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Design a dynamic automation system to adaptively allocate functions between humans and machines

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Abstract: As automation spreads, the relationship between humans and machines brings increasingly questionable challenges. The static allocation of functions and features among the systems shows that automation brings more than just benefits, causing, for example, the out-of-the-loop condition of operators and the degradation of system performance over time. New Dynamic Automation (DA) rationales are emerging, although still marginally in manufacturing, showing theoretical and application potential. To date, the characteristics of DA systems are not addressed jointly and comprehensively, but the literature focuses on specific issues (e.g., adaptive functions or interfaces). The following paper provides a framework for Design A Dynamic Automation System (DADAS), e.g., the dynamic design aspects to implement a DA approach. By means of a sequential approach, the research also highlights logical relationships between the various aspects.

Keywords: Industry 4.0; Adaptive Automation (AA); Adaptable Automation; Human-Machine-Interaction (HMI); Human-In-The-Loop (HITL); Level Of Automation (LOA);

1. INTRODUCTION

Industry 4.0 enables new modalities of interaction between workers and machines, to suit the variability of production and emphasize the centrality of man in future factories (Bortolini *et al.*, 2021). A paradigm shift toward a human-automation symbiosis shaped by the collaboration of humans with machines arises (Romero *et al.*, 2016). In this context, Dynamic Automation (DA) can optimize the system's performance over time. The literature refers to Adaptive Automation (AA) as the dynamic assignment of functions to a machine and/or humans over time when the decision-maker authority is the machine (Sheridan, 2011). Since the current research considers three different decision-maker scenarios (human, machine, and hybrid), the topic is addressed as DA in general. The static allocation defines who is doing what. Instead, the DA defines who is doing what, and when. A third logical dimension emerges (Figure 1).

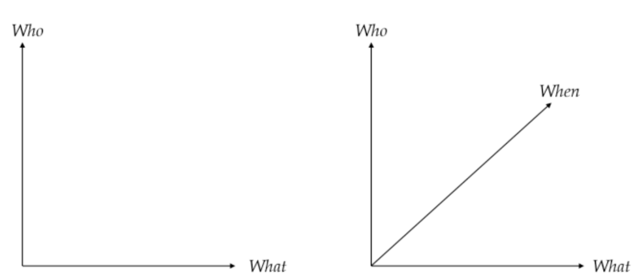

Figure 1. Static VS Dynamic Automation (DA).

DA major applications exist in aviation, aeronautics, and automotive (Hancock *et al.*, 2013), primarily concerning safety issues. However, even in manufacturing the dynamic interaction between man and machine can improve performance, productivity, and flexibility (Bortolini *et al.*, 2021). Also, it may ensure greater involvement of operators within the automated systems, reducing the out-of-the-loop condition that triggers awareness, loss of skills, behavioral adaptation, and job dissatisfaction. Consequently, the automated system performance and the level of operator safety may deteriorate (D'Addona *et al.*, 2018). DA applications in manufacturing appear residual, despite the research showing efforts in this field as well, and some test cases are emerging (Burggräf *et al.*, 2020). In manufacturing, applications mainly concern assembly stages. A representative scenario in human-robot interaction is the one concerning the implementation of an Intelligent Self-Adaptive Assembly System (Bortolini *et al.*, 2021). Here, assembly station features and connected activities are dynamically adapted over time, resulting in improvements in flexibility, productivity, and operator's well-being. Nevertheless, the literature lacks a comprehensive definition of the system aspects for designing a DA system. To fill this gap, the paper provides a framework with 7 system design aspects, and it presents the possible options for each aspect. The framework resulted from a literature in-depth analysis of DA conceptualization and implementation. By analyzing practical and theoretical scientific results, the paper outlines the distinctive aspects of a dynamic system, to be considered from the initial stages of system design. As a first theoretical result, the framework has yet to be tested and validated in a manufacturing operational environment.

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2. DESIRED BENEFITS OF DA APPROACH IN MANUFACTURING

A DA system aims at improving different concerns arising from the static allocation of functions (Lim *et al.*, 2021; Planke *et al.*, 2021). The possibility of dynamically adapting functions between human and machine provides a solution to the out-of-the-loop condition, e.g., the trouble for operators to know and govern automated processes. This leads to an improvement in identifying automation breakdowns and resume manual control. Operators can become more aware of the inherent automation changes and can avoid experiencing unexpected mode transitions. DA can also prevent the loss of skills, by empowering the opportunity to train manual skills, which are effective when an urgent manual control of the system is needed. Moreover, DA can compensate for new forms of unexpected human errors, the so-called automation-induced errors. Also, it can avoid the behavioral adaptation of operators, arising when humans' perception of safety increases in front of automation, and they may adapt their behavior encountering new risks. Trust in automation could vary considering the perception of its reliability, and DA approaches can generate adequate trust levels. Finally, it can result in a higher job satisfaction: automation may no longer be perceived as a threat to workers, mainly when adequate transition and training processes arise.

3. FRAMEWORK FOR *DESIGN A DYNAMIC ALLOCATION SYSTEM* (*DADAS*)

To design a DA system, 7 aspects need to be defined (Figure 2).

1. **Object of modification definition** – *What is dynamic in the system?*

There are several forms of adaptation, dependent on the dynamic part of the system. This aspect is linked to the motivation that led to the design of the DA system. For example, the activities performed, the characteristics of interfaces, the level of interaction, and the timing or prioritization of tasks. Considering the system design aspects presented in the following, categories of possible dynamic rationales emerge. Those depict the range of potential adaptations. There are four major ways in which a designer renders the automated part of a human-machine system dynamic to meet current needs. These are the objects of modification (Feigh *et al.*, 2012). Specifically, a system can dynamically change the **function allocation**, e.g., who (machine or human) makes each function; the **interaction**, e.g., how it presents information to users; the **content**, e.g., what information it presents to users; the **task scheduling**, so when tasks are performed, together with the performing sequence. While change in function allocation is inherent in any dynamic system, the other categories can arbitrarily be treated adaptively. A dynamic system is expected to comprise adaptations in more than just one category.

2. **Set of dynamic activities and tasks definition** – *Which system boundaries, in terms of tasks and activities, are treated dynamically?*

When designing a dynamic system, not all the constituent activities are dynamic. Only certain sets of activities and tasks may be dynamic, while the rest remain static (e.g., no properties altered over time). To this end, when a process and its activities are identified, each activity can be divided into elementary units. This is to define the boundaries of the activities since the DA can alter their characteristics and their assignment. For example, it's important to define which portion of the activity is assigned to man or machine and which will be treated dynamically. The breakdown to obtain the elementary units follows two main criteria (Bindewald *et al.*, 2014). The first criterion is the **cluster-based techniques**. It consists of clustering tasks or activities by technological, human, or environmental affinity, by required machine and human characteristics, or environmental elements. Then, the designer choose with set of tasks or activities is static and which is dynamic. The second criterion is the **function to task technique**. Firstly, the functions are decomposed to the atomic level, and the designer ensures a decomposition without allocation requirements. Then, the induced allocations are made, i.e., allocations that comes from procedures, guidelines, skills, or obtainable resources. Finally, the designer choose the functions for which a dynamic allocation is feasible, basing on graph-analysis considerations.

3. **Level Of Automation (LOA) definition** - *Who makes the activities?*

LOA is the scale that identifies the functions involving man and machine. An increasing level of LOA corresponds to a greater number of tasks given to the machine. A wide range of available design alternatives, alongside the totally manual or automated, is possible. A debated question in the literature is how to choose an appropriate LOA considering human confidence in automation and self-reliance in task execution (Musić and Hirche, 2017). To design a dynamic DA system, it is essential to characterize the starting LOA and how it may change. The analysis and comparison between the different LOA classifications (Endsley, 2017, 2018), led to the definition of an activities set that can be performed by human, machine, or shared. This set consists of five primary activities: **generate, select, implement, communicate, and control actions**. The system's LOA level impacts human performance, workload, and Situation Awareness (SA). Improving SA addresses out-of-the-loop, a human-damaging issues in automated environments. Previous studies outlined that as Degree Of Automation (DOA) increases, human workload can decrease, but return-to-manual control and SA decline. Thus, within some critical contexts, operators should be maintained engaged in execution stages (Tatasciore *et al.*, 2020).
As the literature revealed (Vagia *et al.*, 2016), greater LOA taxonomy has been established. However, those with more levels seem to feature wider applicability across contexts (Johnson *et al.*, 2011). The need to extract and merge the types of activities presented in different taxonomies is because a single taxonomy does not present a sufficient number of topics to guide the design of DA systems (Endsley, 2018). Furthermore, the Human Machine Interface (HMI) must support this shift effectively. Before designing the HMIs, it is necessary to determine who has the authority to intervene in

the system, as well as the rationale governing whether actions are required or permitted.

4. **Allocation authority agent definition** - *Who is the decision-maker that determines the LOA shift?*

When the LOA is adjustable over time, the designer has to define who can authorize the shift. In line with the principles of *adaptive* and *adaptable* automation (Parasuraman and Wickens, 2008), the allocation authority agent (Sheridan, 2011) can be the human, the machine, or hybrid, if the authority belongs to both the human and the machine. In real scenarios it would be safer or more efficient to leave authority to the human under certain circumstances, and to the machine under others. When the authority agent is hybrid, different invocation strategies can be defined for each agent, and consequently all the next system design aspects may be tailored. The literature is skeptical about the implementation of adaptable automation in high-complexity and high-criticality domains (Calhoun, 2022).

5. **Invocation strategy definition** – *Which strategy defines the shift?*

The shift may be based on the observation of different aspects of the system, either proactively or reactively. For example, the prediction or occurrence of critical events for operators or machines, and the degradation of system performance. For all the strategies is necessary to define what is of interest (event/indicator), when is critical (threshold), and how to monitor it (detection systems – intrusive or not). In literature emerge five main strategies. **Critical events** strategy shifts the allocation when a critical event arises. Such an event determines the performance degradation of the system or introduce risk within it (Kaber and Endsley, 2004). The second strategy is based on **psycho-physiological measures** and requires the measurement and monitoring of human parameters. Appropriate policy and regulations must ensure the privacy and security of human data collected. Some measures are (Cotter *et al.*, 2021): Electroencephalogram, Electrocardiogram, Eye-tracking and Heart Rate. The sensitivity of human physiological measures are heritable from the neuroscience and human factor fields (Memar and Esfahani, 2016). Before defining such measures, the MWL (Mental-Workload) must be defined (Inagaki, 2003). In DA contexts, the NASA-Task Loader Index is typically employed, a WML score based on a weighted average of 6 subscales: mental effort, physical effort, temporary effort, performance, effective efforts, and frustration (Sauer *et al.*, 2012). The third strategy is based on **performances measures**. They refer to the whole system and can be external (e.g., flexibility, service), internal (e.g., productivity, logistic), or based on sustainability issues. Then, the **modelling** strategy arise since the above-mentioned aspects can be modelled to prevent future events and behaviors and act proactively (Yoo, 2012). Finally, **hybrid** techniques can be applied. The described strategies are not mutually exclusive and can be implemented in a hybrid way.

6. **Trigger definition** – *What triggers the shift?*

The evaluation of contextual elements serves as a trigger to initiate the changes underlying the adaptation. For example, task status, operator features, and environmental conditions. There are several triggers to initiate the changes behind the adaptations (Feigh *et al.*, 2012). The trigger design must be consistent and coherent with the invocation strategy. The major trigger identified are five. The **operator-based** trigger requires adaptations by the evaluation of the operator's status; **system-based** trigger, by the expected states of the system; **task and mission-based** trigger, by a dynamic depiction of the human and machine activities; **environmental-based** trigger, by the statement of the environment apart from machines and operator. Finally, **spatio/temporal-based** trigger, by the estimations of spatio/temporal criteria.

7. **Human-Machine-Interfaces definition** – *How information is shown, shared and communicate between human and machine?*

Since the communication and sharing of plans and actions prevent unexpected and unusual behavior of the system, a suitable Human-Machine-Interface (HMI) is needed. It allows operators to use and control the machine, observe the status of the system, and get action in the process. To identify the most suitable HMI, the user's constitutional and situational characteristics need for consideration, as well as the type of task performed and the working environment. There are three levels of interface adaptation (Villani *et al.*, 2017, 2021): perception-level, e.g., how info is presented; cognition-level, e.g., what info is presented; interaction-level, e.g., how interaction is enabled. Dynamic HMI allows high levels of production processes' customization, with no increasing the complexity of the interaction. Moreover, the dynamic HMI, adapting to the user's capabilities, makes users comfortable with advanced tools. The effect could be positive on working conditions considering the increased usability and the reduction of the cognitive load (Villani *et al.*, 2017). However, how often HMIs' information and feedback needs to be exchanged between human and machine depends on specific contexts, considering entities', environmental and task's features. More than just a case-specific issue, this is a choice that needs on-going revision for adequacy.

The 7 design aspects, summarized in Figure 2, are presented sequentially, since some choices limit and define the domain of the subsequent. As an example, designing a dynamic HMI without defining the dynamic boundaries of the system and the authority agent of the shift could be inconvenient. Nevertheless, as the interdependence between the aspects shows, having a comprehensive perspective on all these simultaneously is useful to make consistent choices.

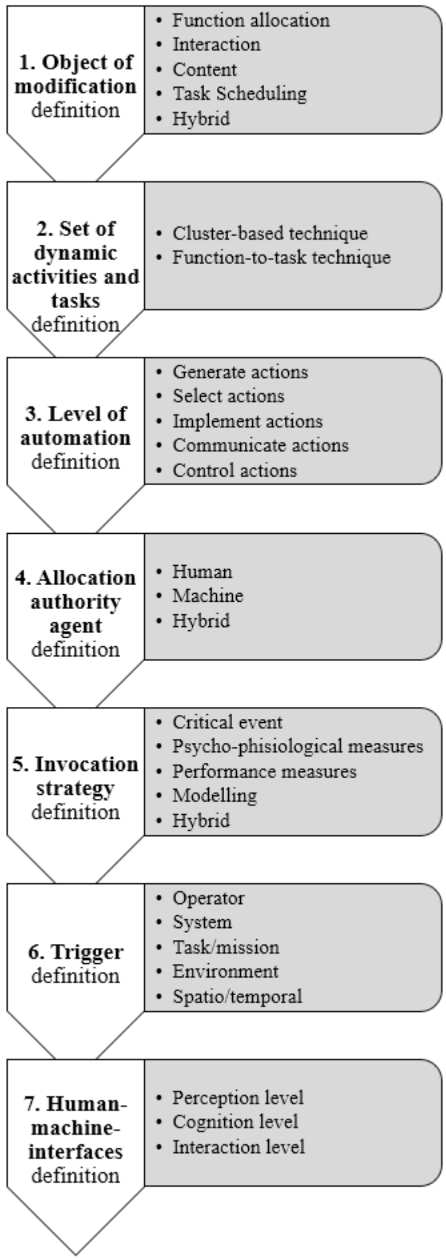

Figure 2. DADAS Framework.

There are also further aspects, that need for an on-going design and assessment. Those ensure the always effective and efficient implementation of a DA system. The most important on-going ones are the human instruction on DA rationales and on the interaction with it. Moreover, the monitoring of how the DA system is performing to ensure that the expected benefits are always met. If analyses show negative trends or results, interventions on the DA system design aspects become necessary, in a timely manner depending on the criticality detected.

4. CONCLUSION AND FUTURE DEVELOPMENT

The DADAS framework defines the 7 main aspects to be designed to implement a DA-based system. In literature, these issues are currently only addressed and discussed partially and independently. The framework innovatively joins those systemic aspects and define the sequence of design, highlighting logical links between the various aspects. Considering these aspects all together provides a comprehensive insight on the effects that DA choices have on different aspects of the system. When implementing a DA approach in an existing system, the entire system should be reviewed to ensure its effective, coordinated, and consistent operation. On the other hand, when a DA system is designed from the outset, the features of the system elements should be designed to be changeable over time. As an example, defining dynamic activities but designing the connected interfaces in a static way can generate criticisms for the system's entities. Possibilities for reordering these aspects could stem in already existing DA systems where some aspects have already been defined and others have not, or where choices made need to be modified pointwise. The framework represents an initial theoretical research result. Future developments concern the testing and validation of the framework in a manufacturing operational environment. By selecting manufacturing processes where collaborative technologies are implemented, it is possible to understand whether the expected benefits of DA are achieved. Furthermore, comparing the implementation of DA in different operational contexts may reveal specific needs and guide the customization of the framework according to the context.

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