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Human-Machine Interaction Design in Adaptive Automation

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Abstract

Advances in adaptive automation are reshaping the relationship between humans and machines in manufacturing, emphasizing human safety and active involvement in production processes. The research background is in the Advanced Manufacturing Technology (AMT) domain, and in particular, in a Case-based analysis, collecting the best of class HMIs design cases on the market. Such analysis showed a gap between the potentials of adaptive automation interaction design research and industry application needs. This literature review explores adaptive automation technologies that dynamically allocate tasks between humans and machines based on real-time conditions and performance. By focusing on collaborative technologies such as Co-bots, this review highlights innovative approaches and practical applications that enhance human-machine co-evolution, improve situational awareness, and maintain cognitive and ergonomic standards. The study describes two main results: describes main research themes with the goal of defining the future research questions to be investigated in novel phases of the research and, by following this approach, proposes a framework for integrating adaptive solutions in manufacturing to promote human-machine collaboration and performance adaptability.

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Keywords: Adaptive Automation; Human-Centric Manufacturing; Dynamic Task Allocation; Collaborative Robots (Co-bots); Human-Machine Co-Evolution; Ergonomics; Situational Awareness; Cognitive Load; System Performance; Human-Machine Collaboration.

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1. Introduction

In today's factory environment, production systems are characterised by the increasing integration of flexible material processing technologies with intelligent control and supervisory systems (ICT technologies), to meet the demands of advanced customers and the competitive variables of advanced markets with quality, speed and efficiency. Automatic machines not only operate on materials and products, but also co-operate and adapt intelligently and safely with operators and other units in the factory and integrate with higher-level systems for managing and monitoring manufacturing processes [1]. This systemic feature of the contemporary factory environment calls for a design reflection on the characteristics of new industrial and adaptive machine control interfaces [2].

In this article we want to focus on the concrete and tangible mechanisms and dynamics that happen 'at the interface' [3,4]. Machine interfaces in the era of automation represent the place where the dialogue between technologists, engineers, production managers as well as machine operators and automated machines happens. In particular the focus of this research is on the role of adaptive automation in human-centric manufacturing and the aim is to promote human-machine co-evolution, where both entities continuously adapt and improve.

The present literature review is based on the previous research conducted by the researchers as state-of-the-art [5] searching the best of class HMIs design cases based on the recently awarded projects related to two of the world's largest design competitions, the iF Design Award (iF Design Award, n.d.) and the Red Dot Design Award (Red Dot Design Award, n.d.)[6].

By means of the application of the Case-based analysis method [7] the authors focused on the systematic analysis of the selected projects to generate findings, lessons and conclusions across multiple design projects. That research was useful to understand and generate an in-depth, multi-faceted understanding of the complex issue of industrial HMI design by focusing on two main interface functions:

- display elements, that can present the machine parameters, the status of the machines, the production automation information and the pictorial schematics.
- control elements, that are used to provide input to the machines and involve interaction models and alarm management strategies [8].

The present bibliometric scientific literature review aims to address the gap between the research in adaptive automation interaction and the needs, requirements and expectations of European industry and considers the two specific functions of industrial HMIs design mentioned above. The specificity of this article resides on the need of verifying the authors' hypothesis of limited investigation of the role of interaction design in adaptive automation and manufacturing in scientific research.

It builds on top of the case-based analysis by starting with a strong focus on five research themes for investigating the HMI design scientific literature. Such research themes are described in Paragraph 2, Methodology, that summarizes methods, limitations, workflow and phases of the review process, to let the reader acknowledge the replicability of the study. Paragraph 3 will then present the outcomes of the review, by discussing how the existing literature is providing the research with meaningful results. Paragraph 4 will critically discuss the lessons learnt, the implications, and how the outcomes of this review inform the implementation of quality research in this field. Paragraph 5 will offer synthetic summative conclusion from the study.

2. Methodology

This systematic review comprehensively assesses and synthesize the existing body of knowledge in the realm of adaptive automation solutions in manufacturing, guided by the ProKnow-C (Knowledge Development Process-Constructivist) method (see Figure 1) [9]. The methodology indeed focuses on identifying adaptive automation technologies that facilitate dynamic task allocation.

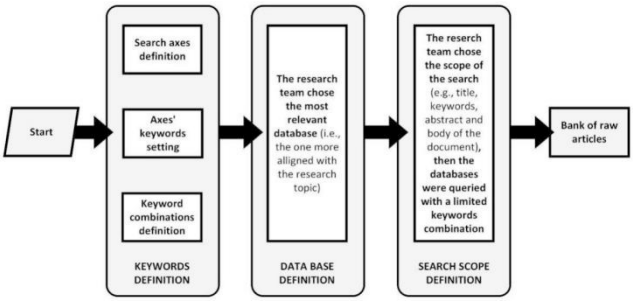


Fig. 1. The methodological workflow adapted from [9]

The overarching methodological framework is structured around three main stages: the first posed to define the sets of keywords best suited to drive the research; a following stage necessary to identify the most valuable databases; the last one, dependently on the contingencies choses where to look for those sets of keywords.

2.1. Keywords definition

In the case at hand, the dimensions had to be crucial for understanding the evolution and impact of interfaces and interaction innovation in the realm of industrial design. The search axes definition step has thus been defined based on the outcomes of the case-based analysis [5]. They are presented in Table 1.

Table 1. Research themes and descriptions.

Theme	Description
Interaction model and interface navigation	System model, standard navigational patterns and task-based interactive strategies.
Production automation process	Visual and interactive solutions helping users to better understand the manufacturing process and the production operations' status.
Schematics and system representation	Graphical representation of electrical infrastructure or general production processes providing the users with intuitive and clear information about the system.
Visual identity	Visual style of interface and custom-based visual strategies based on accessibility standards and brand style guide.
Alarm management	Alarms visual representation and interactive strategies designed to support users in critical situations.

The goal of the researchers was to address the following general research question: "What are the current trends and advancements in human-machine interface (HMI) and industrial design, specifically exploring aspects such as interface design, control panels, man-machine interfaces (MMIs) in fields like interaction design, visual design, and experience design? Moreover, how do concepts like CNC (Computer Numerical Control), Industry 4.0, and Industry 5.0 contribute to the evolution of interface design and industrial processes in the context of manufacturing and production lines?". The very initial dimensions, therefore, were HMI (or Human-Machine interface) and industry (and the related semantics).

In the second iteration of the keywords definition the researchers' team got engaged in a Focus Group session to discuss, review and finalize the axes keywords setting. The researchers exchanged perspectives over the research

themes and how the axes keywords could be defined. Main outcome of the Focus Group was the revised set of research themes addressing ergonomics and human factors, the operator experience and the experience of digital technologies in industry according to the following axes. The focus on automated machines and CNC in the Industry 4.0/5.0 domain indicates the strong research interest in investigating the impact of advanced manufacturing technologies on automated machine interface design and industrial processes. Keywords and search terms were adapted to include adaptive solutions, Co-bots, and human-centric manufacturing.

Together with common research topics of interest, the team also defined exclusion criteria, among which the most relevant is the decision of excluding research coming from the automotive industry since automotive HMIs mostly refers to vehicles' dashboard and cockpit, which are, differently from industrial HMIs used by industrial workers.

Considering this, the review assesses practical use cases and theoretical approaches to validate adaptive automation in real-world applications. In typical manufacturing scenarios, the role of HMIs relies indeed on the effective communication of information between a machine and an operator, which includes production data, as well as the prompt communication of any errors and alerts on the production line.

2.2. Database definition

This preliminary attempt was conducted upon the Scopus database, since many studies have sought the one from Elsevier sufficiently capable of collecting the large amount of the relevant literature [10,11]. Though this is generally true, it was not confirmed for our research theme. In fact, 95 documents resulting from performing this research through Scopus were analyzed by the research group and, contrasting with the research team's expectations, deemed irrelevant. The analysis of the first corpus of papers included three most populated groups, Autonomous Vehicle (with 25 articles), Engineering and Human-Computer Interaction Methods (with 20 articles) and Automotive (with 18 articles). The remaining articles concern Manufacturing (8 items); Human-Robot Interaction (4 items); Autonomous living and on Transportation (3 items); Toy and on Assisted Technology and Special Needs (2 items); and 1 article for the following themes Consumer Electronics; Design Fiction; Digital Design; Domotics; Education; Exoskeleton; Heritage. Finally, 3 articles were not available.

The full detailed list of results from this research is available at this link: (https://docs.google.com/spreadsheets/d/1gvRzT1FyXC6pzWSVFZ68J0PxR1KmbctP/edit?gid=753934365#gid=753934365).

The lesson learnt from this analysis was related to search engine selection since the authors understood that Scopus database bibliometrics were resulting in Engineering and Human-Computer Interaction, rather than on Industrial and Interaction Design.

The Association for Computing Machinery Digital Library (ACM) was then selected among other potential databases due to its acknowledged contribution in the field of Industrial Design. ACM Digital Library offers also the chance to look for occurrences within the totality of the documents' text, hence performing a much more powerful search with respect to Scopus that is limited to Title, Keywords, and Abstract.

2.3. Search scope definition

A new query consistent with ACM syntax was produced to collect data. However, the previous exploratory attempt on the Scopus database enabled the researchers to exclude the automotive subsector – a research theme nuance that they were not particularly interested in examining further. Indeed, the research team was interested in understanding the intersection of HMI and industrial design, with a focus on the latest technologies and design principles, while excluding certain topics like automotive technology and transportation. To complete the selection stage of the raw article bank, an adherence test was carried out to check if there is a need to include new keywords, so that the portfolio is as aligned as possible.

Because of the Focus Group the authors defined the following keywords combination: they were divided into three keyword groups, Group A, Group B, Group C and Group D. Table 2 introduces the keywords' groups defined through the Focus Group. A combination of keywords from independent groups with the "AND" Boolean, meaning

Group A, B and C, and with the "AND NOT" Boolean (meaning exclusion), meaning Group D, searched the articles from the databases.

Table 2. Keywords used for literature search.

Group A	Group B	Group C	Group D
Interface design	Industrial design	Computer numerical control	Autonomous driving
Human-machine interface	Interaction design	Factory	Vehicle
Control panels	Visual design	Industry 5.0	Transport
Man-machine interface	Experience design	Production line	Mobility
		Industry workplace	Automotive
		Industry 4.0	

On the 14th of November 2023, a researcher performed the following query to ACM Digital Library in accordance with the general research question about HMI design innovation and the rules above described, returning a total of 23 documents (16 conference papers and 7 journal articles). Following this search the researchers met in a dedicated group session to assess and validate the corpus of articles.

2.4. Data analysis strategy

Due to the limited size of the bank of the raw articles, it was not deemed necessary to prioritize it, and all the documents were read by each member of the research team. This decision was taken to reduce the expertise-related biases in the interpretation stage. In addition, this collaborative effort facilitates a holistic examination of the literature, allowing for a nuanced understanding of the diverse aspects of industrial design for HMI design.

A Literature Matrix (available as supplementary material) was built to support the interpretative stage. The methodology followed by the present research assumes a constructivist perspective, partially inherent in the ProKnow-C method, but envisioned by this research team as well. Before and after the reading phase all the researchers participated to two focus group sessions: (a) the first was intended to align the team to the general research theme dimensions; (b) the second served to allow the team members to discuss their personal perspectives on the results, and eventually add specific subdimensions to the corpus under the lens of the investigation. The team collectively engaged in the examination of papers and the analysis exhibited significant relevance to research themes, ensuring a thorough evaluation of pertinent literature.

Only when the participants reached a common understanding, the corresponding dimension was considered saturated [12,13,14], akin to what happens in a Delphi study [15,16]. This methodological framework, anchored in the ProKnow-C method, ensured a rigorous and systematic exploration of the literature on industrial design regarding HMI. There has been an agreement on the evaluation criteria and on the results of it, based on majority, which are summarized in the next paragraph.

3. Results

After reading the articles, 19 out of the 23 articles represented the bibliographic portfolio on indicators for adaptive automation and human-centric technologies. The articles with unconfirmed scientific recognition totaled 4. Then the readings of the remaining 19 titles were carried out to verify the alignment of the articles with the research topic. All authors had only one article cited in the bibliographic portfolio, so they did not have authors with prominence. The group of researchers analysed and discussed the bibliographic portfolio by the research themes described in Par. 3: automated machines, CNC in the Industry 4.0/5.0, advanced manufacturing technologies, machine interface design and industrial processes.

It should be noted that this work is limited to a sample of the research journals and the key words used. The analysis was limited to scientific articles, referring to Human-Machine Interaction and interfaces in manufacturing and Industry 4.0, available on the ACM Digital Library.

Main themes treated in the bibliographic portfolio are highlighted in Table 3:

Table 3. Research themes reported in the articles in the Bibliographic portfolio.

Articles	Research Themes
The Development of a Game Playing Framework Using Interface-Based Programming [Cohen, 2005]	Interface Design
Developing Standards for Affordances on Embedded Devices: Poster Abstract [Perry et al., 2011]	Definition, Usability, Interaction model
Do I Trust My Machine Teammate? An Investigation from Perception to Decision [Yu et al., 2019]	
Experimental Evaluation of Polite Interaction Tactics for Pedagogical Agents [Wang et al., 2005]	Design and Technology
The Future of Our Profession [Dahlbom & Mathiassen, 1997]	Role and contribution of the discipline, Designers skills.
Developer Experience: Concept and Definition [Fagerholm & Münch, 2013]	
The Engineering of Vision and the Aesthetics of Computer Art [Manovich, 1994]	
More Natural End-User Software Engineering [Myers et al., 2008]	
DFSeer: A Visual Analytics Approach to Facilitate Model Selection for Demand Forecasting [Sun et al., 2020]	
Preliminary Explorations of Conceptual Design Tools for Students Learning to Design Human-Robot Interactions for the Case of Collaborative Drawing [Zhao et al., 2022]	
Evolution of the Mind: A Case for Design Literacy [Pacione, 2010]	
Creating Platforms to Support Craft and Creativity in Game Controller Design [Gyory, 2022]	Tangible User Interfaces
Direct and Immediate Drawing with CNC Machines [Li et al., 2017]	Physical Controls, Manual Interaction
Printy3D: In-Situ Tangible Three-Dimensional Design for Augmented Fabrication [Yung et al., 2018]	
Stewardship of Smart Devices Security for the Aging Population [De Carli et al., 2021]	
A Review of the Application of Interaction Design in Modern Educational Product Design [Xia & Rasdan Ismail, 2022]	Mixed Reality in Interaction Design
VRFromX: From Scanned Reality to Interactive Virtual Experience with Human-in-the-Loop [Ipsita et al., 2021	Real Time simulation UI, Tangible UI in VR, input control, animation.
Exploring Tangible VR as a Tool for Workplace Design [Van Campenhout et al., 2020]	Intelligence in Interface Design
	Guidance in human-robot interaction

3.1. Interface Design

The articles [17–19] propose a comprehensive definition of what the interface is and what its role is in industry

and manufacturing. Even though the interface is considered as a contract that outlines the relationship between use and machine programming, its main recognized value is the implementation independence.

As demonstrated [18], usability can have a significant effect on embedded device efficiency. The diffusion of affordances and false affordances suggest a mismatch between users' perception and the allowable actions on the interface itself. Usability of consumer systems goes with standardization: a standardized approach to interface design and affordances would benefit thermostats and other embedded devices since they allow for a more consistent mental model among users.

The interface design is nowadays confronted with intelligent and conversational agents and usability and navigation need to be complemented with novel and further qualities such as the politeness model as part of an interaction tactic. Politeness can influence users' learning experience, by providing positive feedback about achievement and success. Moreover, adaptive automation significantly improves human-machine collaboration by dynamically adjusting task allocations and ergonomic assessments indicate that adaptive systems reduce physical strain and improve operator comfort.

Functional, aesthetic and informational features of interfaces are interwoven as strands useful to build trust through interaction. Article [19] deals with trustiness between human and machine by proposing an experimental study of accuracy systems to measure trust in the human-machine relationship.

3.2. Design and Technology

The articles [20–27] discuss the identity, the borders, and the contribution of design disciplines. We talk about the design disciplines' family, including among the other ergonomics, industrial design, product design, interaction design and service design.

Design fosters the approach towards multiplicity, interpretation and quality with an emphasis on the role of the observer and the value of diverse perspectives on technology, including the one from the user's point of view. A common approach for designers is to address problems not with a pre-defined theoretical framework rather by means of dichotomies like information and data, process and structure, complexity and uncertainty, efficiency and effectiveness. By moving in between such dichotomies the designers can discover, negotiate and apply notions for valuable and meaningful experiences.

A recognized ability in studying designers is the skill of researching visual styles and visual literacy to define requirements for software engineering and machine programming. In particular [25] discusses the quality of visualization strategies in manufacturing, like visual analytics that enable users to compare and select demand computational models, the evaluations of the manufacturing data visualization systems, and time series data visualization. This article also discusses the usability and ergonomics qualities of visual design in multi-dimensional data visualization.

On the role of visual representations in design and robot engineering, [26] focused on collaborative drawing tasks, through the introduction of conceptual and practical design tools. Beyond collaborative drawing, the relationship between the human and the robot is the focus of the research.

3.3. Tangible User Interfaces

The articles [28–31] present and discuss the experiments, and the software and hardware implementation of Tangible User Interface and physical controllers. Tangible interfaces establish novel physical relationships between the player and the system in creative, production and entertainment scenarios. In particular, tangible interfaces and their impact on 2D/ 3D visualizations in Computer Numerical Control (CNC) have been presented in [29]. This research reports the experiment with manual drawing through the LINC (Live Interactive Numeric Control) prototype, a sketch-based digital design tool for authoring 2D or 3D artworks in near-real time.

The article [30] has also the goal to study the combination of manual practice with digital fabrication and computation by using tangible interaction and spatially augmented reality feedback. Main challenge of Printy3D is to fulfill cognitive requirements to conceptualize physical objects in 2D space; this is more difficult than interacting with the physical objects themselves. Printy3D is focused on connecting the real-world object and the digital model

on the screen and to do that by incorporating spatial augmented reality into a tangible design environment. The use of tangible interfaces allows the user to work directly with the existing object as part of the design process.

3.4. Mixed Reality in Interaction Design

The investigation of HMI literature includes the articles [32–34] that focus on Mixed Reality scenarios. They affirm the role of an integrated functional and aesthetic approach in the development of educational materials and products. When people have aesthetic pleasure in using modern information technology, this also enriches the learning experience. In this domain the aesthetic AR technology of [32] proposes a realistic virtual environment of vision, hearing, force, touch and movement generated by a computer to realize the direct natural interaction between users and the environment through the glass's product. This research discusses the design, development and implementation of prototypes for mixed reality interfaces that transform physical reality into interactive virtual experiences inside a VR environment. Furthermore, the research also addresses the reciprocity between human manipulation and AI assistant that guides object retrieval and alignment, and the use of spatial and visual interface for functionality and logic authoring.

Interactions and usability of Mixed Reality have been studied in two industrial scenarios: to retrieve 3D designs for maker-based prototyping and print models remotely and to define systems in Human-Robot collaboration to interact with IoT-enabled devices. In both the control factors describe the manner in which the user performs actions in the virtual environment. Embodied VR employs the physical world and its natural laws (persistence, gravity, friction, inertia, etc.), and allows them to channel the virtual environment.

The article [34] discusses how to maintain the natural interaction through physical controls by leveraging on the developed skills for interacting with it. We feel that VR relates to embodied interaction by inverting its movement: instead of embedding computational processes in the physical world, VR detaches the human body from its physical surroundings, and places it in a virtual world. The authors also stress the importance of empirical evaluation.

3.5. Intelligence in Interface Design

The article [34] addresses the issues of artificial intelligence-based HMI in Human-Robot interaction and co-bot. The specific concept features a circular table with a rotating control unit (1 degree of freedom). The control unit contains a display-button setup. Above it, a Kuka LBR iiwa co-bot hangs upside down from a horizontal bridge, its working envelope comprising the whole table surface. On both sides of the co-bot, two projectors are mounted on the bridge, augmenting the table and the body panels with projected images. Co-bots have also demonstrated enhanced performance and safety in manufacturing environments through adaptive interactions.

The interaction between human and artificial agents is studied by the authors to optimize the industrial process through visual feedback. In the reported case, the user interacts indeed with the co-bot by activating the buttons on the control unit with the standard VR controller. The co-bot reacts by executing certain tasks and movements, while the display on the control unit and the projections on the table provide real-time visual feedback. Case studies analyzed in the systematic review reveal that adaptive automation maintains high situational awareness and reduces cognitive load for human operators and the comparative analyses show that adaptive automation can outperform static systems in productivity and flexibility**.**

4. Discussion

There is a great lack of studies on the implications of adaptive automation and on the innovation of Human-Machine Interfaces ergonomics and design in the context of industry 4.0, since most of the studies were focused on traditional user interface and on the design discipline, and there was also a lack of use of the concepts related to visual and interaction design with automated machines.

This finding can be considered as a gap in scientific research, as it is a relevant topic for ground-breaking industrial production today. This also demonstrates the gap between the industrial design practice, with relation to HMI, and the scientific literature.

In this way, it is possible to affirm that the research topic is in progress, which allows different combinations of factors and methods to implement AMT in the industry 4.0. Furthermore, the functions of industrial HMIs investigated in the case-based analysis [5] and selected from Award-winning market projects were not addressed in the scientific literature. In particular machine interfaces are not reported nor shown in scientific articles. The review demonstrates that, since the dynamic nature of adaptive automation requires continuous monitoring and adjustment to optimize performance, there is a need for developing standards and frameworks for implementing adaptive automation in diverse manufacturing settings. Furthermore, the review demonstrates that the human factors, such as trust and acceptance of automation, play a critical role in the successful integration of adaptive systems.

The gap between the design profession and research findings suggests the researchers extend the analysis of the HMI domain by the engagement of HMI design research groups recognized in the national and international research contexts as experts in the domain. The research results claim for a third strand of investigation, after case-based analysis and literature review, which is the HMI design expert review, with the goal of:

- Retrieving HMI interaction design specialized books and chapters.
- Collecting evidence about HMI design projects by direct involvement of recognized research teams.

By involving well known industrial design professors and researchers, and HMI design professionals in empirical research through individual interviews, expert judges, as well as focus groups, the researchers expect thus to further develop and broaden the research in this field. Collaboration between researchers, manufacturers, and workers is essential to develop user-friendly adaptive automation technologies.

In particular the group of the authors discussed the results of the present literature review with the aim of producing future questions to be investigated in novel phases of the research. These research questions are presented in the following table.

Table 4. Matching between research questions and themes arising from the literature review.

Themes	Research Questions
Interface Design Definition, Usability, Interaction model	RQ1. How does distributed machine interface support contextual exploration and industrial process control by operators?
Design and Technology Role and contribution of the discipline, Designers skills.	RQ2. How do human factors and artificial factors interact in the design process?
Tangible User Interfaces Physical Controls, Manual Interaction	RQ3. How does the absence of physical interactions affect the comprehensibility and intuitiveness of the HMI?
Mixed Reality in Interaction Design Real Time simulation UI, Tangible UI in VR, input control, animation.	RQ4. How does usability must be measured and evaluated in XR? And which are the good design principles for HMI development in an XR environment?
Intelligence in Interface Design Guidance in human-robot interaction	RQ5. What interaction models are used for HMI with artificial intelligence-based systems? And how can design-driven methodologies impact the accountability and transparent user experience of AI-based products?

5. Conclusions

Even with the limitations of of the study, such as having mainly considered the Association for Computing Machinery Digital Library (ACM) and having addressed a limited size of the bank of the raw articles, its results encourage further qualitative and quantitative investigation the interaction design of adaptive automation for human-centric manufacturing both addressing human factors and technological factors: the former including the users' perceptions, the responses and the users' behaviors that occur before, during and after use; the latter including ollaborative technologies such as Cobots to explore the role of agents in enhancing mutual capabilities. In this

context adaptive automation dynamically reallocates tasks between humans and machines to maintain efficiency and safety and Co-bots are integral in creating a collaborative workspace where human and machine capabilities are mutually enhanced.

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