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Augmented Reality Authoring of Digital Twins: Design, Implementation and Evaluation in an Industry 4.0 Context

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2 ABSTRACT

3 This paper deals with Digital Twins (DTs) for Industry 4.0 factories, and their implementation
4 in the context of a reconfigurable factory. This context implies a modification of the layout of the
5 workstations during production, and thus requires a live update of the digital twins according to
6 these modifications. We needed this update done by the operators directly on the workstations
7 using an AR authoring tool. A literature review helped us to determine the criteria that a tool
8 should fulfill in order to achieve this goal. The most important criteria are that the tool should
9 be suitable for use by operators not trained in AR, that the learning curve should be short, and
10 that it should be usable in a reconfigurable factory context. We created a DT containing all the
11 necessary factory data and 3D models of the workstation interaction zones of a real assembly
12 line. We then developed a tool enabling operators to match the DTs with their physical twin (PT)
13 in AR, as well as to update their position in case of a reconfiguration. The experimentation we
14 carried out confirms our analysis and shows us that it is possible to deploy a DT in a factory quite
15 simply if the positioning of the DTs is done by direct manipulation (the 3D objects are co-located
16 with the operator's hand) with the help of an AR display device.

17 **Keywords:** Digital Twin, Augmented Reality, Gestural Interaction, Industry 4.0, AR Authoring

1 INTRODUCTION

18 In a context of industrial evolution (reorganization of production means, need for industrial agility to meet
19 increasingly unpredictable customer demand) and the transition to Industry 4.0, it is important to be able to
20 adapt production lines to demand as well as to train operators to new positions and new ways of working.

21 This problem is common to many companies, and in particular to elm.leblanc¹, a boiler manufacturing
22 factory belonging to the Bosch² group, which sees a strong increase in demand in winter. This increase in

¹ <https://www.elmleblanc.fr/fr/fr/accueil/>

² <https://www.bosch.com/>

23 the number of boilers to be produced leads to the recruitment of temporary operators who can represent up
24 to 50% of the workforce.

25 The training of these new operators is an important process that requires time and human resources.
26 Indeed, during training, an experienced operator is present on each workstation to train a temporary operator.
27 During this time, the assembly line production is not optimal, because the progression and learning curve
28 of each new operator is different. In addition, the experienced operators are focused on training the junior
29 operators, diverting their attention from their main technical production tasks.

30 One of the solutions imagined by elm.leblanc to overcome this training problem is to use Augmented
31 Reality (AR) to train new operators directly on the workstations in complete autonomy. This would allow
32 experienced operators not to manage training in addition of their work.

33 The idea of using AR in an industrial context is not new, and many use cases have been studied. For
34 example, AR can be used to perform remote expert guidance, develop new products by collaborating
35 remotely, or perform an inspection of digital prototypes (Fraga-Lamas et al., 2018). AR is also being
36 used to evaluate workstation ergonomics and equipment accessibility (Berg and Vance, 2017), or to detect
37 manufacturing errors and defects (Barbosa et al., 2016). These uses of AR in industry have a lot of
38 potentials, but the most interesting for our work and most widespread is assembly assistance, with the goal
39 of training (Bottani and Vignali, 2019; Paelke, 2014; Barbosa et al., 2016). It is worth noting that doing
40 assembly and maintenance assistance in AR is more interesting if the staff turnover is high and if the tasks
41 are repetitive (Havard et al., 2021). But in order to properly train operators, it is necessary to have a suitable
42 and well configured assistance tool.

43 This last point is very important given our context of reconfigurable factory, since the layout of the
44 workstation can change during the day. It is necessary to know the functional elements of the workstations,
45 as well as their locations to direct the attention of the user (Funk et al., 2016; Henderson and Feiner, 2011).
46 The most important issue given our context is to keep this tool up to date in the case of a change of reference
47 to be produced during the day (*e.g.*, change of production from boiler A to boiler B), or an update of the
48 workstations (*e.g.*, a box of screw nuts replaced by a box of bolts). One possibility to address the above
49 issues would be to have a complete Digital Twin (DT) of the factory workstations. This DT would contain
50 all the data about the workstations (*e.g.*, items present, quantity, position). The information from this DT
51 would then be used to create, for example, instructions to be visualized in AR and to keep them up to date.

52 However, it is complicated for companies, which often do not have the necessary expertise, to set up DTs.
53 It should be noted that the implementation constraints also depend on the application (*e.g.*, simulations,
54 predictions) that will be made of the DTs (Shao and Helu, 2020).

55 In our case, we are in a reconfigurable factory environment, which means that our workstations can be
56 modified several times in one day, depending on the boiler model to be built. These modifications imply
57 to often modify the DT to match the workstation. It is therefore necessary to make these modifications
58 directly on the assembly line without having to involve other stakeholders (such as method engineers), and
59 therefore gaining a lot of time. Therefore, it is important to involve production staff in the placement and
60 updating of the DTs, as they are the ones who know the workstations best. In this work, we aim to enable
61 operators in a factory to configure and update the DTs on their workstations so that they can ensure that the
62 assembly aid instructions are in the right place. However, the creation of the instructions themselves is not
63 the subject of this article.

64 In the following section, we present the work related to DTs and 3D authoring tools. We then propose,
65 after collecting the needs of users and data from our partner factory, a DT of the factory containing all the

66 important data of the factory, as well as 3D models of important elements, in order to locate them and
67 update their location according to the evolution of the workstations. We then present a tool that we called
68 WARD allowing the production staff to be involved in the process of constructing the DT. We finally detail
69 an experiment of WARD used by the production staff in an industrial environment and its results. Finally,
70 we conclude this article with a discussion of the results obtained, which allow us to conclude that WARD
71 is more efficient than the most industrialized 3D authoring tool of our state of the art: Microsoft Guides.

2 STATE OF THE ART

72 2.1 The concept of Digital Twin

73 The initial concept of the Digital Twin (DT) was defined in 2003 by Michael Grieves during one of
74 his courses at the University of Michigan as "a virtual representation of a physical product containing
75 information about said product". Grieves later extended this definition in 2014 (Grieves, 2014) to define
76 the DT through three components: 1) the physical product in real space, 2) the virtual product which
77 is the representation in virtual space, and 3) the bi-directional data connections that link these two
78 spaces (cf. Figure 1).

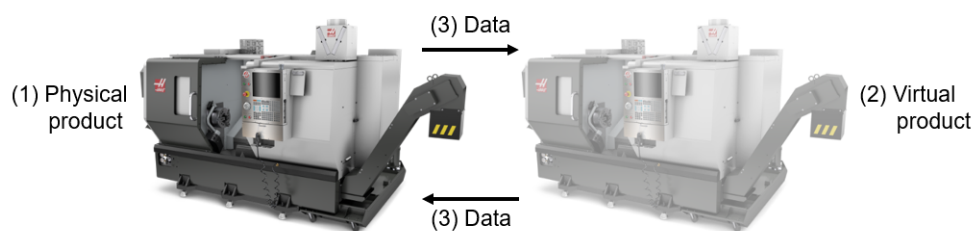


Figure 1. The Digital Twin concept, from Grieves (Grieves, 2014)

79 More precisely, the physical product can be a simple component to be manufactured (*e.g.*, a screw nut) or
80 a complex system comprising several elements working together (*e.g.* an automatic assembly line). The
81 data from the physical space comes from internal or external sensors of the physical product, for example,
82 data on the torque of the bolts screwed on a gasoline reserve, but also the reserve level. Note that the
83 sensors and data collection systems are also part of the physical space.

84 The virtual product is the virtual representation of the physical product. It can be composed of several
85 modules (*i.e.*, 3D model, simulation, testing, optimization) that make it possible to use the data coming
86 from the sensors of the physical space and to send back new data to adjust the production or the settings of
87 a physical machine for example. The data coming from the virtual space are the results of simulations and
88 analyses of the behavioral models of the physical products.

89 Using a DT enables to link a virtual representation to a physical product throughout its lifecycle (Grieves
90 and Vickers, 2016). The physical and virtual environments can then be used together. The available
91 information from the physical product is stored, evaluated, and used in the different modules of the virtual
92 space. A simple analysis of the data enables the monitoring and detecting malfunctions of the physical
93 product for example. The behavioral models produced during the design stages enable simulations to be
94 carried out on the virtual product, which results are used to predict the behavior of the physical product.
95 Overall, this enables to increase the modularity, autonomy and connectivity of the factories (Rosen et al.,
96 2015).

97 2.2 Usage of the Digital Twin in Industry 4.0

98 With the rising of industry 4.0, interest in using the DT in the industrial domain is growing (Jones et al.,
99 2020), with increasingly connected factories using IoT, sensors, big data, and a need for more agility.

100 In industry, there are mainly three fields of application for the DT : 1) predictive management of the state
101 of products or systems, 2) design, 3) production. More secondary fields of application are maintenance
102 support and training support (Tao et al., 2019).

103 The most widespread field of application is predictive management with the simulation and monitoring
104 of the life cycle of a product (a single product or an entire system). The DT will allow to simulate the
105 behavior of the product or a system during the whole duration of its use according to parameters coming
106 from the real product, from the user, or from the technical specificities of the materials (Revetria et al.,
107 2019). The results of these simulations can then be used to adjust or modify parameters on the real product.

108 Having access to these behavioral models and simulations, combined with 3D modeling also enables the
109 virtual design of new products (Guitard et al., 2020). Furthermore, using a DT enables the virtual design
110 and ergonomic assessment of workstations and production lines (Havard et al., 2019).

111 As far as production is concerned, the DT enables the monitoring and the anticipation of problems thanks
112 to the simulation models of the production lines. This allows to optimize the changes of references to
113 be produced and to modify the layout of the factories. This last point is very interesting in the case of
114 reconfigurable factories. Using a DT allows to evaluate the different reconfigurations and their gains. For
115 this purpose, simulation models of the production lines are used (Yang et al., 2022; Zhang et al., 2019). DTs
116 are very useful in the case of smart factories, where the assembly lines are fully connected through IoT to a
117 cyber-physical system. The DT will use data from the workstations and production orders to evaluate the
118 best configuration, and send instructions to reconfigure the assembly line (manually or automatically) (Leng
119 et al., 2020b, 2019b, 2020a), or commission new ones (Leng et al., 2021b). The DT can also be used in
120 different parts of the factory, like the warehouse, where the DT can be used to optimize the layout and
121 storage of spare parts and materials according to their date and frequency of use (Leng et al., 2019a).

122 Still on the subject of production, the DT makes it possible to detect malfunctions during production and
123 to test different corrections virtually before sending possible corrections, or proposing optimizations (Leng
124 et al., 2021a; Liu et al., 2018).

125 However, deploying a DT of this scale requires a lot of sensors and IoT on the factory equipment, which
126 is why the term smart factory is used. It is difficult to implement the entire system described in the articles
127 above in an existing plant where most actions are performed by a human operator. These factories are often
128 old, there is very few sensors available and compatible with the current systems, and the documentation
129 about the technical operations is hard to translate into a simulation model for the DT. It would be very
130 expensive and long to equip a factory with enough sensors and activators to cover the whole production.

131 Many of the uses of DT in industry rely on these simulation and behavior models, as well as numerous
132 sensors for monitoring and updating the DT in real time. However, the implementation and updating of the
133 DT is often overlooked, especially the matching of the DT position with its Physical Twin.

134 In light of these problems, we aim to contribute to the use of the DT in production, and more precisely in
135 its implementation and updates to match the production lines layout evolution. As a reminder, our work
136 takes place in a elm.leblanc factory which is a reconfigurable factory, where changes in the production are
137 planned for the day, which implies that the reconfiguration of workstations are also planned. The gains
138 were evaluated beforehand during the creation of the workstations and the production planning. We mainly

139 have to be able to easily create the DT of the workstations and match the DT with the Physical Twin (PT)
140 in their different configurations. Although the factory is old and has almost no IoT, we still aim to offer a
141 usable solution, which is not really explored in the articles quoted above. We need to be able to interact
142 with the DTs to update their location in accordance with their PTs location.

143 In order to achieve our goal, we have to overcome some issues of DTs, such as the use and generation of
144 a huge amount of data that is not always easy to visualize, sort and store, and difficulties to interact with
145 the DTs (Guitard et al., 2020).

146 **2.3 Combining Digital Twin and Mixed Reality**

147 In order to tackle some of the issues we discussed in the section above, we propose to use Virtual Reality
148 (VR) and Augmented Reality (AR) devices to visualize the DT and to interact with it.

149 Therefore, the use of immersive Virtual Environments (VEs) applied to DTs enables new uses, such as
150 the monitoring of production optimization tasks, training and maintenance assistance (Ke et al., 2019).
151 Thus, the optimization of production can be done with simulation models of activities of a chain. The
152 visualization of this system with the help of a VE allows to check the correct operation of the simulation or
153 even to modify certain parameters in real time (Lyonnet and Toscano, 2016). This then enables to adjust
154 the production according to the results of these simulations.

155 DT also enable to simplify maintenance operations thanks to VEs. The latter enable to display the
156 information coming from the PT (*e.g.*, sensors) and DT (*e.g.*, simulation results) directly on the PT to guide
157 the operators (Schroeder et al., 2016; Zhu et al., 2019; Rabah et al., 2018).

158 Finally, the use of a DT associated with a 3D model of its PT makes it possible to simulate workstations in
159 VEs, not only to train operators in their jobs but also to validate the ergonomics of the workstations (Havard
160 et al., 2019). Moreover, having a 3D model of the workstations corresponding to the real ones allows to
161 determine where technical instructions for novice operators should be positioned (Noël et al., 2020).

162 Our work is particularly focused on this last point related to the matching of 3D models and the real
163 workstation. Indeed, elm.leblanc aims at proposing scenarios to train operators thanks to the display of
164 technical instructions in AR. To do so, we need to identify the important elements of the workstations,
165 then implement the DT of the workstations, and match the DTs with their PT, and thus allow instructions
166 related to the workstation elements to be attached to the DT. However, the use of a DT within a production
167 environment implies time constraints and constant updating of the DT. It would be more efficient to allow
168 operators to directly perform updates to the DTs of the workstations without having to involve other
169 stakeholders (such as methods engineers). Therefore, we propose to explore the various tools for creating
170 and editing content for VR/AR in the following subsection.

171 **2.4 3D Authoring tools**

172 As we saw in the previous section, we need to be able to place DTs on their PTs, and easily update their
173 position. Therefore, we propose to study the different tools that allow to create 3D content for VR/AR.

174 3D models of workstations, components and machines are already used in the industrial field to design
175 new products, test the layout of workstations, or evaluate their ergonomics (Berg and Vance, 2017).
176 These models are generally realized thanks to CAD or 3D creation tools (such as SolidWorks³, Inventor⁴,

³ <https://www.solidworks.com/>

⁴ <https://www.autodesk.com/products/inventor/overview>

177 3dsMax⁵ or Maya⁶). These tools are very powerful because they allow you to create very precise 3D
 178 models, but they take a long time to learn and require advanced skills in 3D modeling (Kostic, 2012).
 179 Moreover they generally require to make all the modeling on computer. This implies alternating between
 180 the use of a visualization device in AR to check the conformity of the 3D model (and the DT) compared
 181 to its PT, and the return to the modeling tool on the computer to make the necessary modifications. Note
 182 that it is possible to use existing frameworks for content creation for AR such as APRIL (Ledermann and
 183 Schmalstieg, 2005) or Vuforia⁷, but they are generally complex to use and require knowledge in computer
 184 science, XML for APRIL and C# for Vuforia (Bégout et al., 2020). The need to have knowledge of 3D
 185 modelling or computer development does not allow operators to carry out the placement, which is our main
 186 criteria to evaluate the different tools.

187 To achieve this goal, we have studied tools based on a graphical interface, which does not require
 188 advanced technical knowledge of 3D modelling and computer development. In ACARS (Zhu et al., 2013),
 189 for example, AR content is created on the computer by an industry expert (*e.g.*, a method engineer who
 190 creates assembly lines) using a 3D model of the equipment and placing 3D elements around that model.
 191 The operator can then make changes in AR using a tracked physical object as a cursor (*cf.* Figure 2(a)).

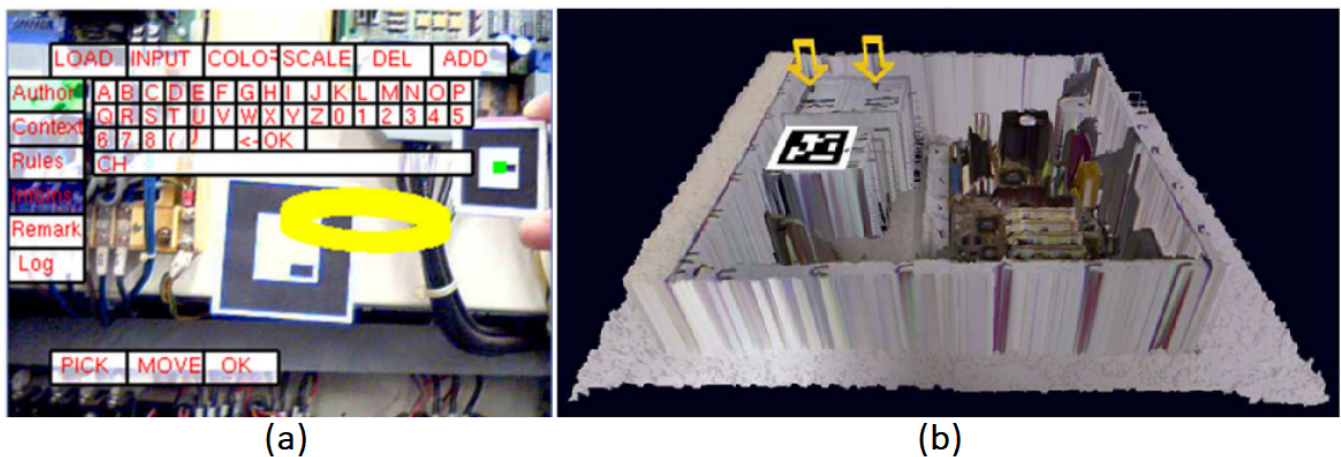


Figure 2. (a) Editing content in ACARS (Zhu et al., 2013), (b) Editing AR content in SUGAR (Gimeno et al., 2013)

192 AR content creation is also computer-based in SUGAR (Gimeno et al., 2013). Photos of workstations
 193 containing depth data are used to place 3D models and instructions by an expert (*cf.* Figure 2(b)).

194 It is also an expert who creates the content in ARAUM (Erkoyuncu et al., 2017). He enters information
 195 about the technical operations into the tool. This information will then be displayed in AR around the
 196 workstation thanks to the spatial, temporal and positioning context of the user.

197 In these tools, the placement of the 3D models is done by an expert on the computer, which is complicated
 198 to set up for use by assembly line operators. In addition, the placement of the models cannot be modified
 199 once deployed in AR except for ACARS. It is therefore more complicated to update the models. Unlike the
 200 previous tools, non-expert users create the content for AR in Meta-AR-App (Villanueva et al., 2020) by

⁵ <https://www.autodesk.com/products/3ds-max/overview>

⁶ <https://www.autodesk.com/products/maya/overview>

⁷ <https://developer.vuforia.com/>

201 dragging simple 3D models into the work area. Again the authoring is done on the computer and is not
202 editable once deployed. This is an issue because of the time constraints in our industrial context. We need
203 to be able to perform the authoring directly on the assembly line, in AR, using a Head Mounted Display
204 (HMD).

205 For exemple, a tool like INSITER (Riexinger et al., 2018), which is based on the BIM (Building
206 Information Model) of the factory and uses the available 3D models. The overlay of the 3D model on the
207 real one is done by environment and object recognition and modules that can track several AR markers.
208 This method is interesting if we can have precise 3D models of the workstations so that the environment
209 recognition works, as well as a very complete BIM. These requirements are difficult to meet for many
210 factories, which are either old, partially modeled, or reconfigurable.

211 Finally, some commercially available tools exploiting AR exist, such as Microsoft Guides⁸. This tool
212 allows the creation of AR learning scenarios through a computer-based module and an AR placement
213 module. The computer-based module creates the instructional panels and adds the 3D models to be placed
214 on the workstation. The AR module then allows to place the 3D models linked to the different instructions,
215 through a distant manipulation of AR elements using the raycast starting from its palm. Here again, the
216 authoring is done by an expert for the creation of scenarios, and the modeling of a workstation is very time
217 consuming, which is not acceptable in our use case.

218 All these tools allow us to create 3D content for AR in different ways and with different possibilities.
219 However, they do not all fulfil the criteria that we consider important for operators to achieve the placement
220 of DTs. These criteria are the following (see table 1):

- 221 • Digital Twin placement: we can place the workstation DTs with the tool.
- 222 • GUI-based: it should be possible to use the tool throughout a graphical interface without requiring any
223 knowledge about programming.
- 224 • HMD compliant: it must be possible to use an AR HMD to visualize the DTs.
- 225 • AR authoring: the modification of the DTs placement should be doable directly in AR and not require
226 additional material (such as a computer for example).
- 227 • Usable by operators: operators should be able to realize the placement of the DTs with the tool without
228 the intervention of another stakeholder.
- 229 • Short learning time: users should be able to learn quickly how to use the tool to place DTs.
- 230 • Reconfigurable factory compliant: the tool must be suitable for a reconfigurable factory context, and
231 should provide easy ways to update the DTs in case of a production change.

232 A good tool should fulfill all these criteria, and many tools fulfill the first 4 ones, so we will focus on
233 the last 3 which are particularly important in our opinion to enable operators to perform quick and easy
234 placement and updating of DTs. Since none of the tools we discussed in the state of the art fulfills all these
235 criteria, therefore, we need a new tool, focused on the ease of use by production staff, by simplifying the
236 interactions as much as possible. We also need to focus on the presentation of the DTs, to be sure not
237 clutter the user's field of view. Data management and the creation/retrieval of 3D models should not be the
238 responsibility of any such AR authoring tool, only leaving the placement to be managed by the users.

⁸ <https://dynamics.microsoft.com/en-us/mixed-reality/guides/>

	SolidWorks	3dsMax	Autodesk	Maya	APRIL	Vuforia	ACARS	SUGAR	ARAUM	META-AR-App	INSITER	Guides
Digital Twins placement	○	○	○	○	○	○	○	○	○	○	○	○
GUI-based	○	○	○	○	×	×	○	○	○	○	×	○
HMD compliant	×	×	×	×	×	○	○	×	○	×	○	○
AR authoring	×	×	×	×	×	×	○	×	×	×	×	○
Usable by operators	×	×	×	×	×	×	×	×	×	○	×	?
Short learning time	×	×	×	×	×	×	×	×	×	○	×	?
Reconfigurable factory compliant	×	×	×	×	×	×	×	×	×	×	×	×

Table 1. Summary of the main features of 3D authoring tools suited for AR matching of Digital Twins

239 In the next section we will explore the collection of user needs which influenced our choices on the
 240 structure of the factory DT, and to the development of WARD, our authoring tool developed to fulfil all the
 241 criteria we discussed.

3 COLLECTION OF THE USERS NEEDS

242 In order to create a faithful DT and to match it with the PT, it is first necessary to determine and know
 243 the different information related to the workstations (*e.g.*, the layout of the workstations, components and
 244 tools present on the workstation, the presence of test benches, assembly benches or machines). These are
 245 the elements we need to locate precisely and the ones we will match with a DT. As we are in the context
 246 of a reconfigurable factory, the layout of the workstations can change during the workday (*e.g.*, some
 247 component boxes can change position or be replaced). It is therefore important to know these different
 248 layouts and adapt the DT accordingly. That is why the operators need to be able to perform the update
 249 of the DT directly on their workstation, without using a lot of equipment. They also need to be able to
 250 perform these updates quickly.

251 We therefore carried out observations in the factory to determine which elements of the workstations
 252 the operators interact with, as well as the elements that are modified during a reference change. We first
 253 observed operators during their work on an assembly line. We spent an entire shift observing them and
 254 taking notes and pictures, to see the way they interact with the workstations. We then assembled a boiler
 255 using the instruction sheets to see for ourselves the difficulties a new operator might encounter. Finally, we
 256 analyzes the BOM (Bill Of Materials) files to see what data was available about the workstations.

257 Using our observations and the available data, we determined the following interaction zones that needs
 258 to be located precisely (see figure 3):

- 259 1. The "supermarket" which is a shelf containing the following items:
 - 260 a. The component bins (*e.g.*, a box containing nuts).
 - 261 • The components themselves (*e.g.*, nuts).
 - 262 b. The bulky components (*e.g.*, heating elements).
- 263 2. The tools present on the station (*e.g.*, screwdrivers, riveters)
- 264 3. The assembly area which is composed of several elements which can be present on a workstation:

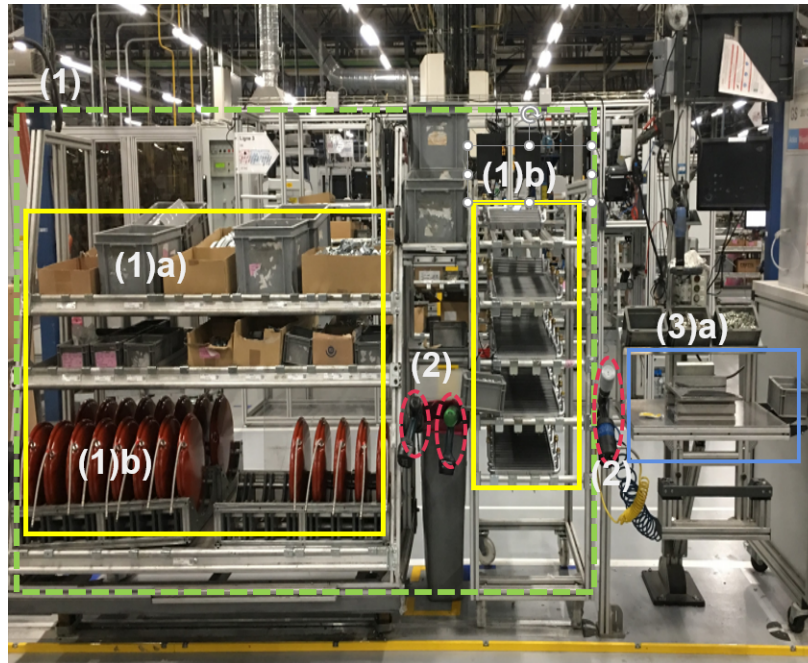


Figure 3. Visualization of the interaction zones of a boiler assembly workstation in an elm.leblanc factory

- 265 a. The assembly bench which is an area on which the operator assembles components before integrating
 266 them into the boiler (e.g., an assembly support for the boiler body).
 267 b. The test bench that allows the boilers to be tested for compliance (e.g., leak test, electrical component
 268 test) not visible on the figure 3 because only a few stations have them.

269 We need to be able to locate these interaction zones very precisely. Therefore the DT of these interaction
 270 zones must perfectly match the PT. These DTs will then serve as spatial anchors to AR instructions. This
 271 will ensure that the attached AR instructions are well positioned, and to make sure the instructions follow
 272 in case of a layout modification, since the DT will match the new layout.

273 Using these observations, we worked on the development of the DT, which will be the base of our WARD
 274 tool. It will be the back-end of the tool and serve as the base for all AR operations.

4 DESIGNING THE FACTORY WORKSTATIONS DIGITAL TWINS AND THE AR PLACEMENT TOOL

275 Following this collection of requirements and the analysis of the state of the art, we have extracted
 276 the principles to be respected for the creation of factory DT. The structure of the factory DT and the
 277 workstations DT must mirror the real structure. The important elements of the workstations (i.e. the
 278 interaction areas) must be precisely located and correspond to the location of the real element. Finally,
 279 updating the position of the digital twins must be simple to achieve.

280 We have taken these principles into account when creating our DT, based on the observations made
 281 in the previous section and the available data. Our DT contains all the data regarding the factory, their
 282 workstations and their elements, including their 3D models when necessary.

283 We then present WARD (Workstation Augmented Reality Digital twin), an AR tool we developed to
 284 allow operators to match the DTs of the interaction zones with their PT, directly on the assembly line.

285 4.1 Implementing the Digital Twin of the workstations

286 To achieve our goal of matching the DT of workstations with their PT, we have created a database that
 287 contains information about the composition of the factory: the relationships between the assembly lines,
 288 workstations, their composition (*i.e.*, the interactions zones). We need to be able to locate those interaction
 289 zones precisely. To achieve this goal, we propose to use a 3D model of the interaction zone to visualize it
 290 in AR and place it at the right location on the workstation. The location of the DT and its 3D model will
 291 then be saved in the database. In this case, using AR allows us to realize the placement task directly on the
 292 workstation.

293 The database contains all the information regarding the different elements of the factory. Each element
 294 of the factory, its assembly lines and workstations are saved in the database. The composition of the
 295 workstations are also saved in the database following the model in Figure 4 (a). This model is based on the
 296 observations detailed in the previous section. In this model, a factory is composed of assembly lines, which
 297 are composed of workstations. The workstations are composed of a supermarket, tools and the assembly
 298 zone. The supermarket is composed of the component boxes which contain the components, and the bulky
 299 components. The assembly zone can be composed of a workbench and a test bench. The factory data that
 300 fills this database comes from the BOM (Bill Of Materials) files provided by the production engineers, as
 301 well as from the workstation sheets. For example, the "Boiler Body Assembly" workstation is part of the
 302 second assembly line of the elm.leblanc factory. It is composed of a supermarket containing 20 component
 303 bins, each containing 50 components. It also consists of a boiler body assembly bench, a screwdriver and a
 304 riveter (see Figure 4 (b)).

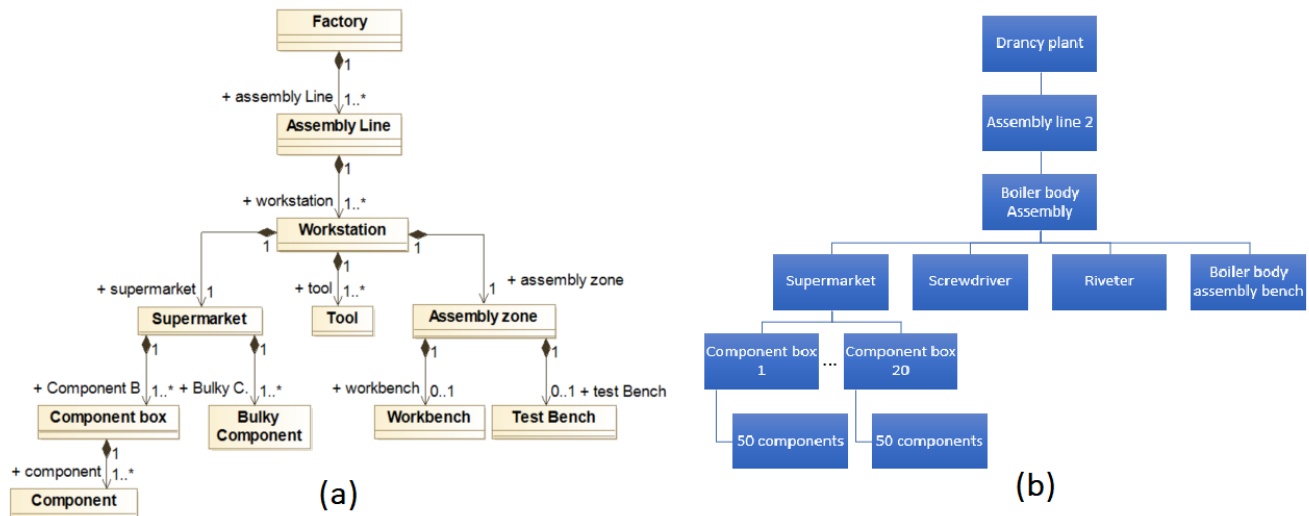


Figure 4. (a) UML diagram of the factory composition, (b) example of the instantiation of the "Boiler body assembly" workstation

305 Once the plant data was created, we needed a way to accurately locate our interaction zones and easily
 306 update their position. Therefore, each interaction zone also has a 3D model representing it (*cf.* Figure 5),
 307 which is part of the DT. The location of the 3D model has to be the same as the real interaction zone, and it
 308 can be easily moved by an operator in case of an update of the station. The link between the 3D model and
 309 the interaction zone in the database is made by using the ID of the interaction zone in the database.

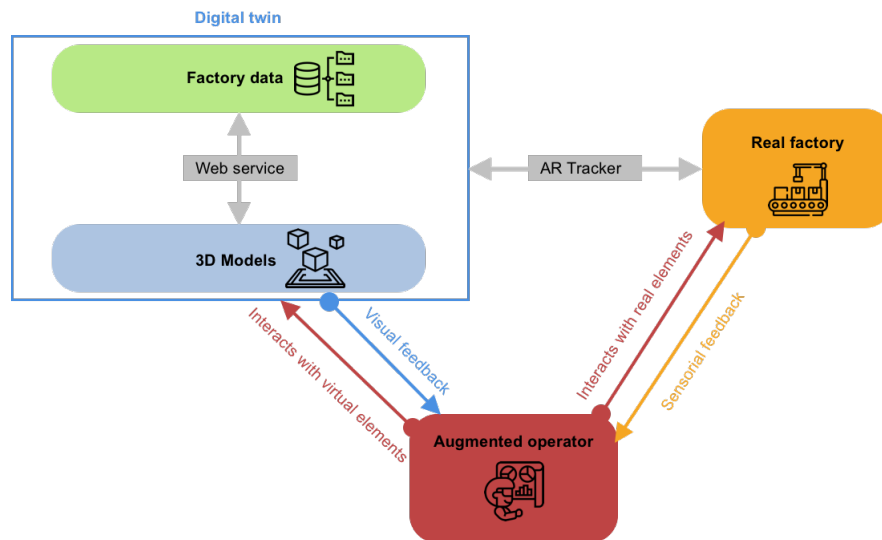


Figure 5. Architecture of our model: Integration of the augmented operator within the relationship between the Digital and Physical Twin and their bi-directional relationship

310 In our architecture model (Figure 5), both parts of the DT (3D models and factory data) communicate
 311 through a WebService. We made this choice because we cannot store all the necessary data in the AR
 312 visualization device. Therefore, we need to access the data dynamically to load only the data needed for the
 313 task at hand. Only the DT of the interaction zones are displayed, and the information about their location
 314 are updated through the webservice. The link between each interaction zone and its DT is done with the
 315 help of an AR tracker (in our case, a QR code positioned on the workstation and referenced in a database).
 316 Interaction with the DT is done by an "augmented operator" (*i.e.*, an operator with an AR visualization
 317 helmet). He will interact with the 3D models of the interaction zones to place them at the right location. In
 318 case of an update of the workstation, the position of the DT should follow the PT thanks to the AR tracking.
 319 It is important to note that until the end of this article, what we call DT refers to the data of the DT as well
 320 as its 3D model, which will be visualised and manipulated by the operators.

321 After the creation of the factory DT, we developed the AR application enabling the operators to become
 322 augmented operators who can perform the authoring task. The goal of this application is to enable the
 323 operators to visualize the interaction zones DTs and to manipulate them to match them with their PT. Since
 324 the future users of this application are not trained to use AR, and considering the concepts we discussed in
 325 the state of the art, we made sure to propose very simple and natural interactions with UI and the DTs, and
 326 we have been careful not to display too much information to avoid overloading the user's field of view.

327 4.2 WARD (Workstation Augmented Reality Digital twin)

328 As said previously, we aim to develop an AR authoring tool to enable operators to perform the matching
 329 of the workstation DT with its PT. With our industrial context of a reconfigurable factory, the operators
 330 need to be able to update the DT in accordance with the evolution of the workstation. Therefore, we focused
 331 on the ease of use of our application, since the operators (workers who assemble boilers in our case, with
 332 no knowledge in AR) are not yet trained to use AR. Furthermore, since the placement of the DTs doesn't
 333 require the involvement of other stakeholders (*e.g.*, methods engineers), it should reduce the needed time to
 334 set up the DT.

335 So we developed an application for HoloLens 2⁹ with Unity3D¹⁰ using MRTK¹¹. We called this tool
 336 WARD (Workstation Augmented Reality Digital twin). Operators will use WARD when configuring
 337 a workstation for training. Before creating the instructions (let's remember that the creation and the
 338 visualization of the instructions are done with another tool that is not the subject of this article), the DTs of
 339 the workstation interaction zones must be superimposed to their PTs. This application enables operators to
 340 1) detect a workstation 2) to manipulate the DTs of the interaction zones of the workstation 3) to overlay
 341 them on their PTs.

342 The use of WARD is exclusively in AR. To start the placement process, the operator has to detect the
 343 workstation. He will use the depth camera from the HMD to scan the QR code of the workstation he is
 344 working on. Once the QR code is identified, the application will query the Webservice to determine the
 345 workstation on which the operator is working, and retrieve the information from the DT. The application
 346 will get all information about the workstation, which assembly line it belongs to and which interaction
 347 zones are present. Note that all this is transparent for the operator.

348 Once the information is retrieved, the application will determine if the DTs have already been placed.
 349 The application will check in the database if there is a saved location for each interaction zone. If the DTs
 350 are already placed, it will display them at the saved location so that the operator can visualize them and
 351 interact with them (*cf.* Figure 6(a)). The operator can update their position by grabbing the 3D models
 352 directly with its hands and move them at the right location if needed (see Figure 6(b) and (c)).

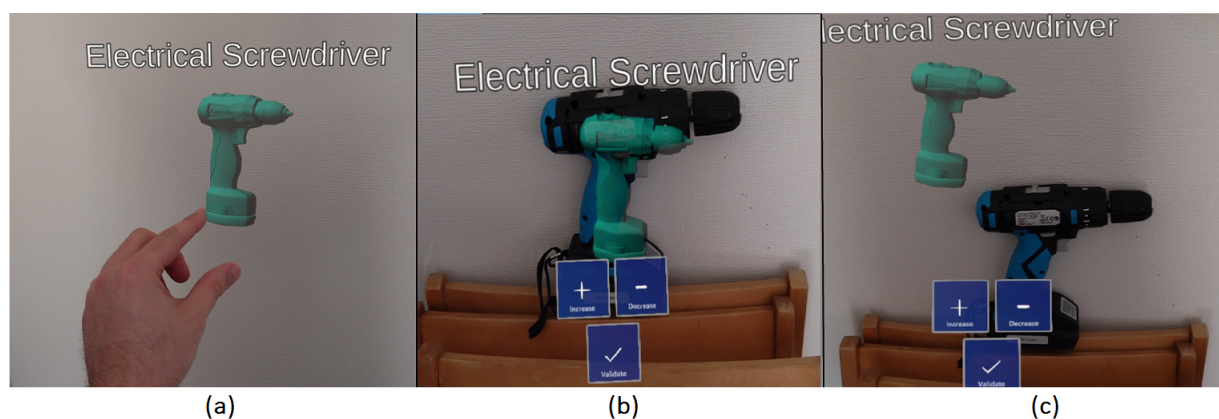


Figure 6. (a) Interaction with a DT in WARD, (b) DT placed at the right location in WARD, (c) Misplaced DT in WARD

353 If the DTs have not been positioned, they will be presented one by one to the operator to be placed on
 354 their corresponding PTs. The operator will grab the first one and place it at the location of its PT. He will
 355 then validate the position by pressing the button located in the floating menu at the bottom (*cf.* Figure 6(b)
 356 and (c)). The first DT will disappear and the next one will appear to be placed. Once every DT is placed,
 357 their position relative to the QR code is saved in the database, and every DTs are displayed in order to check
 358 the positioning and correct potential placement mistakes. All these steps for using WARD are summarised
 359 in the BPMN diagram in Figure 7.

⁹ <https://www.microsoft.com/fr-fr/hololens>

¹⁰ <https://unity.com/>

¹¹ <https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/?view=mrtkunity-2021-05>

360 Regarding user interactions in WARD, we have chosen to propose simple interactions such as such as
 361 grabbing 3D elements and pressing AR buttons because the operators are not trained to use AR devices
 362 and they need to be able to perform the placement tasks as quick as possible. We also chose to hide the
 363 previously placed DTs to avoid the overloading of the operator field of view. It was indeed reported to us
 364 during pre-testing by operators that the previous DTs were getting in the way, and that they had trouble
 365 placing the DTs.

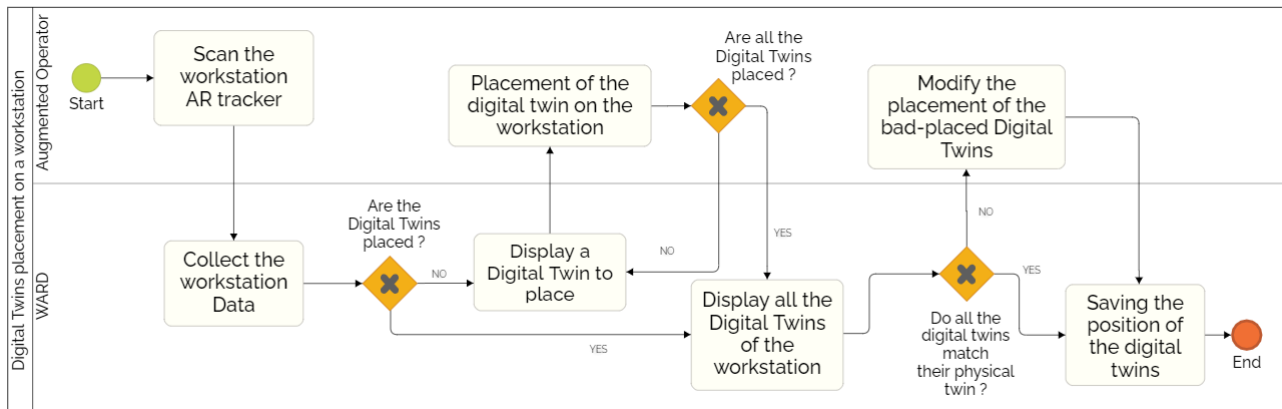


Figure 7. BPMN diagram of the use of WARD to place or update the digital twins of a workstation

366 Since our goal was to enable operators to perform the placement of DTs on their PTs, we verified whether
 367 this was achieved by experimenting with factory operators. We describe this experiment in the next section.

5 IN-SITU WARD EVALUATION

368 To verify that our tool is usable by production staff, we conducted an experiment in an ecological situation
 369 directly in the factory with operators and line managers, who are experienced in boiler assembly and know
 370 the workstations, but are not trained in the use of AR. We compared the task of placing DTs between WARD
 371 and a commercially available tool already implemented in the industrial domain: Microsoft Guides¹¹.

372 We compared the usability of the tools by operators by asking them to perform the matching task between
 373 the DTs and their PT on a workstation.

374 For this experiment with matching task, we made the following assumptions:

- 375 • H1: Task completion is faster with our tool than with Guides.
- 376 • H2: Participants make fewer placement errors with our tool than with Guides.
- 377 • H3: The usability of our tool is better than Guides.
- 378 • H4: The estimated mental load is lower with WARD than with Guides.

379 5.1 Participants and set-up

380 We involved 14 production staff (12 men and 2 women). We conducted our experiment with participants
 381 having different roles in the factory, all of them could be required to match and update the DTs (method
 382 managers, production team leaders, method engineers, workstation preparer, health and safety managers,

¹¹ <https://dynamics.microsoft.com/en-us/mixed-reality/guides/>

383 operators). With this panel of participants, we cover the whole lifecycle of workstations, from design with
384 method engineers, to operation with line managers and operators.

385 The test sessions took place at a workstation in the factory where packages of spare parts are prepared.
386 This workstation consists of 37 component boxes and a work surface.

387 The task the participants had to achieve was to match 37 DTs with their corresponding PT on the
388 workstation. The DTs were presented in the same order for each tool. For each DT, participants had to
389 locate the corresponding PT using the reference, then place the DT on it. Seven participants started with
390 WARD and seven started with Microsoft Guides. We did not tell participants where the tools came from so
391 as not to bias the results.

392 For each tool, we measured the number of DT placement errors. To control the DT placement, the
393 examiner placed virtual bounding volumes over the PTs corresponding to an acceptable placement. We then
394 compared the placement of the DT with the acceptance zone and counted an error when the DT exceeded
395 the acceptance zone border. We also measured completion time, usability of the tool, and the estimated
396 mental load of using it. For the usability we used the SUS questionnaire. To measure the mental load we
397 used the raw NASA-TLX (Hart, 2016) questionnaire.

398 5.2 Experimental procedure

399 Each participant began by filling out a consent form as well as a questionnaire that we produced allowing
400 us to know their experience with AR and VR.

401 Then, they performed the interaction tutorial of the AR headset used (Hololens 2) to familiarize themselves
402 with the possible interactions. This tutorial lasts 5 minutes and train the participant to manipulate a 3D
403 model by grabbing it directly with the hand, then manipulating it remotely using a raycast from the palm of
404 the hand.

405 After the tutorial, they performed the placement task with the first tool, and then completed a SUS and
406 NASA-TLX questionnaire for this first tool. They then performed the task with the second tool and filled
407 out the same questionnaires as well as one more questionnaire to tell us which tool they preferred and if
408 they had any comments.

409 During each session, we filmed the execution of the experiments through the camera embedded in the
410 AR headset used, to eventually check the number of errors as well as to determine the exact completion
411 time of the task.

412 5.3 Results

413 We statistically analyzed the participants' results for the values measured during the experiment. We first
414 performed a normality test to verify the distribution of our data. We observed that only the data about the
415 completion time was following a normal distribution. The data about the number of errors, the SUS score
416 and NASA-TLX score were not following a normal distribution.

417 Figure 8(a) shows that the results of the completion time per tool are different, with Guides above WARD.
418 We can immediately see that the median of the completion time with WARD is less than the lower quartile
419 of the completion time with Guides. We can therefore assume that the completion time is lower with
420 WARD than with Guides. To verify this hypothesis, we performed a one-way ANOVA to compare the mean
421 completion time between the tools. The analysis shows us that there is a significant difference ($p = 0.0004$)

422 between the completion time of the placement task between WARD and Guides, with 9.92 minutes for
 423 WARD and 13.84 minutes for Guides.

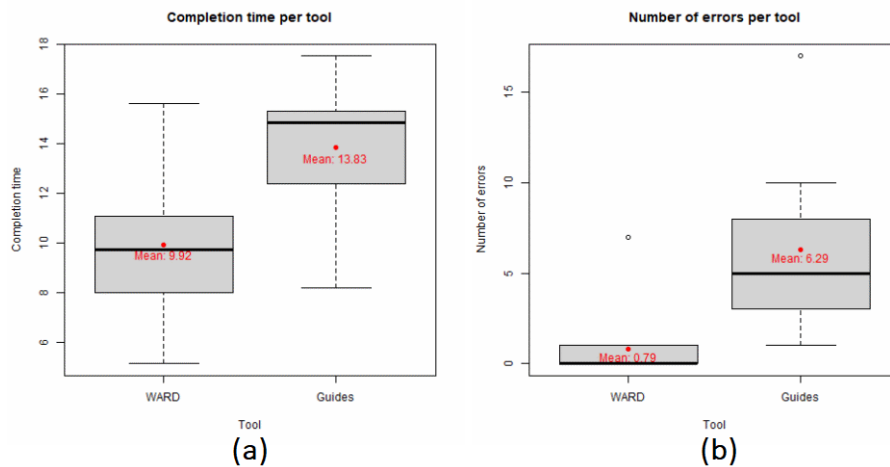


Figure 8. (a) Comparative boxplots of the time per tool with means in red showing that the completion time is longer with Guides, (b) Comparative boxplots of the number of errors per tool with means in red showing that operators make fewer errors with WARD

424 For the number of errors, Figure 8(b) shows that the data are much less scattered for WARD than for
 425 Guides. Moreover the median of WARD is lower than the lowest value of Guides. We can therefore assume
 426 that the number of errors is much lower with WARD. We used a Wilcoxon signed rank test for paired
 427 samples to compare the number of errors between the tools. We obtained a significant difference in the
 428 number of errors between the tools ($W = 12, p = 0.000059$). We can see that on average, participants
 429 made much fewer errors (0.8) with our tool than with Microsoft Guides (6.2).

430 As for the results for the SUS score by tool, Figure 9(a) shows that the median for WARD is similar to
 431 the third quartile limit of the Guides results. Furthermore, the upward skewness for WARD indicates more
 432 concentrated values towards a high score, while for Guides they seem to be evenly distributed. We can
 433 therefore hypothesise that the SUS score is generally higher for WARD. We also used a Wilcoxon signed
 434 ranks test for paired samples to analyze these results. We obtained a significant difference between the
 435 SUS scores for each tool ($W = 147.5, p = 0.0231$). On average, users consider the usability of our tool
 436 (85.3/100) to be better than that of Microsoft Guides (73.5/100).

437 Finally, for the NASA-TLX results, Figure 9(b) shows that the interquartile range is similar for both
 438 tools, with a similar symmetry. We can just see that the WARD interquartile is a bit lower than the
 439 Guides, but it is difficult to make an assumption. We verified whether the difference between the results
 440 is significant. The results were also analyzed with a Wilcoxon signed ranks test for paired samples. This
 441 time, we didn't find any significant difference between the estimation of mental load between the tools
 442 ($W = 78.5, p = 0.382 > 0.05$). On average, the mental load estimation for WARD is 20.80/100 and
 443 24.8/100 for Microsoft Guides, which are very similar but low result, which are acceptable for a mental
 444 load estimation.

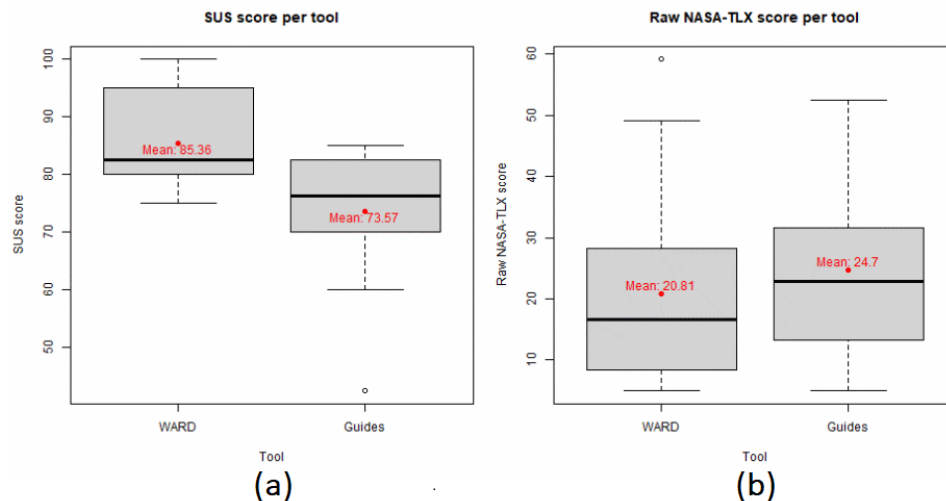


Figure 9. (a) Comparative boxplots of the SUS score per tool with means in red showing that the SUS score is higher for WARD, (b) Comparative boxplots of the NASA-TLX score per tool with means in red showing a similar result

6 DISCUSSION

445 We conducted an experiment to compare the usability by production staff of our tool (WARD) and the
 446 Microsoft tool (Guides). The difference between the tools is mainly in the handling and selection of the
 447 DTs to be placed. In WARD, the Digital Twins are presented one by one. The user has to validate the
 448 placement of the current DT before displaying the next one. In Microsoft Guides, the DTs are contained in
 449 an AR panel in which the user must select the one to be placed. Regarding interaction methods, in WARD,
 450 the user will grab the 3D model of the DTs to move and rotate them. In Microsoft Guides, the user will
 451 select and manipulate the DTs remotely using the raycast starting from its palm (*cf.* Figure 10).



Figure 10. Interaction with a Digital Twin in Microsoft Guides using the raycast

452 The results show that the completion time of the placement task is shorter with WARD, which validates
 453 our hypothesis H1 (completing the matching task is faster with WARD). This can be explained by the
 454 difference in the selection and placement of the 3D models.

455 It also contributes to explain the lower number of errors with WARD. For many users, distant manipulation
456 in Guides leads to errors in judging the depth for placement of the DTs. Many participants were
457 manipulating the DTs 3D models without moving around the workstation, because from their perception,
458 and the fact that they are not accustomed to using AR, the placement was correct. Therefore, they did not
459 change their viewpoint, and could not see their depth errors. This result allows us to validate H2 which was
460 that the users would do fewer placement mistakes with WARD.

461 The results of the SUS show that WARD is more appreciated than Guides by the participants. This
462 result in favor of WARD is also reflected in our questionnaire where one of the questions was about their
463 preference between the two tools (13 out of 14 participants preferred WARD). They described WARD
464 as: "*easier to use*", "*more intuitive*," and "*way faster to learn*" than Guides. Here again the fact that
465 the models were presented one by one, and the fact that the users were manipulating the DTs 3D models
466 naturally by grabbing them, may help explain this result which validates H3 (The usability of WARD is
467 better than Guides). However, it is interesting to note that the only participant who preferred Guides was
468 the only one who indicated using a VR headset regularly for video games.

469 As the NASA-TLX results are not significant, we can only deduce that the tools lead to a similar
470 estimated mental load, which does not allow us to validate H4. The fact that there is no time constraint in
471 the realization of the requested tasks as well as their low difficulty can explain these results. It should also
472 be taken into account that the mental load is estimated by the participant, we could have set up a secondary
473 task to have a more precise measure of the mental load, but the implementation of the experiments in
474 the factory being already complicated, it was too constraining to add this measure for this experiment.
475 However, we keep in perspective the implementation of a secondary task for future experiments.

476 We achieved these results by focusing on the criteria of operators usability and learning time. Presenting
477 the DTs one by one and manipulating them directly with the hand in WARD reduces the number of
478 interactions and therefore reduce the completion time. Furthermore, completing the authoring all in AR is
479 also a time-saver, because there is no switching between devices to perfect the placement of DTs, unlike in
480 SUGAR or Meta-AR-APP (Gimeno et al., 2013; Villanueva et al., 2020). In these tools the DTs would be
481 placed in a work space using a computer software, then the positioning of the DTs would be checked in
482 AR to ensure the matching with the PT. It would take a lot of extra time to repeat this process a few times
483 to ensure everything is at the right location, which is not possible in a production environment. Having
484 an automatic placement system like in INSITER (Riexinger et al., 2018) would be the best option, but
485 the implementation of such a system is very complicated in a reconfigurable factory like ours, where the
486 workstations change during the day and there are no 3D models of the stations. It is easier to implement
487 a manual update by an operator who knows the workstation layout. This is why focusing on the natural
488 manipulation and having an uncluttered workspace allow us to fulfil our most important criteria, of enabling
489 operators to perform the placement task with a short learning time, in a reconfigurable factory context.

490 However, there are still limitations to our implementation. As the DT update is not automatic, unlike
491 the systems implemented in smart factories (Leng et al., 2020b, 2019b, 2020a), if the update is not done
492 properly, other users may encounter problems such as information being displayed at the wrong position.
493 Moreover, manual updating can be time consuming if many workstations have to be updated, which seems
494 unacceptable in a production context.

495 On the other hand, WARD allows us to implement a DT in an existing factory without having to modify
496 the factory to integrate IoT. To achieve the automatic update of the DT, we could record continuously
497 with the AR helmet to detect a modification, but it is not feasible (both in terms of operators privacy, and

498 comfort because they can't wear the HMD during a whole day). Moreover, the updates of the stations
499 concern only some elements and not the whole layout, which is not very long to achieve with WARD.

500 To support this, we have seen that it was really easy to set up WARD in the factory. Operators were able
501 to perform the matching task with only a five minutes tutorial. It would have been very different if we
502 used a tool with a computer-based module like ACARS, SUGAR or ARAUM (Zhu et al., 2013; Gimeno
503 et al., 2013; Erkoyuncu et al., 2017), or even with a CAD tool, with a more complicated interface and
504 interactions, since the operators do not use computers regularly.

505 These results show that WARD is easily usable by production staff in a factory, and that having a dedicated
506 tool for operators, developed following the concepts of natural interactions and uncluttered display, is
507 better in term of performance and completion time. Limiting the interactions to manipulating 3D models
508 directly with the hand, but also limiting the number of visible models, enables the operators to perform the
509 authoring task quickly and easily with very few mistakes.

7 CONCLUSION & PERSPECTIVES

510 Industrial developments, and more specifically the transition to Industry 4.0, are leading us towards the
511 digitization of industrial processes. The DT is an example of this and is particularly used in industrial fields.

512 In the case of our boiler manufacturing factory, and in order to train new operators on production tasks,
513 we collected user needs in order to design a dedicated DT of the workstations, allowing an AR display of
514 assembly instructions.

515 We first proposed an implementation of a DT containing data about all the functional elements of the
516 factory as well as their 3D models. We then developed WARD, an AR authoring tool enabling operators
517 to easily superimpose the DTs to their PTs directly in AR, thus avoiding the need to use several different
518 platforms or software.

519 Our evaluation of WARD by production staff, comparing it to the Microsoft Guides tool, allows us to state
520 that WARD performs better than Guides in terms of completion time and usability. WARD also generates
521 fewer positioning errors than Guides. These results can be explained by the difference in interactions with
522 the DTs in the two tools. Indeed, the direct manipulation of the 3D models with the hand with WARD
523 makes our tool easier to use than Guides.

524 These results allow us to define the following guidelines for AR authoring tools designed for operators.
525 Handling should be as natural as possible, like a simple grab, and not all DTs should be displayed to avoid
526 overloading the field of view. More specifically, the development of new tools should be done by fulfilling
527 the criteria we have outlined in the state of the art, focusing particularly on ease of use by operators, and
528 learning time. The criterion on AR support, however, can be modulated according to user needs.

529 Our work shows that the implementation of a DT within a production environment, as well as its
530 maintenance, can be done directly by the production staff considered as non-expert. This opens many
531 perspectives for the use of the DT in the factory by the production staff.

ETHICS STATEMENT

532 Written informed consent has been obtained from the person(s) concerned for their participation in the
533 experiment and the publication of any identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

534 Digital Twin and authoring tool development, PB; Methodology, PB, SK, TD and EB; Supervision, SK,
535 TD and EB; Experimentation, PB; Writing original draft, PB, SK, TD.

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