a process of iterative evaluation and flexibility to deal with new demands (Cherns, 1976, 1987; Maguire, 2014).

The incompletion principle recognizes that HRT systems are inherently unfinished and should incorporate built-in flexibility to adapt to emerging requirements. Thus, initial design is treated as a starting point rather than a final product, implementing mechanisms for continuous evaluation and improvement, and empowering the HRT (both humans and robots) with the capacity for self-regulation and adaptation to enable refinements over time.

1.16. Information management

Cherns (1976, 1987) states that information should go directly to where it is needed. Information systems need to be designed in cooperation with primary users. In HRT development, this involves creating systems that ensure efficient and direct flow of information to where it is needed. This principle emphasizes that developers should consider how information flows across the human-robot interface, and that boundaries between team members do not impede the sharing of critical information. The goal is an HRT system where humans and robots have timely access to the information needed to perform their tasks effectively and make informed decisions.

1.17. Integrative, systemic and holistic

STS theory advocates for a systemic, holistic and integrative view of both the social and technical aspects in a system. Careful consideration to the spatial arrangements and distances between system parts and roles is needed (Trist and Bamforth, 1951). Clegg (2000) views design as systemic and considers all aspects of a system as interconnected and suggests integrating core processes, while Carayon (2006) includes integration across disciplines and expertise across boundaries. Thus, 'integrated processes' in STS principles refers to the design and management of processes within the STS that promotes seamless interaction, collaboration, and synergy between different social and technical components. This extends to designing collaborative workflows, ensuring interoperability, prioritizing safety and efficiency, and maintaining adaptability while supporting human-centered design principles.

As an integrated HRT work system, this principle emphasizes the importance of multidisciplinary collaboration in the design process, bringing together expertise in robotics, human factors, AI, ergonomics, psychology and relevant domain knowledge to create a cohesive and effective human-robot team.

1.18. Joint optimization

STS scholars view joint optimization as a core principle for optimizing both social and technical subsystems (Cherns, 1976, 1987; Maguire, 2014; Oosthuizen and Pretorius, 2016; Pasmore et al., 2019; Trist, 1981). Social subsystems comprise organizational structure, knowledge, skills, attitudes, values, and needs (Oosthuizen and Pretorius, 2016). Winter et al. (2014) emphasize the mutual causality between social and technical elements.

For HRT development, joint optimization involves balancing and simultaneously enhancing the capabilities of both humans and robots. This means creating synergies between the social (human) and technical (robotics) aspects of the HRT system, rather than optimizing them in isolation. Developers should design for mutual adaptation and learning between human and robotic team members, where each enhances the other's capabilities. This means considering the strengths of humans (e.g., physical strength, uncertainty handling, perception, empathy, creativity, problem-solving) and that of robots (e.g., precision, consistency, endurance, high-speed data processing, speed of operation) to enable optimal task allocation and execution. The goal is a HRT system where the combined performance exceeds what could be achieved by either humans or robots alone, recognizing the mutual influence and causality between the social and technical aspects of the team.

1.19. Learning opportunities (continuous)

STS authors stress the importance of learning opportunities for each team member (Emery and Thorsrud, 1976; Pasmore et al., 1986). Carayon (2006) integrates individual and organizational learning into continuous system adaptation.

In developing HRT systems, learning should support continuous adaptation and improvement and potentially developed co-generatively. This principle focuses on fostering continuous learning and skill development for all multidisciplinary HRT design teams, stakeholders, and within human-robot teams, enabling two-way learning and skill transfer between humans and robots. This principle extends to organizational learning, allowing the entire system to evolve through collective experiences. Continuous adaptation is essential to keep pace with technological advancements, with multidirectional skill and knowledge transfer as a unique feature of AI-enhanced HRTs.

1.20. Minimal critical specifications

This principle emphasizes specifying only what is absolutely essential, ensuring that objectives are specified while allowing flexibility in methods (Cherns, 1987). Klein (2014) highlights a system that allows workers initiative in how to accomplish tasks.

Minimal critical specification for HRT design involves defining only the essential parameters necessary for the HRT system to function effectively for a task, while allowing flexibility in how tasks are accomplished. This principle encourages developers to specify clear objectives for the HRT but avoid over-prescribing methods, allowing for local adaptation and innovation in human-robot collaboration. This approach fosters resilience and adaptability in the HRT system to be able to respond effectively to changing conditions and requirements.

1.21. Multidisciplinarity

This involves human factors and ergonomics designers working collaboratively with domain experts and other disciplines for understanding system elements (Carayon, 2006). This principle supports a diverse range of expertise in the HRT development process to ensure a comprehensive understanding of both the technical aspects of robotics and the human factors involved in team dynamics. This approach enables the creation of HRT systems that are technically sound, user-friendly, and effectively integrated into their operational contexts.

1.22. Multifunctionality

This STS principle emphasizes the need for workers to have diverse skills for greater flexibility (Cherns, 1976, 1987; Emery and Thorsrud, 1976; Pasmore et al., 1986, 2019). Clegg (2000) discusses shared task allocations between humans and machines.

In HRT development, multifunctionality means designing human-robot teams where both humans and robots can perform various tasks. This encourages flexible role allocations based on each member's strengths and includes building redundancy, so humans and robots have overlapping skills for resilience and adaptability. The goal is to create HRT systems that can adapt to changing demands and unexpected situations by leveraging the diverse capabilities of all its members.

1.23. Open systems

As open systems, every sociotechnical system is embedded in an environment that affects its behaviour (Trist and Bamforth, 1951). This indicates that sociotechnical systems are influenced by and must adapt to their environment (Klein, 2014; Maguire, 2014; Trist and Bamforth, 1951). Open systems imply that technical structures and work roles need to be considered together as part of an inclusive system.

Consequently, developers should design HRT systems with the flexibility to respond to external changes and pressures. This principle emphasizes the need to consider the HRT as a holistic system, where humans and robots are viewed as interconnected parts of a larger whole.

1.24. Participation and co-design

Design should reflect the needs of the business, its users and managers (Clegg, 2000). This means involving workers, employees, managers and users in designing and redesigning work as needs and systems evolve (Carayon, 2006; Clegg, 2000; Davis, 2019; Davis et al., 2014; Eason, 2013; Maguire, 2014; Pasmore et al., 2019; Trist and Bamforth, 1951). Klein (2014) links worker participation to ethics and quality of life, emphasizing the opportunity to participate in decisions that affect them. However, some organizational aspects of participation and decision making extend beyond the scope of HRT development.

In HRT development, participation and co-design should actively engage all stakeholders, including workers, end-users, and developers in the design process. This collaborative approach values even the input of robot capabilities. Participation extends beyond initial design to include ongoing adaptation and system improvements. While some participation aspects are outside HRT design, this principle supports congruence, adaptation, incompletion and continuous improvements by leveraging insights from system users.

1.25. Self-managing groups

The STS principle of self-managing groups emphasizes giving teams the authority and knowledge to control their activities without external supervisors (Emery and Thorsrud, 1976; Klein, 2014; Pasmore et al., 1986, 2019).

In HRT development, developers can be empowered with the authority, knowledge, and tools to manage their work and decisions. Developers should design systems that enable teams to self-regulate, adapt to changes, and optimize performance without constant external supervision, thereby fostering a collaborative environment where tasks are effectively managed, and practices can evolve.

1.26. Simplicity and transparency

Systems should be designed to be manageable and understandable for users (Clegg, 2000). Simplicity in design involves reducing unnecessary complexity and making system structures and operations transparent, visible and comprehensible to stakeholders.

Simplicity in HRT development implies clear and transparent interactions between social and technical components to support coordination and collaboration among humans and robots. Decisions by humans or robots should be understandable and interpretable.

1.27. Socially shaped

Design practice is viewed as a sociotechnical system (Clegg, 2000) that is socially shaped and contextually dependent for the solution being developed and objectives to be achieved.

In HRT development, this implies that systems are influenced by social factors and processes. Creating a HRT is not purely a technical endeavour; it is shaped by the social context, including organizational culture, team dynamics, and broader societal factors. Social implications need to be considered when designing and introducing intelligent robots and how this might reshape existing work attitudes, behaviours, relationships and practices.

1.28. Support structures

The presence of support structures such as resources and organizational support are required for design (Clegg, 2000; Emery, 1980; Griffith and Dougherty, 2001). This includes education, democratized work environments and cooperative management (Emery, 1980), considering workers'' own needs, understandings, and constructions (Griffith and Dougherty, 2001).

Developers should design support mechanisms that facilitate smooth human-robot interaction, including training programs for humans to collaborate and work effectively with the robot counterparts, and maintenance systems for robots. The principle includes social and psychological aspects of support to meet the needs of humans in the HRT design.

1.29. Task interdependencies

Task interdependencies are critical for effective design and analysis of STS (Eason, 2013; Waterson and Eason, 2019). This principle is directly applicable to HRT development in terms of how work is shared, planned and coordinated to achieve the shared goals. This principle is closely related to joint optimization and requires intelligent adaptability in the HRT design.

1.30. Transitional

This principle applies to a system's adaptability to change, such as transitioning to new forms as needs change (Cherns, 1976, 1987). The design team drives this transition while operating teams must develop skills for operation, teamwork, and redesign.

In HRT systems, being transitional implies that designs are flexible, reconfigurable, and able to evolve. Developers should build adaptability into the system to accommodate changing needs and emerging technologies. The development process is transitional, thus facilitating continuous learning and adaptation so both humans and robots can grow and adjust their roles and capabilities accordingly.

1.31. Values and mindset

Clegg (2000) emphasizes that values and mindsets are central to design, while Klein (2014) advocates human-centric systems that prioritize employee rights and needs.

In HRT development, this principle suggests embedding ethical and human-centered values into the core of the HRT system. Developers should prioritize human well-being, rights and needs when integrating robots. This principle views technology as enhancing and complementing, rather than replacing human capabilities to balance human and robot strengths while focusing on human dignity and development.

1.32. Variance control

Variance control includes controlling deviations that affect performance within the system at the point of origin while managing these variances within boundaries (Cherns, 1976, 1987; Trist and Bamforth, 1951).

Variance control in HRT design involves creating mechanisms to manage deviations and unexpected events effectively. The HRT system needs to detect and respond to variances as close to their point of origin as possible, leveraging both humans' and robots'' adaptive capabilities to collaboratively solve problems and handle variances. This creates a resilient HRT system capable of maintaining performance stability while adapting to changing conditions.

1.33. Work roles and job design

Trist and Bamforth (1951) emphasize organizing meaningful jobs and work roles so workers feel responsible for entire tasks.

This principle focuses on creating meaningful and well-structured roles for both humans and robots in HRTs. Developers should design tasks and responsibilities that leverage the unique strengths of both humans and robots, ensuring that human roles remain engaging, satisfying, and cognitively stimulating. The aim is a cohesive HRT system with complementary roles and optimized task allocation.

2. New STS principles added for HRT development

The emergence of HRTs requires a re-examination and extension of these STS principles. From our collaborative review, 8 new STS principles have been introduced for the context of designing and developing HRTs (see Table 2). The new additions to the set of STS principles for HRT design and development include Adaptive Autonomy, Agile & Responsive Thinking, Cognitive Workload Management, Ethical Considerations, Collaborative Sensemaking, Transparency and Explainability, Trustworthiness, and Unpredictability Management.

These new STS principles address the unique challenges posed by AI-enhanced HRTs, focusing on the dynamic nature of human-robot collaboration, need for understanding and trust between humans and robots in HRTs, importance of ethical guidelines, and ability to manage unexpected situations arising from complex AI behaviours. They emphasize the need for developing responsible HRT systems.

2.1. Adaptive Autonomy

The traditional separation of Adaptability and Autonomy made conceptual sense when dealing with static and predictable technological

Table 2
New STS Principles for HRT design and development.

	New STS Principle	Brief STS Description
27	Adaptive Autonomy	Dynamic bidirectional adjustment of autonomy, task-based flexibility, responsive system.
28	Agile & Responsive	Iterative design, state-of-the-art knowledge, proactive approach, future thinking.
29	Cognitive Workload	Manage cognitive challenges, reduce burden, complement human abilities.
30	Collaborative Sensemaking	Mutual understanding, shared mental models, anticipatory strategies.
31	Ethical Considerations	Incorporate ethical guidelines, address AI-related concerns in HRTs, build trust.
32	Transparency and Explainability	Address "black box" problem, promote understanding, inform decision-making. Understandable AI processes, enable validation.
33	Trustworthiness	Design for mutual trust, multi-perspective trust, reliable HRT systems.
34	Unpredictability Management	Address inscrutable AI-based decision-making in HRTs, human oversight, handle unexpected situations.

capabilities and clearly delineated human roles. However, the emergence of AI-driven robotics has fundamentally altered this landscape, creating hybrid intelligence systems that blur traditional boundaries between human and machine capabilities. Building on Wolf and Stock-Homburg's (2023) insights, the principle of Adaptive Autonomy suggests that the level of HRT autonomy should be dynamically adjustable based on human preferences, task requirements, variances and changes over time, encompassing situational or environmental adaptation and dynamic autonomy allocation. This principle builds on the concept of adaptability but focuses specifically on autonomy in HRTs. This creates a bidirectionally coupled HRT system where autonomy levels must adapt in real-time, making it a fundamental component of system adaptability rather than a separate concern.

1. The principle of Adaptive Autonomy addresses the dynamic nature of human preferences and HRT tasks requiring continuous reconfiguration of autonomy allocation as an adaptive mechanism including task complexity, criticality and contextual safety.
2. It allows for flexible allocation of autonomy between humans and robots, where cognition, decision making, learning and performance feedback are distributed across human and intelligent robot agents which is crucial in AI-enhanced HRT systems.
3. The principle promotes a more responsive and efficient HRT system that can adjust to changing circumstances and team member capabilities. AI systems can exhibit emergent behaviours that were not explicitly programmed and, as such, managing these emergent properties requires adaptive autonomy mechanisms that can dynamically adjust control allocation, making autonomy adaptation a critical subset of overall system adaptability.

2.2. Agile & responsive (future thinking)

HRT developers need to have current state-of-the-art knowledge, and work with stakeholders to ensure technologies meet requirements (future view). This principle is about preparing for what is ahead, to keep pace with anticipated technological changes. This is not to be confused with another principle, 'open systems thinking', that looks at how systems interact with and adapt to their current environment in real-time, recognizing that system behaviour emerges from complex environmental interactions that might not always be predicted during design. Therefore, we draw upon these concepts to derive a modified principle that combines agile responsiveness and future thinking that is relevant because.

1. Agility and responsiveness as a principle acknowledges the fast-paced evolution of AI-embodied robotics technologies.
2. It emphasizes the need for developers to stay current with state-of-the-art knowledge.
3. The principle promotes a proactive approach to design, anticipating future technological advancements and requirements.

2.3. Cognitive workload

Cognitive workload is a new principle specific to HRTs. The principle recommends that developers address the impacts of HRTs on cognitive demands placed on humans (Ang et al., 2024a; Karakikes and Nathanael, 2023). This suggests the need for careful systems and role design, including skills and capacity development that enables adaptability to changing cognitive loads to optimize performance in HRTs. The reasons for this are.

1. This principle focuses on the unique cognitive challenges posed by human-robot collaboration in a team environment.
2. Cognitive workload emphasizes the need to design HRT systems that reduce cognitive burden on human team members.
3. Cognitive workload as a principle in HRT design promotes the development of intelligent HRT systems that complement human cognitive abilities rather than overwhelming them.

2.4. Collaborative Sensemaking

HRT systems should be designed to facilitate ongoing, mutual understanding between humans and robots. This involves creating mechanisms for humans to comprehend intelligent robot decision-making processes, establishing clear role boundaries, and developing shared mental models of team capabilities and tasks.

This principle addresses a critical gap in traditional STS thinking by focusing on the unique cognitive and collaborative challenges posed by HRTs. It recognizes that effective human-robot teaming requires more than just technical integration; it necessitates a shared cognitive framework and ongoing interpretation of each other's capabilities and actions. The principle is further justified for HRT development because.

1. It promotes transparency and trust by encouraging designs that make robot decision-making processes more understandable to human team members.
2. The principle supports smoother integration of robot systems by preparing human team members in advance, reducing potential resistance or misunderstandings.
3. Collaborative sensemaking enhances team coordination by fostering the development of shared mental models, which are crucial for effective collaboration in complex, dynamic environments.
4. Collaborative sensemaking addresses the potential for role ambiguity in HRTs by emphasizing the importance of clear boundary management between human and robot responsibilities.
5. It recognizes the dynamic nature of HRTs by promoting ongoing sensemaking processes that can adapt to evolving team capabilities and task requirements.

2.5. Ethical Considerations

Ethical aspects of robotic design tend to revolve around physical and psychosocial safety (Ang et al., 2024b). An ethics-based STS principle for HRT development focuses on transparency, informed consent, fair distribution of risks and benefits, and robust safety measures that anticipate unintended consequences (Vermaas et al., 2011). This principle is essential because HRT systems, as experimental technologies with partially unpredictable outcomes, can have significant societal impacts beyond immediate operational concerns.

The value of incorporating ethical considerations as an STS principle lies in its ability to.

1. Guide responsible development of HRT systems through systematic consideration of social implications and human factors
2. Create frameworks for transparent decision making and accountability across stakeholder groups
3. Build trust between humans and robotic systems through ethical design practices
4. Facilitate early stakeholder engagement and informed consent processes.

2.6. Transparency and Explainability

Transparency and Explainability are added as a new principle relevant to HRT design and development as it addresses the 'black box' problem often associated with AI-enhanced intelligent robots. This principle focuses on making the internal operations of AI-driven robots visible and understandable to human team members (Nagbøl et al., 2021; Wolf and Stock-Homburg, 2023). The principle ensures that humans can interpret, question, and trust the decisions made by robots, fostering collaboration and safety in dynamic HRT environments. This is differentiated from the principle 'simplicity and transparency' which is about making the overall system clear and manageable. Simplicity ensures systems are easily understandable and manageable at the operational level, emphasizing clear feedback mechanisms and visible system structures to help users detect and resolve problems efficiently. On the other hand, 'transparency and explainability' is about understanding why and how AI-driven robots make specific decisions.

This principle of Transparency and Explainability is essential and valuable for the following reasons.

1. Promotes increased transparency which builds trust among human workers, leading to higher acceptance of robots in team settings (Ang et al., 2024a)
2. Enhances decision making whereby human teammates can better evaluate and leverage intelligent recommendations, leading to more informed and accurate decisions (Wolf and Stock-Homburg, 2023)
3. Explainability ensures that intelligent robot actions align with ethical standards and regulations, such as data privacy and bias mitigation (Nagbøl et al., 2021)
4. Transparency allows humans to anticipate and mitigate potential hazards posed by robotic actions (Ang et al., 2024a, 2024b)
5. Ensuring transparency and explainability encourages clear explanations to facilitate communication and collaboration among diverse stakeholders, ensuring smoother integration of HRTs in organizational processes (Ang et al., 2024a, 2024b; Wolf and Stock-Homburg, 2023).

2.7. Trustworthiness

Linked closely to transparency and explainability, trustworthiness is another new principle added as it recognizes the criticality of mutual trust between humans and robots for design. Trustworthiness is important in HRTs because it directly impacts the effectiveness, efficiency, and safety of interactions (Wang et al., 2023; Ye et al., 2023).

For HRTs, this principle suggests addressing trust from multiple perspectives: human-human, human-robot, and robot-human. Designing for trustworthiness would include trust among developers, human factor considerations of safety of the robot, trust in the effectiveness and efficiency of the robot on site to perform tasks, and trust in the ability of the robot to collaborate in a HRT (Onososen and Musonda, 2022). It would also entail whether humans can be trusted by the HRT to judge and make decisions.

Its value as a principle in HRT development is as follows.

1. Trustworthiness enhances collaboration. When humans trust robots to perform tasks accurately and safely, and robots are designed to anticipate and respond to human needs, synergy between them improves, leading to higher productivity and better outcomes in complex environments (Wang et al., 2023; Ye et al., 2023).
2. Trustworthiness increases acceptance and adoption. Trust in robots encourages users to adopt and rely on them in various settings. When users perceive robots in the HRT as reliable and safe, they are more likely to integrate them into their workflows and daily lives, accelerating technological innovation and adoption (Ye et al., 2023).
3. Trustworthiness is essential for safer interactions and minimizing risks in HRTs (Wang et al., 2023; Ye et al., 2023). Human trust in a robot's ability to operate safely and predictably reduces accidents and errors. Similarly, intelligent robots designed to recognize and adapt to human limitations and behaviours enhance overall safety.
4. Trustworthiness enables mutual learning between humans and robots. When trust exists, humans are more likely to share feedback and insights, allowing robots to adapt and improve their performance. Similarly, intelligent robots designed with trustworthy algorithms can provide humans with actionable data and recommendations, enhancing human decision making (Wang et al., 2023).
5. Linked to the principle of ethical considerations, trustworthiness addresses ethical concerns about the autonomy and decision-making capabilities of robots. A trustworthy HRT system would ensure transparency, explainability, and accountability, which are essential for gaining stakeholder trust and ensuring ethical use of intelligent robotic technologies.
6. Trust can reduce the cognitive load, uncertainty and emotional burden on users (Wang et al., 2023), making interactions more sustainable over time, and ensuring continued collaboration and system reliability.

2.8. Unpredictability Management

This principle is drawn from Nagbøl et al. (2021) and Makarius et al. (2020) who discuss the challenges of inscrutable AI systems. In the context of HRTs, Unpredictability Management refers to the strategies, systems, and design principles that address unexpected behaviours or outcomes in intelligent robotic systems working alongside humans in dynamic environments. This principle becomes particularly critical as robots increasingly operate with artificial intelligence (AI) that can exhibit autonomous decision making, which may lead to actions that are unpredictable or inscrutable to human teammates. Unpredictability Management as a principle emphasizes the need for human oversight, transparency and intervention (e.g. in unexpected behaviours) in a HRT system. In HRT development, this principle would foster.

1. Human oversight and control where the design enables human operators to monitor, intervene, and override robotic actions when necessary, especially in critical situations where unexpected behaviours could pose risks
2. Designing HRT systems that are transparent and where robot systems can explain their decisions and actions to human users to help mitigate the challenges posed by inscrutable AI systems.
3. Integration of continuous feedback loops between humans and robots to allow the system to learn from unexpected outcomes.
4. Robots ability to adjust their behaviours based on human feedback, making them more responsive in dynamic HRT environment

3. STS principles grouped as themes

For ease of viewing the STS principles, we have organized the 34 principles into 7 themes relevant to the design and development of HRTs. The STS principles that relate to each of the themes have been identified. The themes are found in Fig. 2 as follows: Systems Design and Adaptation, Human-centered approach, Integration and Optimization, Collaboration and Participation, Information and Communication, Organizational Alignment and Process Management, and Trust and Reliability.

4. STS themes, principles and relevance to HRT development

The theme **System Design and Adaptation** highlights the dynamic nature of HRT systems. This theme supports developers in creating flexible (agile), evolving systems that can respond, adapt to changing requirements (adaptive autonomy) and unforeseen challenges (unpredictability management) in human-robot team collaboration.

Under the theme of **Human-Centered Approach**, HRT developers should prioritize human well-being and ethics, ensuring that the HRT system enhances rather than overwhelms human capabilities, including taking into account cognitive workloads. This ensures that the integration of robotic technologies complements and enhances human capabilities, rather than replacing or diminishing them.

Integration and Optimization is about creating synergies between human and robotic elements. This theme widens HRT developers'' considerations of creating HRT systems where human and AI-enhanced robot capabilities complement each other, with the flexibility to adjust

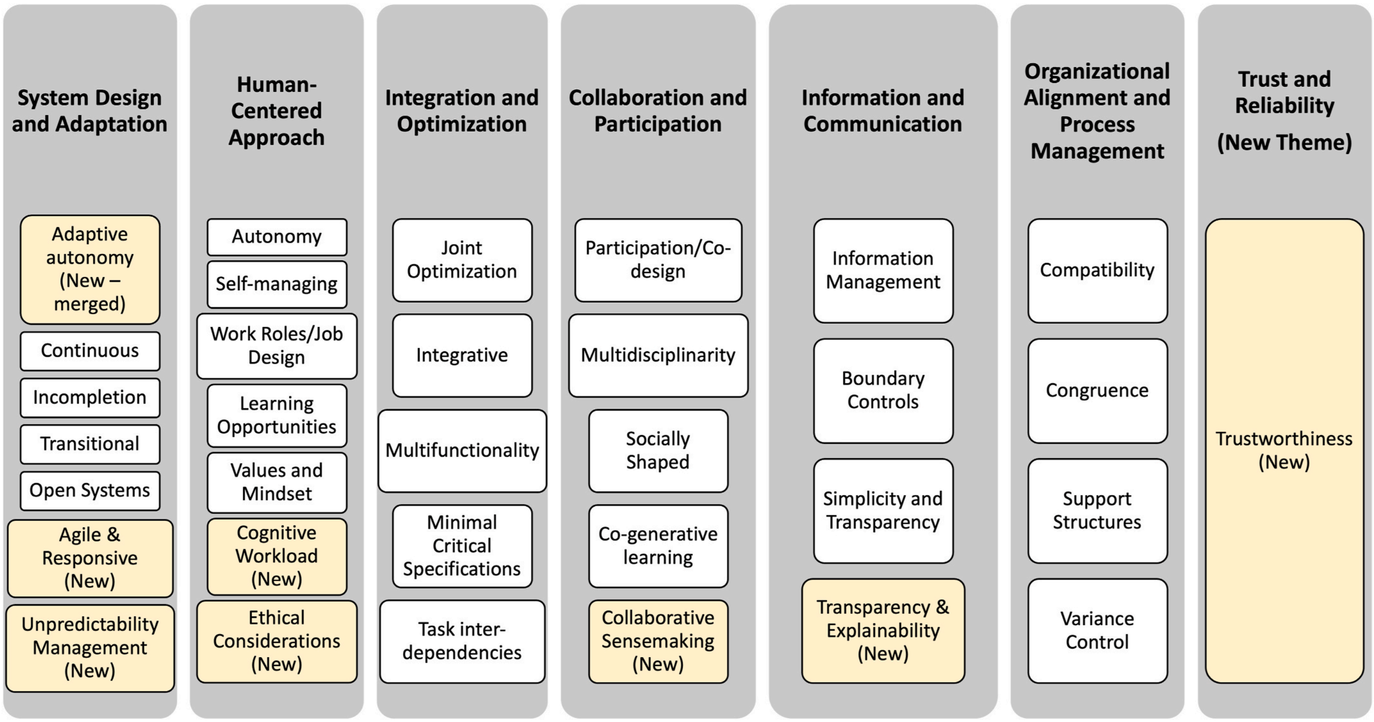

Fig. 2. Thematic organisation of the STS Principles for HRT design and development.

the level of autonomy as needed.

The theme **Collaboration and Participation** stresses the importance of socially shaped and inclusive multidisciplinary design processes and addresses the unique challenges of creating shared understanding, and co-generated learning in human-robot teams through collaborative sensemaking that are technologically AI-enhanced. This is crucial to ensure that diverse stakeholders are involved throughout the design process.

Information and Communication suggests that developers need to ensure that information flows effectively within the HRT and that AI-enabled decision-making processes are understandable to human team members. This includes flows that are transparent, simple and explainable.

The theme of **Organizational Alignment and Process Management** relates to ensuring that HRT development aligns with broader organizational goals and processes. Although the organizational or macro levels in the system are often outside the realm of control for HRT designers and developers, it is still important for HRT developers to consider how HRTs align with and potentially transform existing organizational structures and processes.

Trust and Reliability addresses the critical issue of building trust in AI-enhanced HRT systems when humans and robots work closely together in a shared space. This enables HRT developers to consider how to create reliable HRT systems and foster trust in human-intelligent robot interactions, which is fundamental to effective HRT performance.

5. Conclusion

This article has presented a comprehensive review of sociotechnical systems (STS) principles for Human-Robot Teams (HRT) design and development, emphasizing the importance of balancing technical and social factors in these AI-enhanced HRT systems.

We modified 26 existing STS principles to address unique HRT challenges including dynamic human-robot interaction, adaptive autonomy needs and AI-driven decision-making complexities. These adaptations ensure that the principles remain relevant and applicable in the context of advanced technological integration and continuous improvement.

Eight new principles were added to fill crucial gaps in traditional STS thinking, addressing issues specific to HRT development such as Adaptive Autonomy, Agility and Responsiveness (future thinking), Cognitive Workload Management, Ethical Considerations, Transparency and Explainability, Collaborative Sensemaking, Trustworthiness and Unpredictability Management. These reflect the evolving nature of human-robot collaboration and the increasing sophistication of AI-embodied technologies for HRTs.

These 34 principles were then thematically organized as: Systems Design and Adaptation, Human-centered approach, Integration and Optimization, Collaboration and Participation, Information and Communication, Organizational Alignment and Process Management and Trust and Reliability.

The article's value lies in providing a comprehensive STS Principles framework bridging established STS theory and the emerging HRT field. The STS framework contributes to designing HRT systems that support bidirectional adaptation between human and intelligent robots; establishing guidelines for managing dynamic trust relationships in AI-enhanced teams; offering design criteria for systems that can engage in collaborative sensemaking; and incorporating risk management approaches tailored to AI system uncertainties.

This framework can help researchers, developers, and organizations to create technologically advanced, ethically sound, human-centric, adaptive ecosystem requirements and ergonomic HRT systems that are aligned with organizational goals. This article has the potential to influence the development and implementation of HRTs across various industries, encourage enhanced collaboration between humans and robots, and contribute to more effective and responsible integration of AI technologies in the workplace by addressing the unique sociotechnical challenges that emerge when artificial intelligence becomes a peer team member rather than just a passive tool.

However, these theoretical principles require extensive practical testing. Future research should focus on empirical validations in real-world HRT development and implementation, developing industry-specific methodologies, creating assessment tools, and integrating these principles into existing engineering processes. The collaboration between STS specialists and engineers along with STS audits and active-iterative evaluations, would support effective implementation.

CRediT authorship contribution statement

Karyne C.S. Ang: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shankar Sankaran:** Writing – review & editing, Validation, Supervision, Investigation. **Dikai Liu:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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