Towards an interface design aiming to limit the cognitive load on operators during manual tool loading on industrial CNC machines

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ABSTRACT

With the advent of Industry 4.0, CNC machines are becoming considerably more complex. The amount of data to be communicated to the operator is increasing and tends to make the interfaces overloaded. This has a non-negligible impact on the operator's cognitive load, reducing his Situation Awareness (SA), defined as his ability to generate a mental representation of how the machine works.

This research paper focuses on manually loading tools onto CNC machines and how the interface can support the operator's SA during this operation. This operation is particularly critical because of the temporary inconsistency it involves between the state of the machine and that of the interface, placing a heavy demand on the operator's working memory.

The methodology used was inspired by the Situation Awareness-Oriented-Design (SAOD) proposed by Dr Mica R. Endlsey, which involved a Hierarchical Task Analysis (HTA) and a Goal-Directed Task Analysis (GDTA). Contextual interviews were conducted with two Swiss machine tool manufacturers, during which experts were asked to perform a tool change. Detailed analysis and comparison of the operators' activity and cognitive functioning enabled the establishment of a high-level theoretical model as well as five action levers aiming to reduce the risk of error. A list of 15 design guidelines for HMI designers, specific to manual tool loading on CNC machines, was then established, filling a gap identified in the state-of-the-art.

Keywords

User Interface, Human Machine Interaction, Situation Awareness, CNC machine, Design

LIST OF ABBREVIATIONS

CNC	Computer Numerical Control
GDTA	Goal-Directed Task Analysis
HTA	Hierarchical Task Analysis
IHM	Human Machine Interaction (Refers to the machine interface)
SA	Situation Awareness
SAOD	Situation Awareness Oriented Design
SASUI	Situation Awareness Support User Interface

1. INTRODUCTION

Industry 4.0 is leading to the automation and increasing complexity of numerically controlled (CNC) machines (Gorecky et al. 2014; Krupitzer et al. 2020) (Figure 1). The increasing amount of information communicated to the operator makes interfaces more cumbersome (Lotti et al. 2019). This has an impact on the mental representation of machine operation, called "Situational Awareness" (SA) (Landmark et al. 2019), which is considered a key element in the design of complex information systems (Oury and Ritter 2021). While good SA reduces the risk of errors, it is also strongly influenced by the operator's cognitive load (De Oliveira et al. 2014).

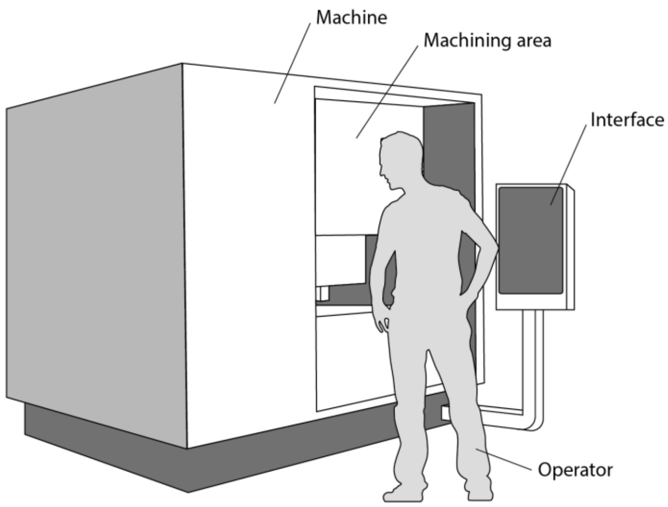

Figure 1 The most common configuration for CNC machines

Some studies about SA in the industry present remote production monitoring solutions, such as tablets, smartwatches (Landmark et al. 2019) or augmented reality (Rani et al. 2022). However, some maintenance tasks still require manual intervention via the interface, which must facilitate access to the information needed to generate the mental model. Endsley (2015) and Oliveira (2016) describe SASUI as "Situation Awareness Support User Interface" used, for example, by Villani et al. (2021a, 2021b) to design adaptive HMIs.

The interface plays a central role in a CNC during the manual tool loading operation (Figure 2) and requires an excellent SA. It implies a lack of coherence between the physical state of the machine and the information on the interface (Lotti et al. 2019), placing a heavy demand on the operator's working memory and exposing him to the risk of error (Lotti et al. 2018). Although the criticality of this operation is recognised by machine manufacturers (Lotti et al. 2019), there are no guidelines to promote SA in this context.
This research aims to determine whether and how the interface can support the operators’ SA during this maintenance operation.

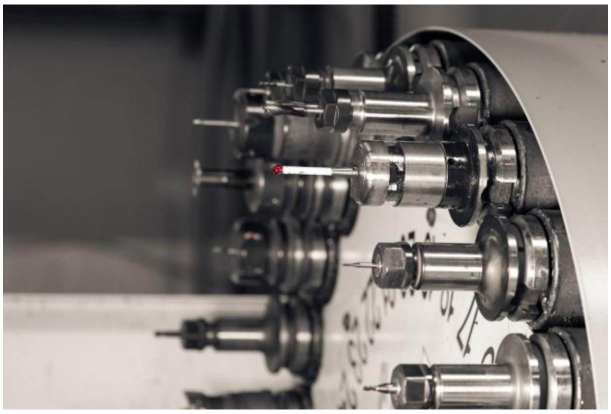

Figure 2 Image of a CNC tool loader. The tools are mounted on the numbered positions. The operator must remember the type of tool and its location to enter this information in the interface. Image from www.stock.adobe.com

2. RELATED WORK

2.1. Situation Awareness

A widely accepted definition of SA is: "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (Endsley 1988, cited in Pesavento 2015).

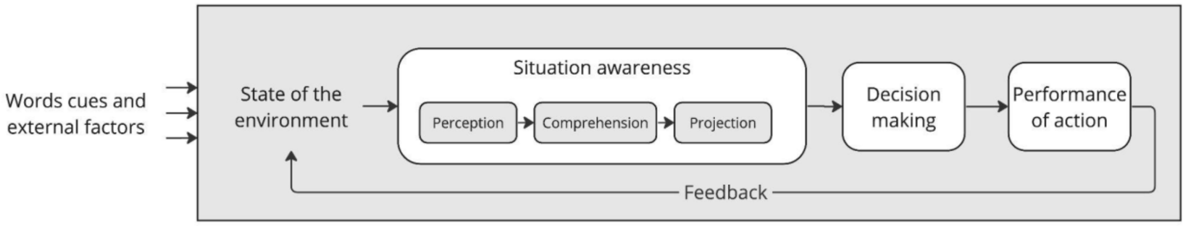

Figure 3 Model of SA. (Adapted from Endsley and Jones 2012: 15)

This definition is proposed by Dr. Mica R. Endlsey, whose research work is a reference. Figure 3 summarises the SA model and refers to the abovementioned three stages.

Based on this model, we understand that an HMI must be able to communicate the right information to the operator so that he can make the decisions needed to achieve his objectives and, therefore, get the job done.

2.2. Situation Awareness-Oriented-Design (SAOD)

Endsley and Jones (2012: 59) and Nwiabu et al. (2012) present a methodology for designing information systems promoting SA. SAOD incorporates an analysis of the operator's activity centred on his objectives[1] to understand his cognitive functioning. It combines a hierarchical analysis of tasks and a form of cognitive task analysis that focuses on the operator's goals and the decisions required to achieve them. Santos et al. (2020) apply SAOD to human-robot

[1] The terms "objective" and "goal" are used interchangeably in this research paper.

interaction in industrial welding, and Onal et al. (2013) to design interfaces linked to mining operations.

2.3. Design guidelines

Endsley and Jones (2012) present a list of high-level UI design principles to support SA. Appendix A, Table 3 shows a selection of principles established by the author and relevant to this research work.

3. METHOD

The methodology adopted (Figure 4) (validated by the University ethics committee) is inspired by the abovementioned SAOD method, aiming to provide a detailed understanding of operator activity and cognitive functioning.

Two case studies with two Swiss machine manufacturers were analysed. They wish to remain anonymous for confidentiality reasons. No captures of the recordings can be published.

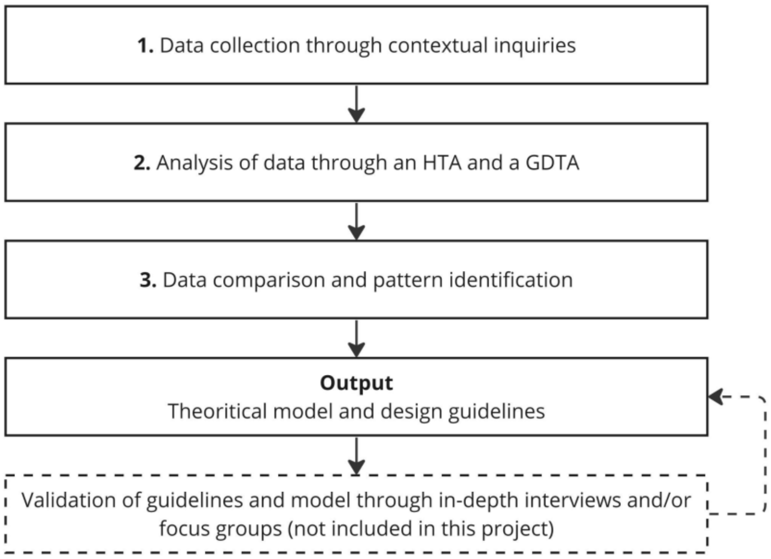

Figure 4 Methodological model proposed by the author, validated by the Falmouth University Ethics Committee

1. Data on the operator's tasks and goals are collected through contextual interviews, during which experts were asked to perform a tool change to launch the manufacturing of a part.
The expert in case study 1 is a trainer with five years of experience on the machine. The expert in case study 2 is responsible for developing the tool loading interfaces. The observations, filmed for in-depth analysis, occur on the machine interface. They combine semi-structured interviews (Salazar, 2020) and the think-aloud method (Nielsen, 2012).

2. The analysis begins with a hierarchical task analysis (HTA) to decompose activities into tasks and subtasks, providing a general understanding of the activity (Nwiabu et al. 2012). The tasks are then transcribed into goals using the Goal-Directed Task Analysis (GDTA) (Endsley and Jones 2012: 68). The cognitive demand can be explicitly described by specifying the

decisions and information required to achieve each goal. Potential problems raised during the interviews are also considered.

3. The operators' cognitive functioning is then compared to identify potential patterns and establish (i) a high-level theoretical model of operator cognitive functioning and (ii) a list of design guidelines relating to this model.

4. RESULTS

4.1. Hierarchical task analysis

The activity in case study 1 can be broken down into four main tasks (Figure 5) (see the full version in Appendix B): (1) preparing the tools, (2) configuring the position, (3) loading the physical tools onto the machine, and (4) validating the configuration.

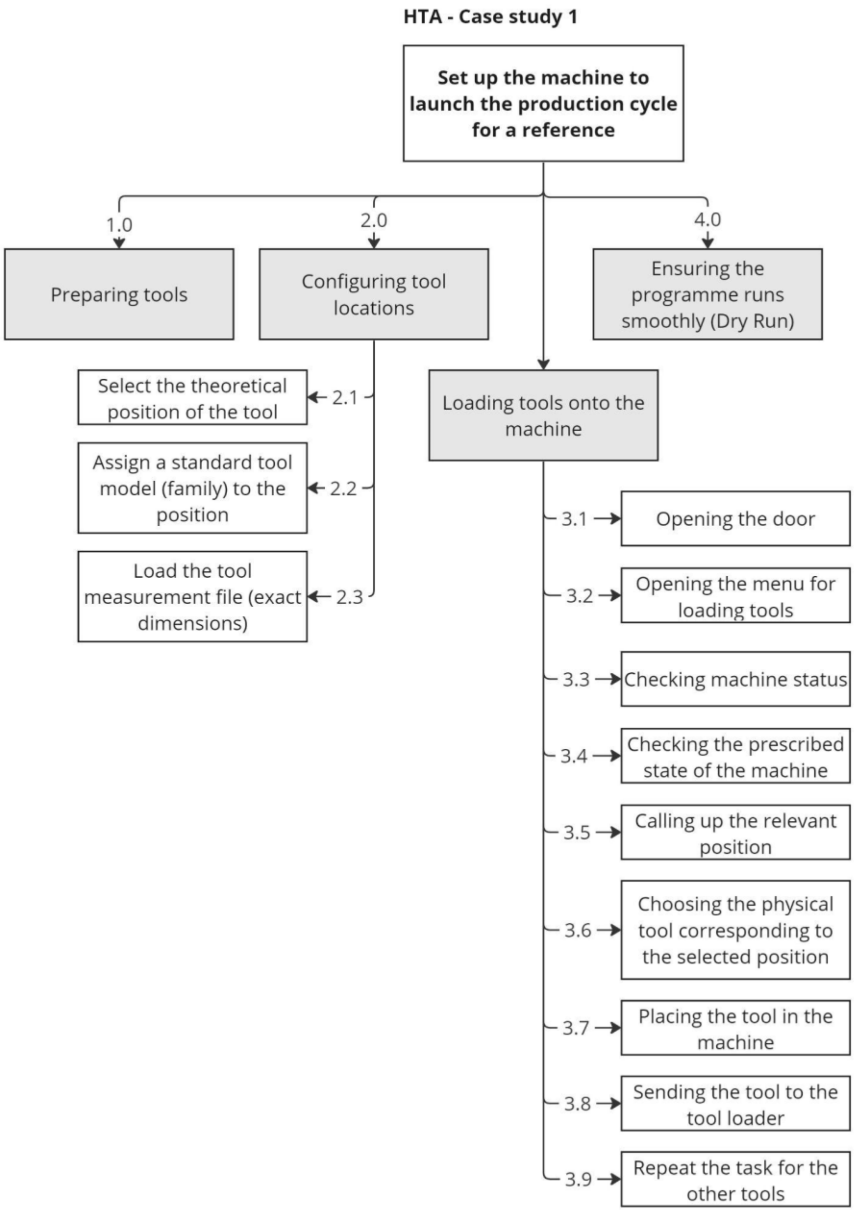

Figure 5 Simplified diagram of hierarchical task analysis for case study 1

The activity in case study 2 can be broken down into three main tasks (Figure 6) (see the full version in Appendix C): (1) preparing the tools, (2) loading the tools onto the machine, and (3) validating the configuration.

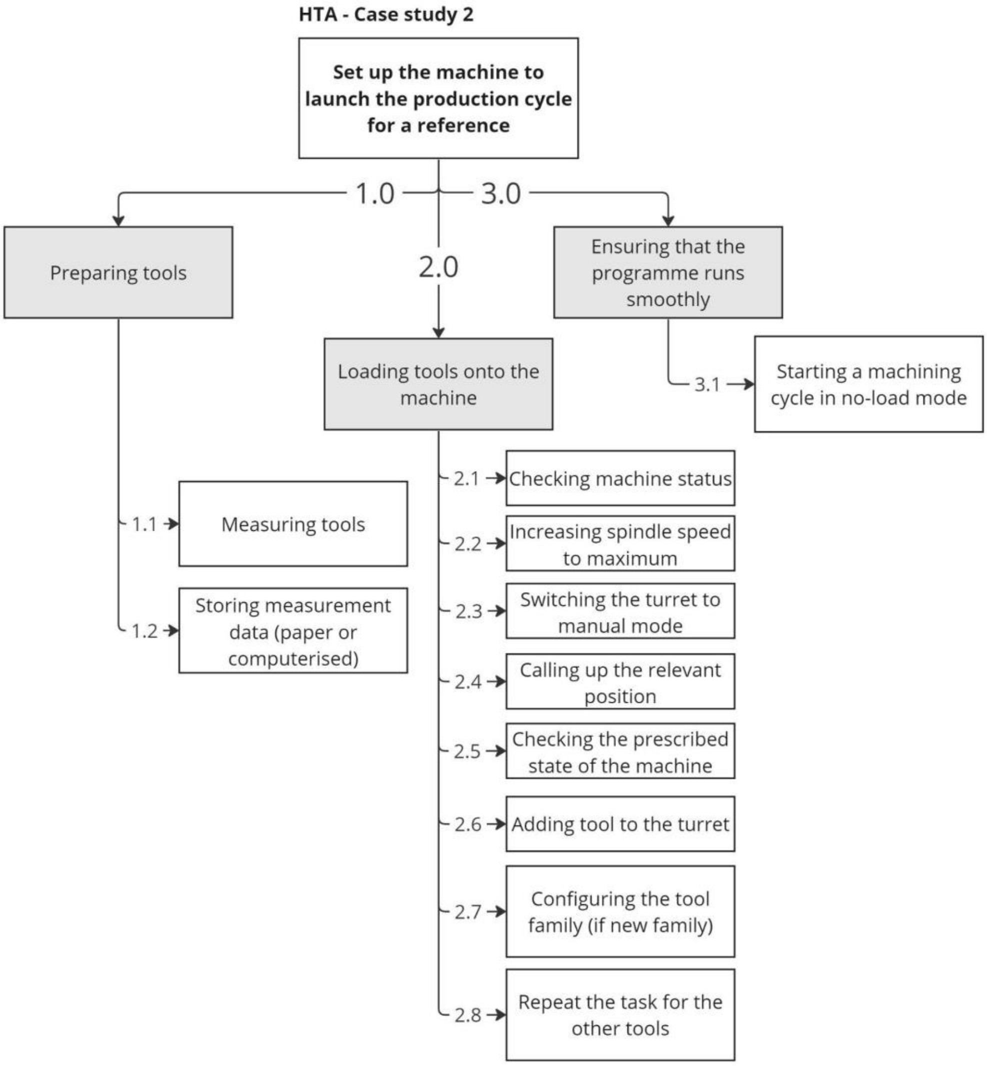

Figure 6 Simplified diagram of hierarchical task analysis for case study 2

4.2. Goal-Directed Task Analysis

The tasks resulting from the HTA have been transcribed in the form of objectives and sub-objectives in Figures 7 and 8 to deal with the cognitive component of the operator.

In addition, each GDTA includes the operator's decisions to achieve the abovementioned objective in the form of questions. The last sheet of each branch of the diagram lists the information required for the operator to make the decisions. The full versions, including decisions and requirements, are shown in Appendix D and E.

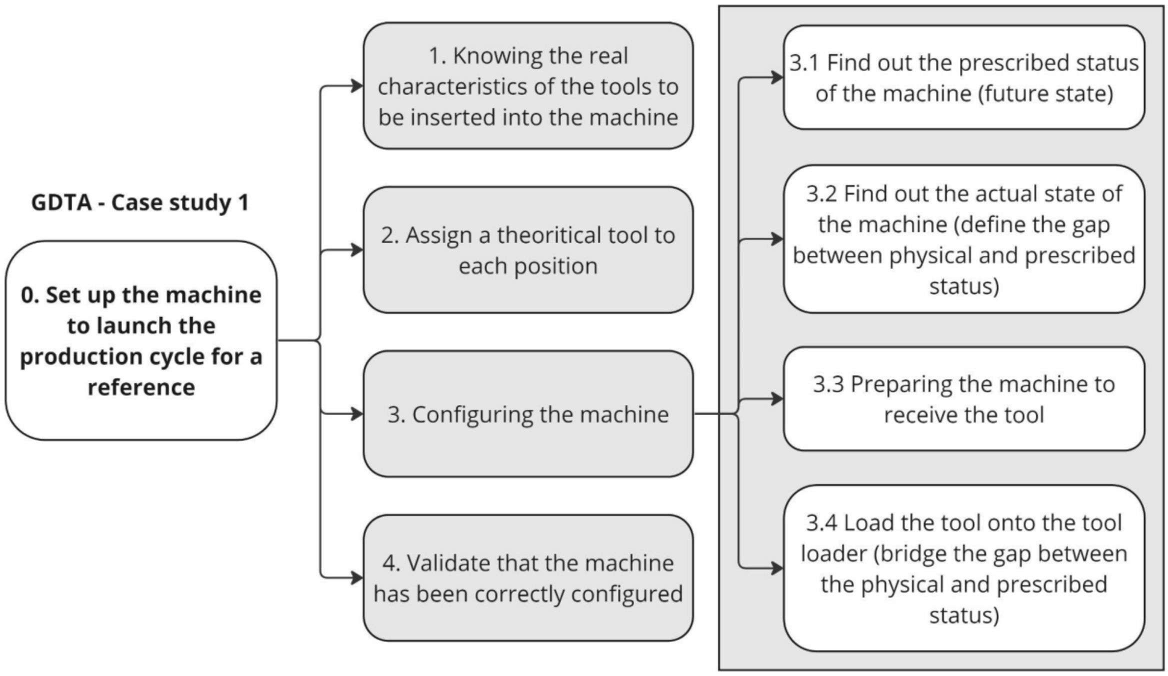

Figure 7 Simplified diagram of Goals-Directed Task Analysis for Case Study 1 (here, decisions and requirements are not specified)

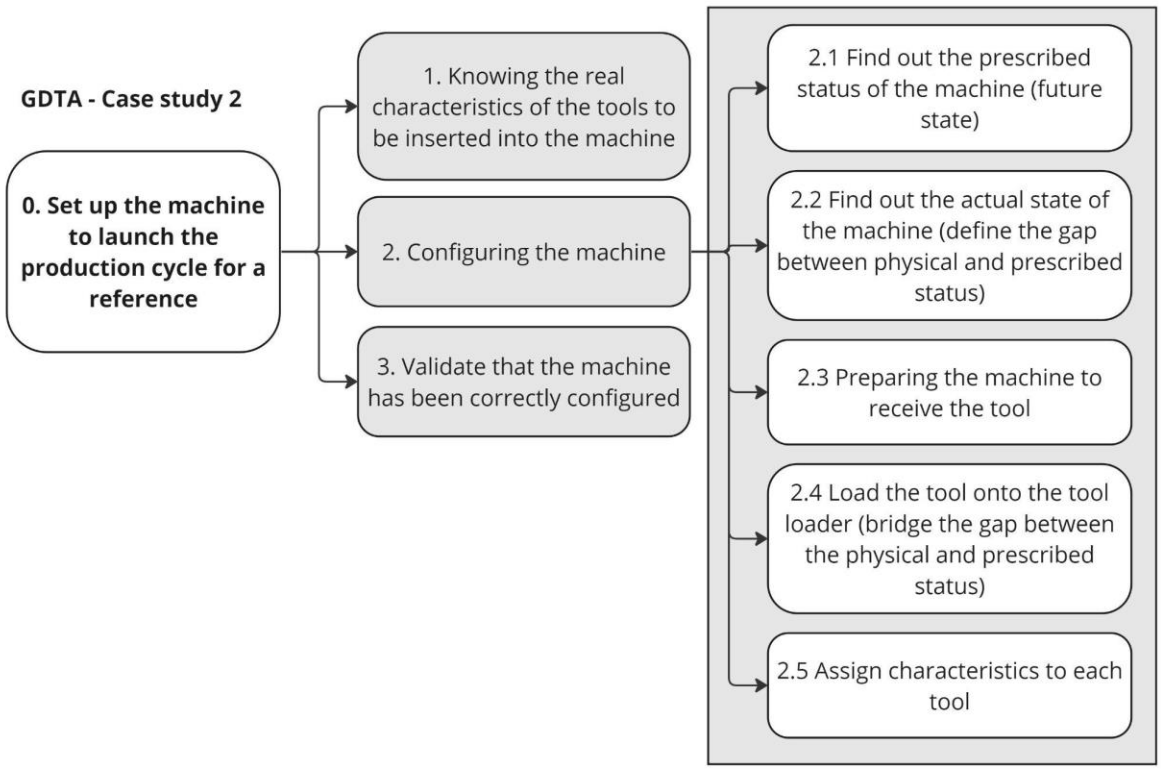

Figure 8 Simplified diagram of Goals-Directed Task Analysis for Case Study 2 (here, decisions and requirements are not specified)

4.3. Identified problems

The interviews enabled the identification of problems the operator may face. Table 1 lists these issues and specifies the case study(s) in which they were mentioned, and the objectives concerned.

Table 1 List of common issues for case studies 1 and 2 and specific to each objective

Common problems	Case 1	Case 2
Assigning a tool to the wrong place	2	
Forgetting to assign a tool to the prescribed status	2	
Misinterpretation of prescribed status	3.1	2.1
Omission of information that requires going back and forth between screens	3.1	
Misinterpretation of machine status	3.2	2.2
Mobilisation of the wrong position on the machine	3.3	2.3
Loading the wrong tool on the engaged position	3.4	
Validation of the configuration despite the machine still containing errors	4	3
Misinterpretation of the mode the machine is in (automatic vs manual)		2.3
Transcription errors when manually transferring complex tool characteristics		2.5
The operator carries out the tasks in the wrong order		2.3
Assigning the wrong characteristics to the loaded tool		2.5
Forgetting to load the tool after specifying its characteristics		2.4
Choosing the wrong physical tools	3.4	2.4

5. DISCUSSION

5.1. Key findings

- A temporary inconsistency between machine and interface status during tool loading places considerable demands on the operator's working memory, leaving room for critical errors.
- Many goals are common to the two case studies, enabling the generation of a high-level theoretical model and highlighting the stages with strong cognitive components.
- Five action levers aimed at limiting errors were identified based on the theoretical model and the theorisation of the operator's cognitive functioning.

- A list of 15 best practices to promote SA with sufficient abstraction to be transposed in both cases has been compiled.

5.2. Definition of a theoretical model

Comparison of the GDTAs has enabled the identification of common high-level objectives that make up the operator's activity. The sequence of objectives shows some variation depending on the case observed. These different flows and the main steps, presented as goals, have been modelled and illustrated in Figure 9. The decisions to be taken by the operator to achieve each of these goals are presented in Table 2.

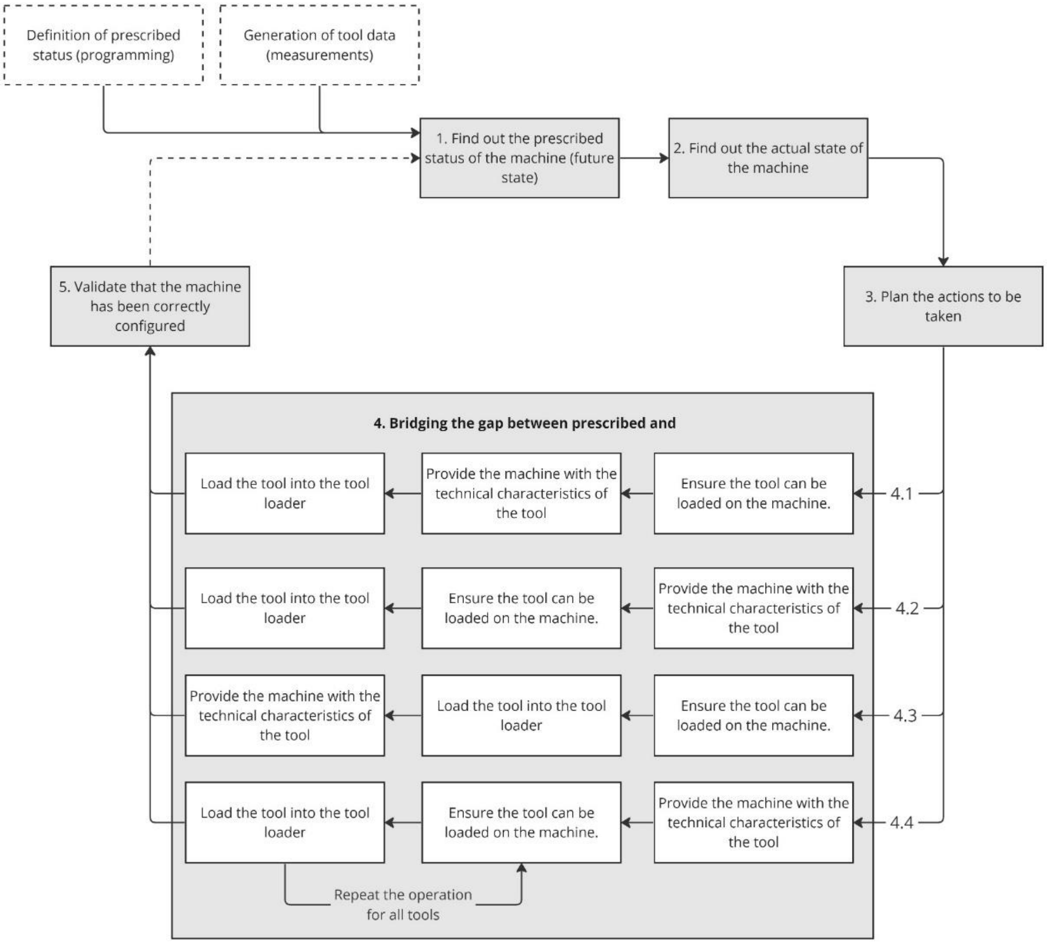

Figure 9 High-level theoretical model of the operator's goal-oriented activity

Table 2 List of decisions to be taken by the operator relating to each goal in the theoretical model.

Goal		Decisions
1	Find out the theoretical status of the machine (future state)	• How must my machine be configured? • What tools need to be loaded and where?
2	Find out the actual state of the machine	• Are any tools already in place? • If so, are they operational? • What operations must be carried out to configure my machine (bridge the gap)? • What mode is my machine in?
3	Plan the actions to be taken	• How can the theoretical status and machine status be matched? • Do any tools need to be removed/replaced? • Is it necessary to change the machine mode?
4.1.1	Ensure that the tool can be loaded onto the machine	• Which position should I call? • How do I access the position where the tool will be mounted?
4.1.2	Provide the machine with the technical characteristics of the tool	• What are the characteristics of the tool to be loaded at the mobilised position? • Do the characteristics entered correspond to the tool to be installed and to this position? • Where do I enter the information?
4.1.3	Load the tool onto the tool loader	• Which physical tool corresponds to the selected position AND to the characteristics entered?
5	Validate that the machine has been correctly configured	• Does the real status of the machine correspond to the theoretical status? • Was the gap correctly closed? • Is my machine capable of manufacturing the requested part?

During steps 1 and 2, the operator tries to generate a mental representation of the machine's prescribed status, i.e. the future configuration in which the machine should be, and the machine's actual status, i.e. the machine's current configuration. He tries to "measure" the gap between these two states. The prescribed status is often on a medium other than the machine interface (paper or workshop computer). The actual status of the machine is given directly by the interface and the position of physical components in the machine.
Generating this image enables him to plan the actions (step 3) to match the prescribed status with the actual status.

Stage 4, aimed at bridging the gap between prescribed and machine status, is divided into several sub-goals. The sequencing of these sub-goals distinguishes the two case studies observed. The interviews show that these variabilities often result from external constraints linked to organisational or technological aspects. This stage consists of (i) a "preparation" stage, which consists of preparing the machine to receive the tools, (ii) assigning the technical characteristics of the tool, and (iii) loading the physical tool onto the machine.

The cycle ends with an evaluation phase during step 5. The operator ensures that the new state of the machine corresponds to the prescribed state.

5.3. Stages with strong cognitive components

The GDTAs make it possible to identify the activity's objectives with a high cognitive load and theorise the operator's cognitive functioning. For clarity, flow 4.1 has been isolated and presented in Figure 10. However, this theory also applies to flows 4.2, 4.3 and 4.4.

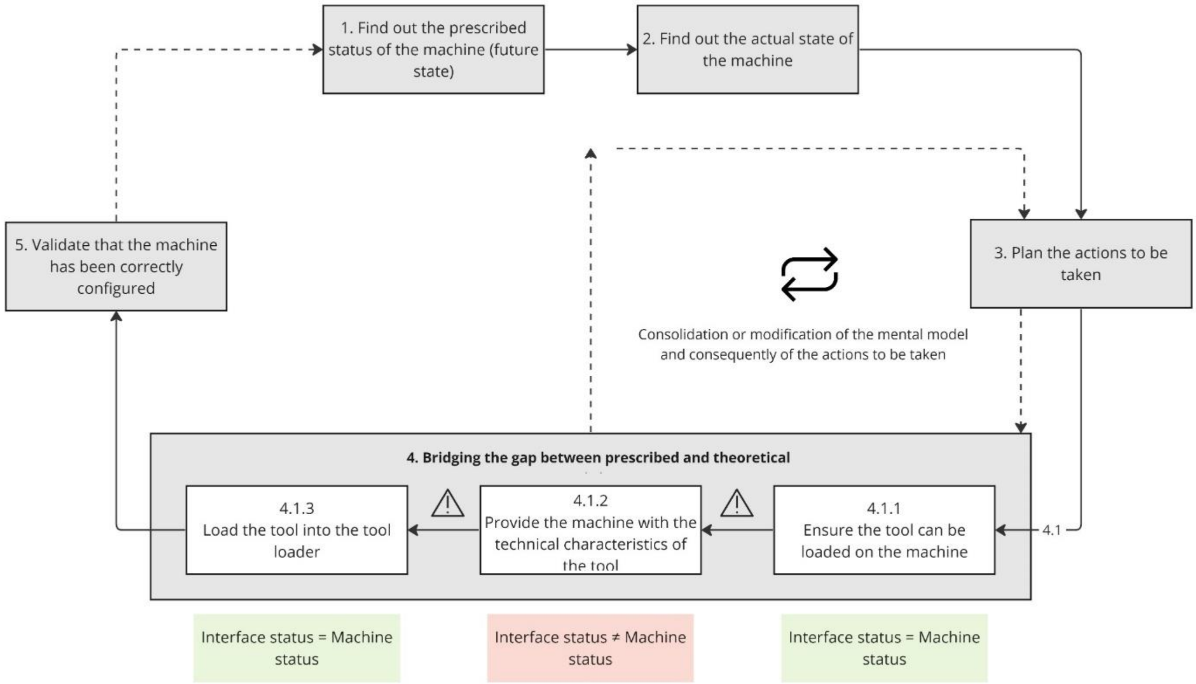

Figure 10 High-level theoretical model of the operator's goal-oriented activity specific to the flow 4.1

Step 4 requires both a high level of attention and a high level of working memory. The observations confirm a temporary inconsistency between the machines' and interfaces' states. This inconsistency must be "corrected" by the operator for the two statuses to correspond again. In between, the operator must keep some important information in memory. The list of problems (Table 2) shows that it is at this point that an operator can make a critical error, such as selecting the wrong tool, using the wrong position, or assigning the wrong characteristics to a loaded tool.

To make decisions relating to objectives 4.1.1, 4.1.2 and 4.1.3 (table 3), the operator must be able to rely on his mental image of the system. As described by Endsley and Jones (2012: 21), this is formed using his understanding of the system (here formed mainly using the prescribed and actual status) and his semantic knowledge, i.e. his professional skills (Figure 11). If in doubt, he will try to reaccess the different statuses to consolidate or correct his mental image and then his planning. The more firmly anchored the image, the lower the cognitive load and the higher the level of attention, leaving more room for working memory.

Based on the above, five action levers have been identified to limit errors:
Lever 1 - Ease of interpretation of the prescribed and actual machine state
Lever 2 - Ease of projecting the future situation and planning actions
Lever 3 - Ease of access to information needed to make decisions relating to goals (table 2)
Lever 4 - Reduction of other demand sources on working memory that are not essential to the goals.
Lever 5 - Operator training and specialist skills

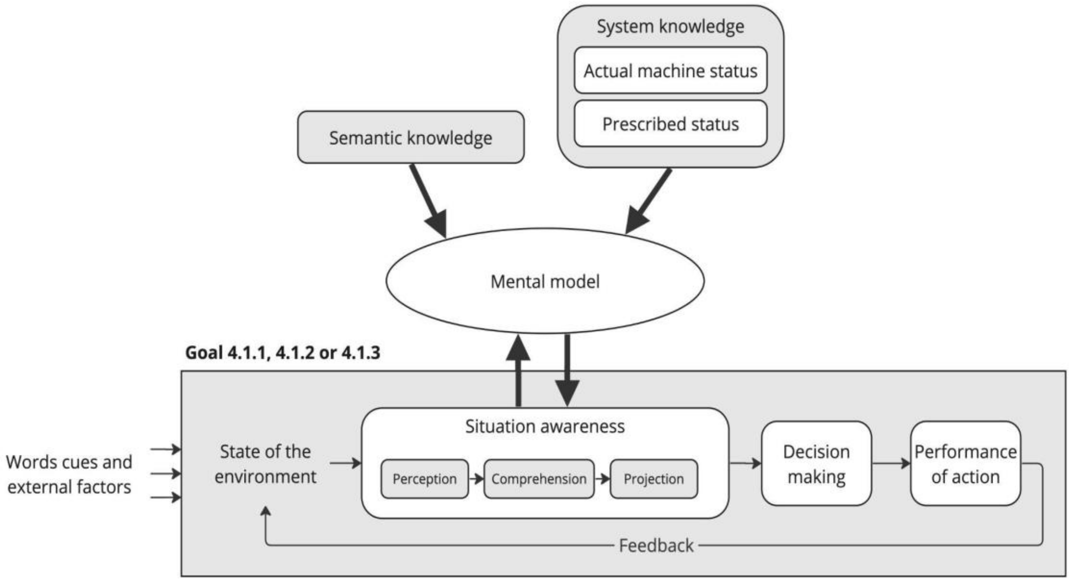

Figure 11 Role of the mental model within the SA model. (Adapted from Endsley and Jone 2012: 21)

5.4. Design guidelines

Guided by the action levers, a list of design guidelines has been compiled, abstract enough to be generalisable and partially transposed from Endsley and Jones (2012) (Appendix A, Table 1). Intended for HMI designers, they are specifically dedicated to designing interfaces for the manual tool loading operation on CNC machines.

Design guidelines are detailed in Annex F, Table 4.

1. Specify information relating to the operator's objectives
2. Provide the operator with a standard, predictable route
3. Facilitate visual representation of machine status in real-time
4. Refer to familiar tool names
5. Clearly identify the mode of the system the operator is in
6. Focus on visual recognition of tools
7. Reduce the need to go back and forth between screens and the proliferation of menus
8. Reassure and guide the operator
9. Minimise complexity
10. Standardise the interfaces
11. Limit manual transcriptions and mental calculations

12. Specify explicitly where information is missing
13. Do not rely on alarms to guide the operator
14. Limit screen density
15. Anticipating the implementation of new functionalities

5.5. Future work

Validation by experts could not be carried out due to time constraints. However, ensuring that best practice is relevant and operational for HMI designers is essential. The next phase of the project will involve validating the results of this research work by conducting interviews with experts and focus groups.

The project has also highlighted the importance of SA in the industrial context and a significant need for design guidelines intended for HMI designers. This work could be continued by analysing other tasks requiring the machine interface.

6. LIMITATIONS

Because of the difficulty of accessing them, this work is based solely on two case studies. In addition, contextual interviews were only conducted with experts, not real operators. Additional cases from other machine manufacturers involving real operators would be necessary to obtain more generalizable results.

The two manufacturers' technological maturity level is relatively similar (see HTA). The validity of the theoretical model and, therefore, some of the best practices is highly dependent on the technologies used by the manufacturers.

7. CONCLUSION

This work was carried out to determine whether and how the interface can support the operators' SA during this maintenance operation. An in-depth analysis of the operator's activity using the GDTA method enabled us to theorise his cognitive functioning. The stages with a high cognitive component were identified, requiring a high level of attention, and making considerable demands on the operator's working memory. The data confirmed that it is during these stages that critical errors occur.
Comparing the GDTAs of the case studies enabled the creation of a high-level theoretical model to illustrate how this works. We can see that the mental image created by the operator plays a central role. Five action levers were defined, based on which a list of 15 best practices for HMI designers was compiled to reduce the cognitive load and, consequently, the risk of critical operator error.

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I would like to extend my warmest thanks to the people who made it possible to conduct the observations within the two companies by giving up their time. Although I cannot name them explicitly for reasons of confidentiality, I hope that they will be able to recognise themselves.

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APPENDIX

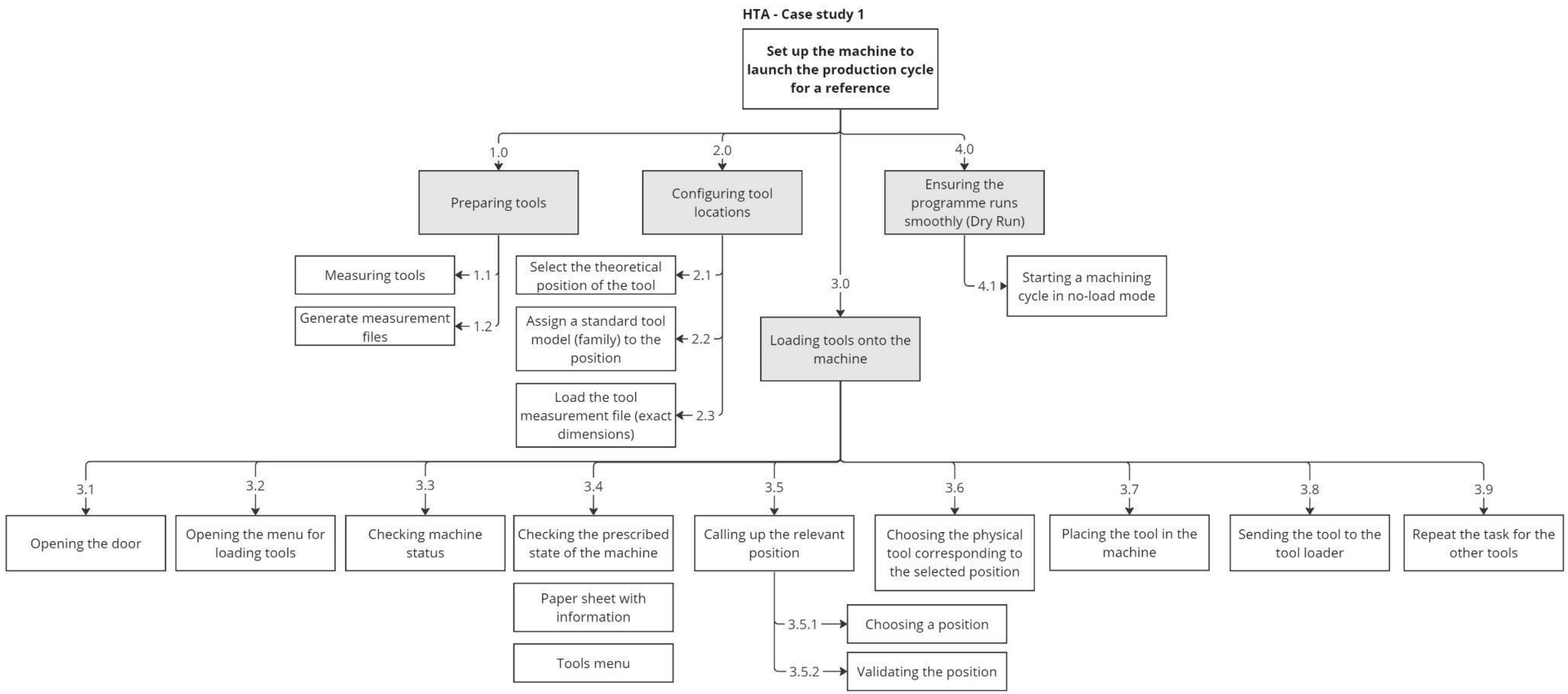
Appendix A, Selection of existing design guidelines

Table 3 Author's selection of design guidelines proposed by Endsley and Jones (2012)

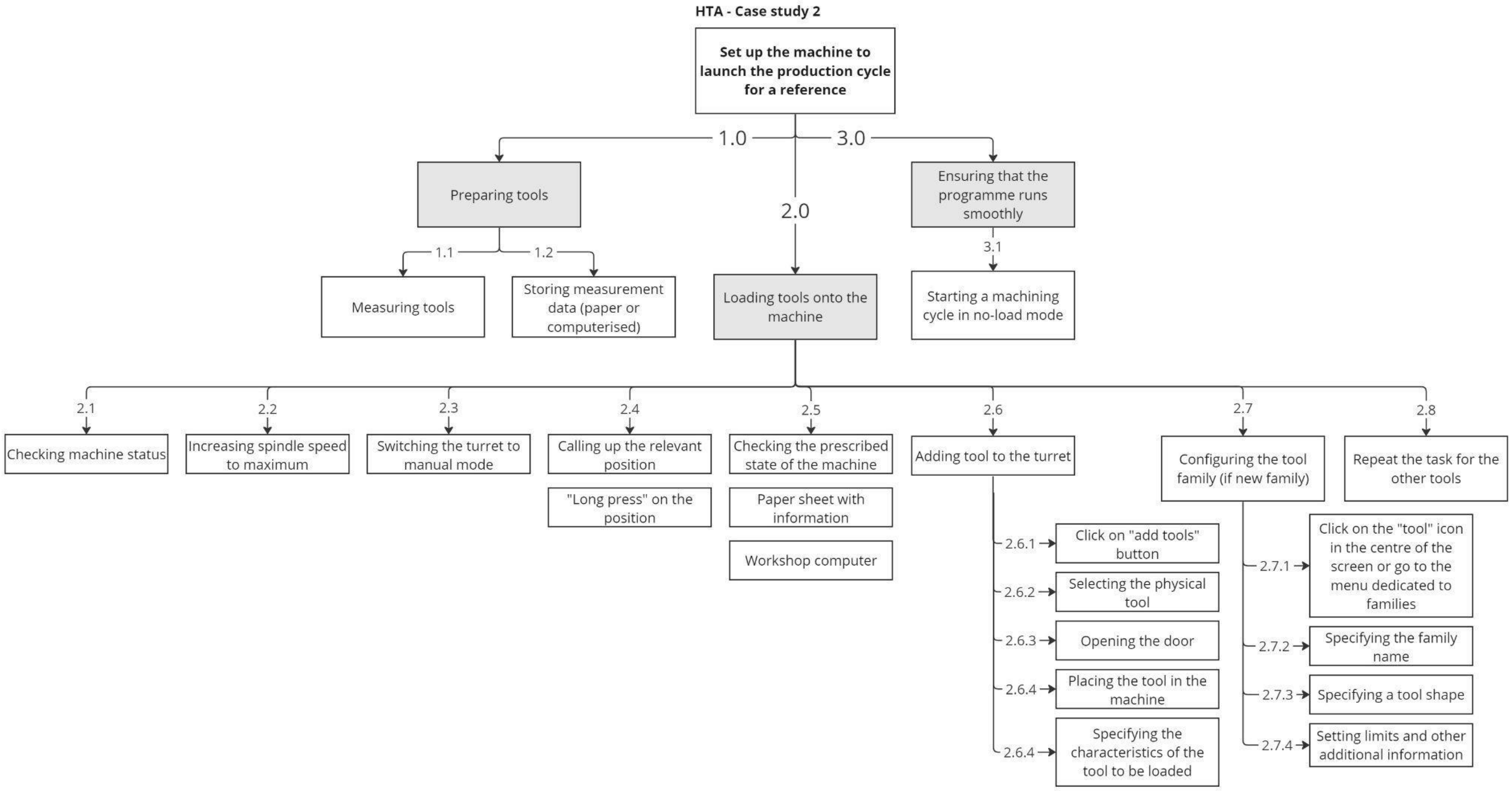
Title		Summary	Reference(s)
1	Support global situation awareness	Avoid drawing attention to a subset of information that contributes to narrowing attention. This is the case with excessive menus or windows, where the operator may miss some critical information, thus undermining the creation of an overall representation of the system.	Endsley and Jones (2012)
2	Organise information around goals and support goal-driven processing	Goal-oriented information displays should group information necessary to make a decision, providing a layout that facilitates for users locating information for each goal.	Endsley and Jones (2012) cited in Oliveira (2016)
3	Provide assistance in projecting future statements	Projecting the system's future state is a mentally demanding process, but it can be facilitated by UIs showing trends in situations or information.	Endsley and Jones (2012) cited in Oliveira (2016)
4	Make critical cues salient	Critical cues for activating mental models through pattern matching should be made evident in the UI.	Endsley and Jones (2012) cited in Oliveira (2016)
5	Manage rampant featurism through prioritisation and flexibility	As systems and features grow, users may get confused by data and feature overload. Besides limiting the number of features to the extreme necessary, managing features occupation of screens (and their salience) and allowing user personalization can be important to allow the collection of features to grow without confusing users.	Endsley and Jones (2012) cited in Oliveira (2016)
6	Use parallel processing capabilities of users	Structuring information among displays to support attention cycling or using different media to present information (auditory, tactile) can improve user's SA acquisition.	Endsley and Jones (2012) cited in Oliveira (2016)
7	Use information filtering carefully	Information not specified by the Cognitive Task Analysis should be dispensed from the User Interface.	Endsley and Jones (2012) cited in Oliveira (2016)
8	Explicitly identify missing information	Clearly indicate where information is missing to avoid misinterpretation.	Endsley and Jones (2012)

9	Insure logical consistency across modes and features	Inconsistencies in the logical functioning of the system dramatically increase complexity.	Endsley and Jones (2012)
10	Map System functions to the goals and mental models of users	Users do not need to understand how the system works to achieve their objectives. Direct support can be provided to help users create a mental model of the system.	Endsley and Jones (2012)
11	Reduce display density but do not sacrifice coherence	Excessive display density can slow down the search and retrieval of needed information.	Endsley and Jones (2012)
12	Minimize task complexity	Limit the number of actions needed to perform the desired task and the complexity of these actions. Requiring the operator to learn and remember a complex series of actions to perform a task adds cognitive load to the operator and leaves room for error.	Endsley and Jones (2012)
13	Provide consistency and standardisation on controls across different displays and systems	The predictability reduces the cognitive load. Standardisation helps to build a mental model.	Endsley and Jones (2012)
14	Provide system transparency and observability	The interface should show the user what the system is doing, why it is doing and what it will do next.	Endsley and Jones (2012)
15	Do not make people reliant on alarms; provide projection support	The alarm adds stress. The interface should provide information to be proactive and to help users project the future state of the machine.	Endsley and Jones (2012)
16	Make mode and system states salient	Mode status is a key piece of information that can affect how other information is interpreted and what expectations for systems behaviour the operator generates.	Endsley and Jones (2012)

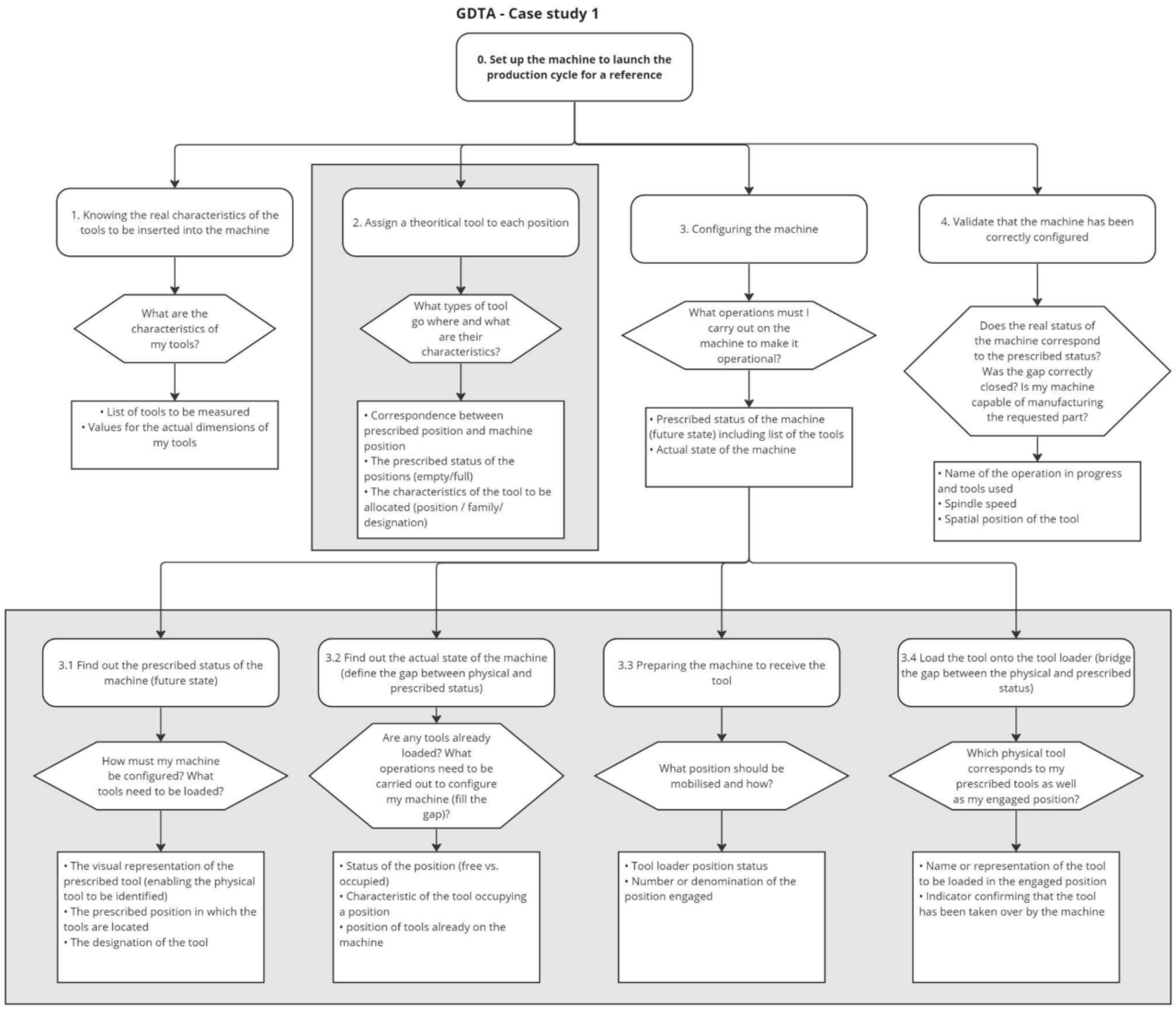
Appendix B, HTA Case study 1



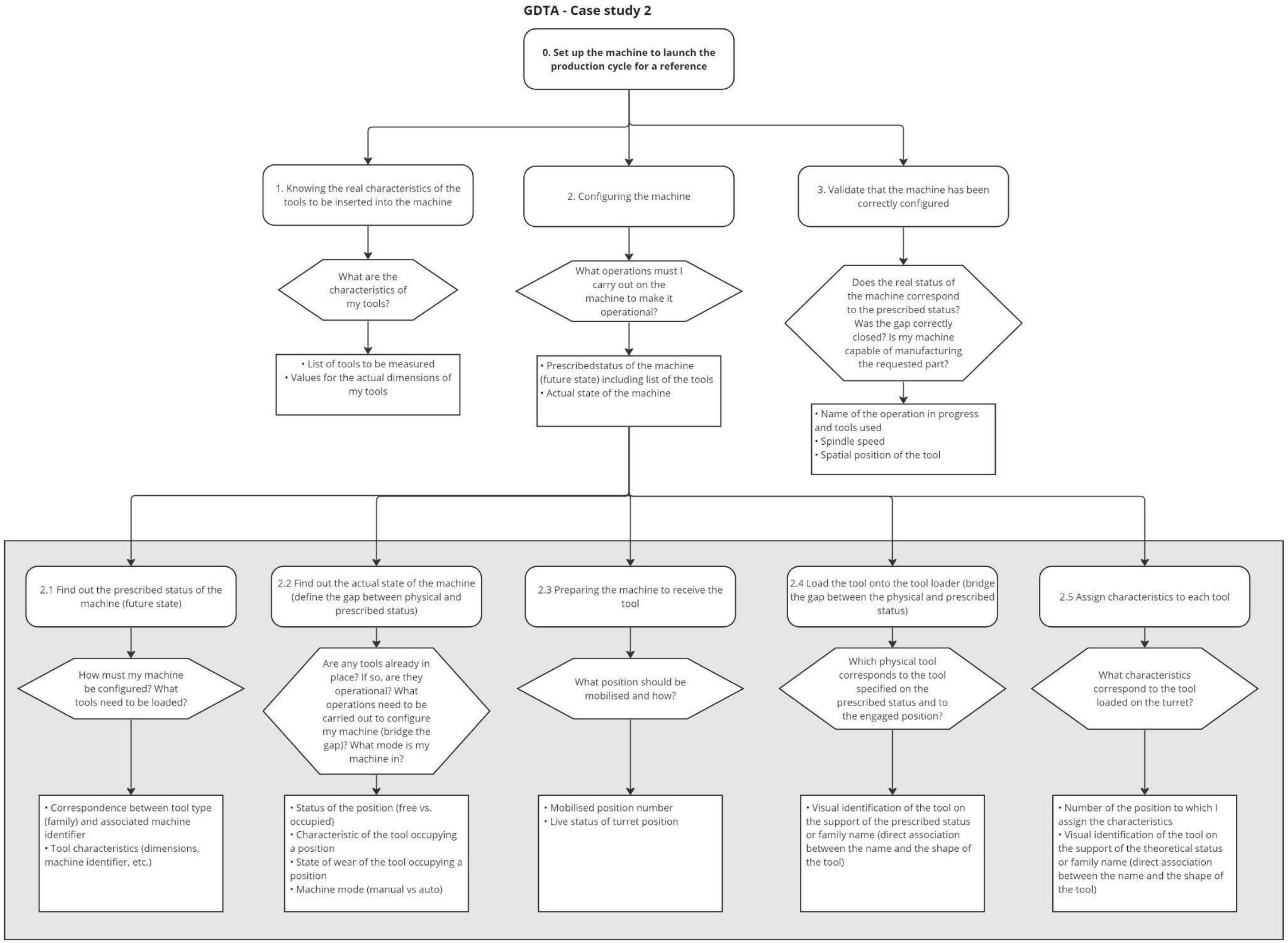
Appendix C, HTA Case study 2



Appendix D, GDTA Case study 1



Appendix E, GDTA Case study 2



Appendix F, Detailed list of design guidelines for manual tool loading operation on CNC machine

Table 4 The detailed list of design guideline, partly transposed from the heuristics of Endsley and Jones (2012)

1	**Specify information relating to the operator's objectives**
	The interface should only present information that enables the operator to achieve his/her objectives and supports decision-making. Select information carefully based on the objectives specified in the theoretical model.
2	**Provide the operator with a standard, predictable route**
	Providing the operator with a single, predictable path reduces cognitive load and assists the operator in the planning stage. Limit the possibility of sequencing variations relative to the theoretical model.
3	**Facilitate visual representation of machine status in real-time**
	The interface must be able to communicate to the operator the status of the machine (e.g. mode, machine position, tool loaded or not), what it is doing and why, through appropriate feedback. Make information appear in a logical and natural order that corresponds to the actual state of the machine and give preference to visual representations.
4	**Refer to familiar tool names**
	The way operators name their tools is often specific to the company or to their own practice. They should not be forced to learn and use the identifiers that the machine needs. Allow the operator to use familiar language rather than system-oriented terms. This will facilitate the link between the machine's prescribed and actual status.
5	**Clearly identify the mode of the system the operator is in**
	The system mode must be clearly identifiable. It must enable the operator to situate his actions in the mental representation s/he has of the system, thereby facilitating the interpretation of the information communicated to him/her. Make sure the operator is aware of the mode in which s/he is operating by using visual elements or dialogue boxes.
6	**Focus on visual recognition of tools**
	Images convey information quickly and effectively. Wherever possible, use visual diagrams to help identify physical tools.
7	**Reduce the need to go back and forth between screens and the proliferation of menus.**
	The overall representation of the system will be enhanced by grouping the information needed to make decisions. Avoid having to switch windows to access critical information.
8	**Reassure and guide the operator**
	The operator must not be in any doubt when undertaking an action. Use appropriate wording and feedback. Guide the operator when the objective involves a large succession of tasks to be carried out in a specific order.

9	**Minimise complexity**
	Asking the operator to remember a series of complex actions adds a significant cognitive load. Minimise the number of actions required to achieve a goal.
10	**Standardise the interfaces**
	The standardisation of interfaces facilitates the creation of a mental representation of the system and limits the number of errors. The operator must be able to recognise (long-term memory training) rather than having to memorise (short-term memory). Standardise processes, graphics and interactions.
11	**Limit manual transcriptions and mental calculations**
	Manual data transcriptions (e.g. tool measurement) and mental calculations place heavy demands on the operator's working memory. Prefer the use of automatic transcription via data import and assisting the operator in his calculations using calculated fields.
12	**Specify explicitly where information is missing**
	Highlight fields where critical data must be provided by the operator.
13	**Do not rely on alarms to guide the operator**
	The operator must not have to make any mistakes to understand how the machine works. The interface must be pro-active and help the user to plan his actions. Restrict the use of alarms to very specific cases, bearing in mind that this will place stress on the operator, thus impairing his/her situational awareness.
14	**Limit screen density**
	A large amount of data on a screen can slow down the search for the information needed to make a decision. Opt for minimalist interfaces without sacrificing coherence. You can also externalise information and use users' parallel processing capabilities (e.g. hearing, peripheral vision).
15	**Anticipating the implementation of new functionalities**
	Technologies evolve very quickly, and HMIs are designed to last. As far as possible, anticipate the introduction of new functionalities such as additional sensors or the automation of certain tasks.