New Technology Relationship Paradigms in Industry: The Transformation of Human-Machine Interaction Through Design-Driven Approaches.

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Abstract
This contribution presents the application of design-oriented practices in two experimental projects developed in the field of human-machine interaction (HMI) in the industrial environment; specifically, the projects discussed are *Advanced human-machine interaction for continuous transformative manufacturing and robotic systems* of Spoke 1 and the *Machine energy consumption* 4.0 of Spoke 2. The application of transversal and multidisciplinary methodologies has resulted in the definition of new paradigms for relationships between people, data, technical systems and operations. The processes are characterized by field research analysis practices, collaborative design approaches, contextual data visualization, and rapid prototyping tools for interactions with AI systems. The aim of this article is to outline the relationship between these design approaches and the outcomes emerged at the current stage of development. Three levels of transformation have been identified relating to interaction models between people and AI systems, communication methods between operators and machines, and visualization of sustainability data.

Keywords
Human-Machine interaction
Industrial technologies
Multiagent relationship
Design-driven processes
Data visualization

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RETHINKING HUMAN-MACHINE INTERACTION THROUGH COLLABORATIVE DESIGN PRACTICES

Over recent years, the progress of adaptive technologies in manufacturing contexts has initiated new challenges related to the design of interactions between humans and automated systems. In particular, the advancing diffusion of artificial intelligence-based solutions has made evident a redefined framework for traditional human-machine interaction (HMI) paradigms, moving beyond linear and reactive models to initiate experiments on cooperative, proactive and adaptive logics. In this scenario, design cultures emerge as a methodological and operational field which has the potential to facilitate this transition, acting as a mediator between the technological opacity of systems and the practical skills of human agents (Giaccardi & Redström, 2020; Dourish, 2004). Moreover, the design-driven approach can provide practical tools for interpreting complex systems, transforming interaction with technology into a more accessible, situated and action-oriented experience.

This paper aims to describe two experiments conducted among the context of action-research on the role of design in technological innovation processes in industry. The projects analyzed were conducted by the University of Bologna, and the University of Florence, respectively during the project *Advanced human-machine interaction for continuous transformative manufacturing and robotic systems* of Spoke 1 *Advanced digital design: technologies, processes and tools*[1] and the project *Machine energy consumption 4.0* of Spoke 2 *Eco-design strategies: from materials to product-service systems (PSS)*[2]*;* the industrial partners involved in the projects are realities of the manufacturing sector, the company SCM Group[3], which specializes in the development of technologies for woodworking and other materials, and the company Italtel S.p.A[4], which operates in the telecommunications sector. Through this collaboration between academic and industrial partners within the projects, it was possible to address in a complementary way the topic of human-computer interaction and cooperation through design-oriented practices for co-creation, visualization and simulation of multi-agent scenarios.

The shared objective concerns the proposal of more transparent and interpretable interaction processes with complex systems, through the development of more accessible and usable digital interaction environments; this has been translated into the design of HMI interfaces and UI elements integrated into existing digital environments, with a specific focus on technological mediation concept (Kudina & Van De Poel, 2024) and feedback (Axelsson, Buschmeier & Skantze, 2022), simulation and visualization of complex data.

Specifically, the first project focused on the development of new paradigms of operational and design interaction with AI-based interfaces for industrial machinery control, through the proposal of a human-AI relationship model based on feedback exchange processes for proactive information mediation and the proposal of a hybrid behavior simulation system. The second project, on the other hand, explored the use of situated energy data visualization models geared toward data literacy and behavioral change in manufacturing contexts. The activities are integrated into a theoretical and applied

[1] https://www.mics.tech/spokes/spoke-1/
[2] https://www.mics.tech/spokes/spoke-2/
[3] https://www.scmgroup.com/it
[4] https://www.italtel.com/

framework, which connects contributions from interaction design, usability research, and cognitive science, with a specific focus on the transformative potential of design-driven practices (Norman, 2013; Bødker, 2006).
This paper provides a retrospective analysis of the processes carried out in two distinct projects, which were managed using different approaches in terms of methods and objectives.
The decision to conduct this comparative analysis of the two projects is based on the same operating methods and the same corporate testing environment. The retrospective dimension is useful for identifying how the design-driven methodologies applied during the research and experimental phase allowed for the creation of artifacts and interaction paradigms different from the established models used in the industrial sector.
Indeed, the methodology adopted facilitated discussion between different disciplines and areas of expertise and produced a remarkable transformation in the actual structure of the design outcomes. The collection and preliminary analysis of information on the context and the actors involved led to unexpected results compared to the initial assumptions and new operational behaviors compared to the original application contexts.
The collaborative and iterative approach highlighted how models proposed by end users, such as students, practitioners, or utilization stakeholders (Miller, 2022) could guide the design of more effective systems. In particular, the interaction between visual language and technical language, between digital prototyping and ethnographic observation, has created some artifacts and experimental environments capable of anticipating the user experience, revealing possible transformative directions.
This article therefore aims to return, in comparative and reflexive form, the design processes and practices that guided the development of the two projects; the focus is on the phases in which design approaches acted as critical tools and enablers of transformation and transition processes towards collaborative and proactive models of human-computer interaction.
The contribution is structured according to a narrative composed of two main sections; the first part relates to the description of the relevant methodological approaches and design practices that were applied in the two projects, while the second part highlights the design results of the application of these design-driven methods.

METHODS FOR TRANSFORMATION: RESEARCH, CO-DESIGN AND PROTOTYPING IN INDUSTRIAL CONTEXTS

To address features revealed in the preliminary phases, such as state-of-the-art, best practice and context analysis, and to translate the identified opportunities into operational actions, both projects used an articulated set of frameworks. The following section describes the practical approaches applied during the research and design phases that allowed for several transformations to the initial design objectives. These dimensions guided the design process and enabled the creation of models and practices for collaboration between human actors and technological systems. The methodologies adopted are reported, with particular focus to the processes of field research, co-design, simulation, and prototyping, which supported and enabled the evolution of the characteristics of the initially proposed solutions.

The experimental character of *Advanced human-machine interaction for continuous transformative manufacturing and robotic systems* project required the adoption of a cross-disciplinary and collaborative methodological approach, based on design-driven practices capable of linking heterogeneous disciplines, skills, and actors (Miller, 2022). The shared goal concerned a more conscious, transparent and dialogic interaction between humans and complex technological systems.
Given the analysis carried out on the implementation of AI models in consolidated industrial environments, design practices were divided into a sequence of phases integrating methodological practices for the design of interactive services and systems; this enabled the definition of an integrated approach between interaction design and user experience design.
The process was based on field research, context analysis, co-creation, and prototyping (Sanders & Stappers, 2008), following models and standards already in use in the field of Human-Machine Interaction (ISO, 2019).
In addition, the different contextual and research requirements called for alternative analytical approaches, proposed through the application of various design-driven situated actions.
Initially, a desk analysis was carried out to map the state of the art and best practices in the field of transparent interfaces and proactive feedback systems. To better understand the complexity of the subject, a topic collaborative exploration was conducted involving a group of students from the Master's degree in Advanced Service Design, of the University of Bologna. The information collected were first validated through field research; this activity aimed to analyze the production processes using SCM machines and the related working methods in the operating centers.
Accordingly, the project team conducted participatory observation activities at production sites, interviews with experienced operators and technical managers, and co-exploration sessions to define critical issues related to interaction with existing digital systems (Bannon & Ehn, 2013). Once the insights were gathered and synthesized, the design phase was started through an iterative and shared process. Interactive prototypes were developed by replicating the structure of the partners' interfaces, using tools such as Figma; due to these items, it was possible to apply the practice of rapid prototyping (Wilson & Rosenberg, 1988) and possible scenarios of interaction and cooperation between operators and AI systems.
These preliminary artifacts provided a tool for the following co-creation of advanced interaction concepts, tested with mixed groups of stakeholders (operators, designers, AI experts) in collective ideation sessions (Bannon & Ehn, 2013). The focus was particularly on three application areas: operator training, predictive maintenance, and production optimization.
An integrative element of the activities was the systematic use of feedback (Wiener, 1984) as an operational and design principle. This feature was the focus of prototyping, intended as a form of communication with the interface and negotiation between humans and non-humans. In fact, the design aimed to create the requisites for a two-way, recognizable, contextualized and adaptive exchange of information, capable of supporting shared decision-making processes and increasing the degree of agency of the participants in the system.

Overall, the practices adopted, in the first component of the experiments, have shown how a design-driven approach can contribute to the redefinition of the role of the interface as a collaborative space (Manovich, 2013) and to the construction of new forms of relationship between operators and intelligent systems, overcoming the tool/user dichotomy toward models of co-performance design (Norman & Verganti, 2014; Giaccardi & Nicenboim, 2020).

BEHAVIOURAL CHANGE AND DATA LITERACY FOR A SUSTAINABLE ENERGY CONSUMPTION

Within the project *Machine energy consumption 4.0*, design-oriented practices related to the field of data visualization played a key role in making the energy data generated by machines more accessible and capable of supporting user intervention. This helped transform human-machine interaction into a more conscious, collaborative, and sustainability-oriented process. Design was involved from the earliest steps, contributing to the construction of visual models able to translate complex signals and predictive models into intuitive communication artifacts, suitable for everyday use in production contexts.

The research aimed to investigate how Data Visualization practices could function as tools for cognitive and behavioral mediation within industrial environments. Specifically, the research explored: (1) how to make complex energy data legible while maintaining a balance between attention threshold and perceptual immediacy; (2) how to encourage micro-behavioral changes through situated visualizations; and (3) how to support operators’ data literacy without relying on formal training.

The first area of focus concerned behavioral change, understood not as a prescribed outcome, but as a possibility enabled by the very visibility of information. When energy consumption data is returned to users in a visual, synthetic, and situated form, it activates a different perception of daily actions, making inefficiencies, anomalies, and opportunities for intervention recognizable. In this sense, visualization is not neutral—it acts as a transformative interface. Recent studies show that interactive interfaces and ambient-type visualizations—such as animated trees or color-coded indicators—are more effective in influencing behavior than traditional technical visualizations (Spangher et al., 2019). Visualizations that "make the invisible visible" can increase engagement and motivate action, even in highly automated contexts (Holmes, 2007; Rist & Masoodian, 2019).

The aim was therefore to provide immediate and intuitive feedback, capable of orienting attention and suggesting corrective micro-actions. Sustainable behavior is not imposed but facilitated through continuous and non-intrusive visual interaction (Masoodian et al., 2015).

The second thematic focus concerns data literacy, understood as the ability to read, interpret, and make sense of visualized information. In industrial contexts, this competence is far from guaranteed: operators with different roles, heterogeneous technical backgrounds, and limited time availability are often confronted with data that is dense, opaque, and cognitively inaccessible. Literature highlights how difficulty in understanding energy visualizations remains a recurring barrier even in professional settings: having accurate and well-structured data is not enough if it is not perceived as understandable, useful, or relevant (Murugesan et al., 2015).

More specifically, recent studies reveal a persistent gap between the representational modes adopted in digital systems and the actual visual competencies of users (Rist & Masoodian, 2019; Spangher et al., 2019). When visualizations rely on overly complex encodings, specialized terminology, or unfamiliar metaphors, they risk excluding users rather than supporting them-generating confusion, distrust in the data, or dependence on technical intermediaries. This is particularly critical in the energy domain, where the ability to act promptly and consciously is closely tied to the clarity of information.
Even in the specific case of energy supervision in production settings, the need to make visualizations understandable to a range of professional profiles becomes evident user often unfamiliar with charts, numerical indicators, or predictive models on a daily basis. In this context, data literacy emerges as an enabling condition for sustainability, since only truly comprehensible data can foster informed behaviors and conscious operational practices.
As Holmes (2007) and Masoodian et al. (2015) argue, it is not enough for information to exist—it must also be visible, readable, and cognitively accessible. Otherwise, even the most accurate data risks remaining invisible in the user experience. The challenge is therefore both cultural and design-related: it requires acknowledging that the ability to interpret a visual interface is not a given, but a skill that must be enabled through coherent, context-sensitive, and user-centered design choices.

DESIGN RECONFIGURATIONS: EMPIRICAL EVIDENCE OF A DESIGN-DRIVEN TRANSITION

The design-driven approach adopted in the two projects generated several outputs regarding the initial operational and methodological premises, generating new behaviors and forms of interaction with digital tools. The adoption of collaborative, iterative and contextual practices not only enabled the development of solutions consistent with the needs that emerged but also triggered a transformation in the very processes of setting priorities, languages and tools for human-computer interaction. These results manifested themselves in different forms, from conceptual changes to design outputs to redefining the role of the users involved (Norman & Verganti, 2014). Specifically, three transformative dimensions are identified, related to: the interaction models with artificial intelligence systems, the key elements enabling communication between operators and industrial machines, and the methods through which data has been represented and interpreted. This section describes these three levels, which are the result of applying the approaches described above and the various results obtained.

TRANSFORMATION IN INTERACTION PARADIGMS BETWEEN HUMAN AGENTS AND AI

In the experimental context of the first project, one of the most relevant outcomes concerns the redefinition of the role assigned to technology in production environments, following an approach that goes beyond a merely instrumental perspective and moves toward a more systemic and non-technocentric viewpoint. The initial design assumptions considered the implementation of AI primarily to optimize production and business processes, in line with traditional efficiency-oriented logic. However, user research activities and co-design sessions revealed a different application trajectory. Operators and representatives from the participating organizations expressed a strong interest in using AI as a tool to support training, self-learning, and the understanding of information flows in work processes. This perspective led to the development of design concepts focused on the use of AI to create digital environments based on hybrid interaction models. These aspects involve the design of interfaces that support training processes for new operators on how to use interactive tools for machine management, thus opening usage scenarios that diverge from the initial objectives (Giaccardi & Nicenboim, 2020).

This approach has led to a change in the role of users within the design process. The use of shared visual tools and collaborative environments enabled operators, often considered passive recipients of innovation, to take an active role in shaping the interaction. The opportunity to directly contribute to the development of models and interfaces led not only to greater alignment with real-world contexts, but also to increased ownership and engagement, laying the groundwork for a more symmetrical relationship between human users and intelligent systems (Muller & Druin, 2012).

From an interaction perspective, digital artifacts design has evolved due to the integration of prototyping and testing activities. This stage was essential to validating a design solution and understanding the UX and UI implications that users might have in terms of usability and understanding the active role of AI in decision-making (Yang et al., 2018).

Participants highlighted the need for interfaces capable of fostering dialogical relationships, where feedback is not simply a mechanical return of data, but a structured, contextual, and understandable response. This led to the experimentation with hybrid feedback models, integrating visual, textual, and interactive components, and to the definition of communication architectures based on transparency, adaptability, and the progressive construction of trust between the operator and the system (Kosch et al., 2022).

Considering the relationship with artificial intelligence systems, AutoML platforms are evolving (Marenko & Van Allen, 2016) that without the use of code make the process of creating machine learning models more accessible, making the process accessible even to those who cannot write code. This allows people with different skills, such as designers, product managers or domain experts, to contribute to the prototyping of AI products (Truss & Schmitt, 2024). Democratization of Generative Artificial Intelligence in innovation (Bilgram & Laarmann, 2023) is a process that significantly improves the ability to imagine and anticipate design scenarios with digital artefacts for which lengthy development processes would be required to achieve meaningful user tests (Hartmann et al., 2006).

Based on these assumptions, a web-based tool was developed to enable the creation of interactive prototypes seamlessly connected to the HMIs of industrial machines. The functionality of the system is based on two main phases: the analysis phase of the existing user interface and the interpretation phase of the video stream through an interactive process with an LLM model. In cooperation with the industrial partner ITALTEL, OpenAI was chosen in the testing phase for the API stability, but the project is easily adaptable to other AI models that can also be activated locally. The development environment chosen is Python, which is configured as an application server on which a webapp is hosted that acts as a user interface to configure the prototype and as a replacement screen to simulate the integration of the interaction component with an AI. Through this tool, an industrial designer who wants to test a possible design within an HMI will be able to set up an interactive behavior on certain areas of the industrial machine to relate the content of the screen to an artificial intelligence.

TRANSFORMATION IN COMMUNICATION PARADIGMS BETWEEN HUMAN AGENTS AND MACHINES

In the second project framework, the transformations relating to the components allowing communication between operators and machines are structured through the analysis of the current interaction tools used in the SCM environment.
The development of the new notification system is based on the possibility of having the information about the machine status and the different conditions/alarm of the machine itself through colors and icon (red indicators, yellow indicators, etc.). Using the information that have been collected during the analysis of the case studies the main actions are about:

- Identification of a series of color to use to notify specific condition of the machine
- Identification of the impact of HMI Design on Energy Efficiency.
- Development of a proper way to visualize the information in the HMI/UI considering element like Cross-analysis of user experience, color perception, and interactive design.

Regarding the first point, the goal is to find specific color type that not interfere with the ones already in use (yellow, red, blue and green) which are referring to specific condition of the machine (warning, alarm, machine in steady condition, work condition) but can be used to transmit the information in a clear way to the operator during the use of the machine itself.
Concerning the second point, the goal is to delve into how the design of human-machine interfaces can influence energy consumption and efficiency in industrial settings. The goal is to understand how the elements of the user interface, now consolidated in the industrial environments, should evolve in relation to a new generation of users and find the best solution for the data transmission to the operator.
The third goal is to extends the discussion to the broader implications of information visualization on user behaviour and overall operational efficiency. It seeks to understand how design choices in HMIs can influence the way users interact with machines and how these interactions, in turn, affect the overall efficiency and productivity of industrial operations.
From the analysis of the literature conducted at this stage of the research, several contributions related to the study of alarm management in industrial settings, both at the level of machine tools and complex industrial plants, have emerged over the past three decades. The fifteen publications collected in this report represent a selection of articles aimed at providing a starting point for further study of the design aspects of industrial machine monitoring and notification systems. Three books published in the second decade of the 21st century on the topic of Alarm Management (Hollifield & Habibi, 2007; Hollifield & Habibi, 2011; Rothenberg, 2018) is useful to frame the issue from a theoretical point of view, complemented by other articles and a White Paper written by SIEMENS on alarm management (2008). The remaining articles

address specific problems, including the attention threshold (Bradbury, 2016; Wolfe et al., 2017) and more general topics on HMI design and the management of complex systems. On the specific topic of interface design, the literature is extensive, and the selection was made with an emphasis on technical publications focused on an ecological approach, in which aspects of the machine or plant are given more consideration (Hollifield et al., 2008; Burns & Hajdukiewicz, 2017), as opposed to an established User-Centered Design approach. In general, the group of publications analyzed highlighted the relationships with ISA-18.2 on the topic of alarms and consolidated the general regulatory framework defined by the standards.
At the conclusion of this design phase, the choice of color to represent the energy consumption overload element has been validated, which will define the graphical appearance of the interface and the notification system in the HMI. This consideration serves as a starting point for the process design phase, which will validate the innovative processes in the HMI system to communicate energy information in a way that is understandable to all users.

TRANSFORMATION IN DATA VISUALIZATION AND INTERPRETATION MODELS

One of the key phases of the design process involved a comparative analysis of the main types of visualizations applicable to the context of industrial energy consumption monitoring. The goal was not only to select an effective graphic form but to understand which visual models could support different modes of reading, interpreting, and interacting with data.
Starting from a mapping of commonly used charts in HMI contexts (line chart, bar chart, pie chart, stacked chart, radar, Gantt, heatmap, etc.), a comparison was conducted based on three main criteria:

- Perceptual immediacy – the ability of the chart to make patterns, deviations, and anomalies immediately apparent (pre-attentive reading), which is crucial in operational environments;
- Comparative capability – understood as the possibility of comparing real vs. estimated values, past vs. present states, and among multiple components or time periods;
- Contextual legibility – the compatibility of the chart with the average user's level of visual and technical literacy.

Several graphic formats were evaluated during this phase: bar charts proved effective for representing aggregate consumption by component or time slot but were less suitable for highlighting temporal trends; line charts were more effective in showing changes over time but less so in presenting both estimated and actual values simultaneously; circular charts (donut or radial), while less precise, proved useful in constructing an analog metaphor with time (e.g., clock), reinforcing the cognitive dimension linked to daily operational routines.
Particular attention was paid to the choice of temporal metaphors. The idea of using a calendar matrix layout or a radial timetable interface emerged in response to the need to associate energy usage with specific moments of the day or week, thereby facilitating the user's self-localization in operational time. This approach favors situated visualization, presenting data in relation to real-time action and the production cycle.

Finally, a comparison was made between technical vs. ambient-type visualizations: the former focused on accuracy and numerical detail, the latter on perceptual impact and emotional clarity (as in the use of color gradients or metaphorical interfaces). The design choice favored a hybrid combination, where data is presented in a synthetic and progressive manner, enabling both a quick overview and a deeper exploratory reading, depending on the desired level of interaction.
Based on the typological analysis conducted in the initial phase, design-oriented practices were applied to construct a visual system capable of integrating the complexity of data generated by predictive models with the simplicity required by industrial usage contexts. The goal was not only to deliver information in an understandable form, but also to trigger sustainable micro-behaviors, offering situated feedback aligned with the operator's actions and rhythms.
The prototype developed is based on a calendar matrix that allows energy consumption to be monitored on a monthly scale, visualizing the daily trend of energy used versus energy predicted. Each cell of the grid corresponds to a working day and employs synthetic color codes to immediately highlight situations of alignment or deviation. This representation allows users to temporally situate themselves within the operational cycle, facilitating the detection of recurring patterns or specific anomalies.
Each day can be linked to a second level of detail, activated through interaction, which returns the hourly distribution of consumption. In this expanded view, the interface shows which machine components were active by synthetic icons and visual toggles. This layered structure supports progressive data reading—from a general overview for orientation and criticality detection, to a more analytical exploration for identifying specific causes of consumption.
The calendar structure was also chosen for its strong metaphorical power: anchoring data to daily time, structured by operational routines, allowed consumption to be contextualized not as abstract information, but as part of a continuous and situated process. In this way, data becomes a relational tool rather than a remote entity. Design thus played an enabling role, supporting recognition, reflection, and the potential activation of even minimal corrective practices that, over time, may contribute to a more efficient and sustainable management of energy.
This visualization is not intended as a prescriptive interface, but as a modular interactive artifact, open to future developments, capable of integrating additional environmental or performance parameters.
Moreover, the system's color and graphic choices were defined in alignment with the visual language already adopted by the company in the Maestro system, to ensure perceptual continuity and operational recognizability. At the same time, they were refined through the color research conducted by the working group, which contributed to defining effective feature codings to support pre-attentive reading and differentiation of machine states.
The design findings developed at this stage are consistent with the three conceptual objectives outlined in Section 2.2 and can be read as a translation of these intentions into concrete visual strategies, illustrating how the design process began to shape the questions that guide the investigation. The calendar matrix was designed to articulate temporal patterns in energy usage and operational routines, while the layered visualisation approach was conceived to enable a gradual reading of the information. Likewise, the use of

a concise colour-coding strategy was formulated to support perceptual immediacy and facilitate different levels of visual access.

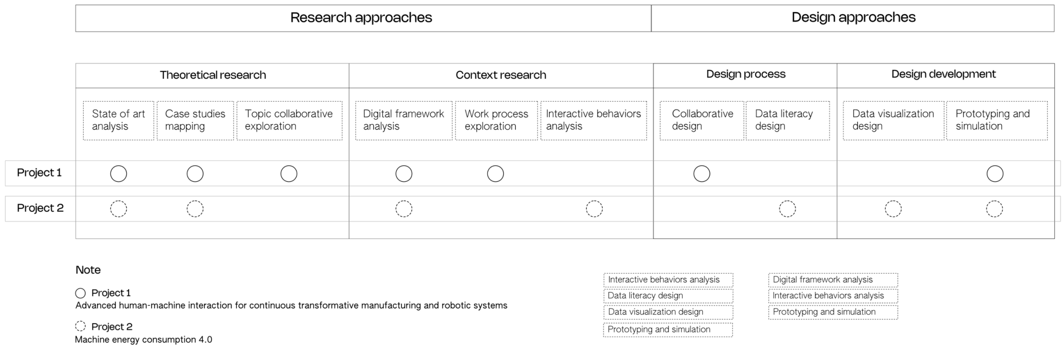

Fig. 1
Schematic representation of the approaches applied to the research and design phases.

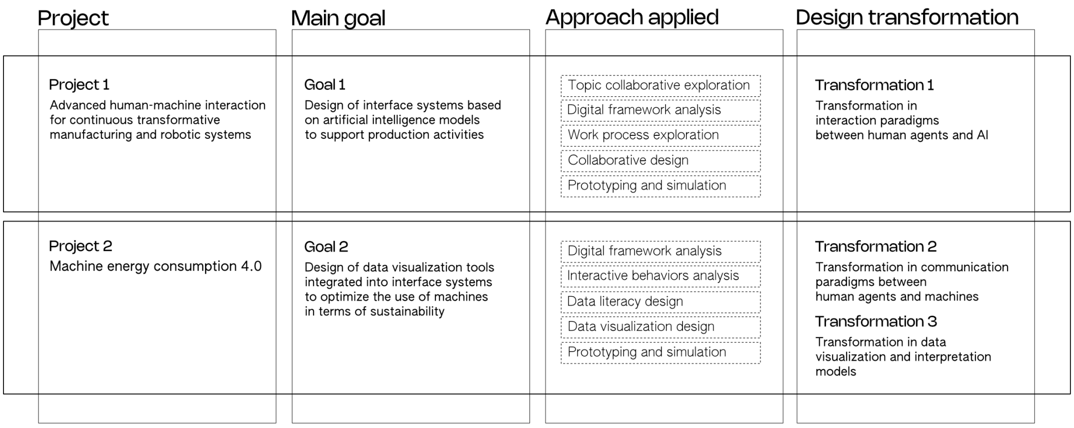

Fig. 2
Representation of the relationship between project objectives and the transformations that emerged thanks to the application of design-driven approaches.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The experimental activities carried out within the MICS projects have highlighted the transformative potential of design-oriented practices in driving technological innovation across industrial contexts. Through an integrated, collaborative, and iterative approach, design has served as a mediator between complex systems and real operational needs, helping to make AI-enabled processes more legible, usable, and cooperative.

Findings show that design can support not only data comprehension, but also the development of hybrid interactive models based on feedback exchange, simulation of realistic usage scenarios, and the emergence of new forms of operator agency. Co-creation with industrial stakeholders and attention to training processes have led to the development of design artefacts that foster learning, reflection, and continuous adaptation.

Future developments will focus on two main directions. For Project 1.8, the goal is to scale the tested practices to new production contexts, aiming to define systemic but context-sensitive design paradigms for human-AI co-performance in diverse industrial domains. For Project 2.05, development will focus on multisensory wearable devices that reduce cognitive-visual load by enabling a tactile or perceptual reading of system data, thereby supporting real-time industrial operations.

In both cases, design is positioned as a strategic enabler for more sustainable, adaptive, and intelligent relationships between people, technologies, and evolving production environments.

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