

Assessing TRL of HCI Technologies Supporting Shop Floor Workers

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ABSTRACT

Successful worker-centered Industry 4.0 solutions depend on the maturity of the technologies supporting workers' interaction with information systems. This paper discusses the methodology we followed while creating and updating the FACTS4WORKERS approach for monitoring available technologies together with an assessment of their readiness for being used on industrial shop floors. Our approach is based on the creation of a taxonomy of technologies to be considered and the assessment of their readiness following an adaptation of the technology readiness assessment methods defined by National Aeronautics and Space Administration (NASA) or European Space Agency (ESA). Further, the approach discussed can be cost-effective, productive, and easily adopted by any company, especially small and medium sized enterprises, which are considering starting an ICT project (with a substantial human computer interaction component). While our approach focuses on technology maturity, we believe that other aspects could also be evaluated to determine the readiness level of a technology to be used on the shop floor, including, for example, the expected benefits for the workers or remaining technology challenges.

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CCS CONCEPTS

- **Concepts** → Transfer of HCI concepts into industrial practice
- **Methodology** → Evaluation methods

KEYWORDS

Evaluation, HMI/HCI, TRL, TRA, Worker centred solution, Industry 4.0, Shop-floor, Methodology

1 INTRODUCTION

Recent advances in technologies have brought about radical changes enabling “Industry 4.0” in manufacturing from water- and steam-powered machines to electrical and digital automated production [1]. For taking advantage of these state-of-the-art (SotA) changes of technologies, Industry 4.0 requires three major components [2]. First, an application layer, i.e., various factory automation applications that consist of backend and front-end building blocks providing workers with the information the task they are executing requires. Second, a network layer, i.e., networking, data storage, and processing centers, such as cloud storage, which transmits real-time information required for applications and enables coordination among different physical entities. Third, the physical entities layer, which composes of sensor technologies, commercial-off the shelf (COTS) human computer interaction (HCI) technologies, i.e. any hardware, software or infrastructure tool which can be used or is required for implementing the interaction between the workers and the information systems they interact with such as smart mobile devices, that provide support for shop-floor tasks. Physical entities play a key role in enabling Industry 4.0 systems and technologies [2] because this layer provides support for more

shop-floor tasks and allows companies to design worker-centered solutions.

However, it is not always possible to utilize available COTS HCI technologies of the physical entities layer on the shop floor due to the work context and environment [3, 4]. For example, Zhou et al. [3] stated that “*Different factories need different smart device configurations, and smart device development requires much time and money before it can be put into production in an Industry 4.0 factory.*” (pp.2150). Moreover, Industry 4.0 faces four digital challenges [9]: i) digitally augmented human work; ii) worker-centric knowledge sharing; iii) self-learning manufacturing workplaces; and iv) in-situ mobile learning. These industrial challenges represent the socio-technical problems to be solved within the industrial project partners to ensure effective knowledge management processes. The aim of knowledge management solutions is to meet workers’ and organizations’ expectations of knowledge aspiration and distribution on the shop floor.

Therefore, the question arises regarding how the quality of a range of available COTS HCI technologies in the market can be identified to reduce projects’ risk, improve safety and reliability, and support their use in manufacturing shop floors since it is not easy to evaluate these devices in advance and to determine the maturity of considered HCI technologies, that is their expected interaction quality, before starting a project.

To answer this question, the FACTS4WORKERS (F4W) [6] project is used as the case study project, which could be utilized by the industry or research community as an affordable and simple way to objectively estimate the technology readiness level (TRL) of a set of technologies of interest to empower workers on the shop floor with smart factory ICT infrastructure. Because of the worker-centered component of the F4W solutions, assessing the TRL of the supporting HCI technologies becomes crucial, as they will influence the solution TRL [7] and, as a consequence, the quality and success of the provided solutions.

The F4W project aims to develop worker-centered solutions that achieve a TRL level between 5 and 7. The TRL [8, 9, 10] scale was introduced by the aerospace industry as a way to objectively determine the maturity of a given technology and the assumed risks when it is used for a given purpose. Risk means the probability of failure; therefore, a higher level of readiness means a higher level of quality. Furthermore, according to the existing technology success models [11, 12, 13], it can be followed that the acceptance and the success of information systems (IS) will depend on their quality.

While aerospace agencies and government departments define their own procedures for technology readiness assessment (TRA) [9, 14, 15], it is claimed they are expensive procedures and cannot be easily used in other scenarios [16, 17]. This is the reason we decided to create a TRA procedure that can be used to objectively assess the technologies of interest of a project – F4W in our case – and that can be executed actively by ourselves, with the project’s available resources. The methodology we follow for creating our approach can be summarized in three main steps: first, creating the taxonomy of HCI technologies

based on the problems to be solved (the industrial challenges); second, assessing the TRL of the technologies included in the taxonomy; finally, creating the conclusions based on the taxonomy readiness assessment.

How we determine the technologies of interest of F4W, how we create the HCI taxonomy and how we assess the TRL of the technologies included in the taxonomy are presented in the remainder of the paper. First, we briefly present the TRL/TRA background, how they have been adapted in other scenarios than official agencies and departments, and how the alternative approaches can be improved. Second, we present the methodology we followed to create the taxonomy and assessing their nodes. Third, we present the current state of the taxonomy. Then we present an adaptation of the methodology to be used by another project. Finally, we present several conclusions about the taxonomy and the methodology itself.

2 TRL

The objective of the F4W project is to develop worker-centered solutions that achieve a TRL level between 5 and 7. This will not be possible if the enabling technologies, in particular HCI technologies, do not achieve these levels. However, the problem involves determining a way to objectively assess the TRL level of a given technology or of a system of technologies. This problem has already been highlighted both for obtaining public research funding [17] and when a company wants to invest for improving their working infrastructure [18].

TRL	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Table 1. European Commission TRL definitions.

Table 1 briefly introduces the TRL as defined by the European Commission [8]. The TRL is a scale of maturity levels. It can help to determine the risk of adopting a given technology. In this scale, items (technologies, hardware, software, etc.) having an evaluation from 1 to 6 present high risks and unknowns for handover; 7 is understood as the minimum level to consider for handover, and 8 and 9 are the desired levels [19].

Each level in the scale provides a description of its meaning, and each description is considered a rule for evaluating the TRL of an item. Because it is possible to subjectively interpret the rules, official agencies provide public guides for TRL assessment [9, 14, 15], which are publicly available. All these agencies follow the same strategy: i) First, gather information about the item under evaluation by answering a set of established questions, which include lower development level ones; ii) Use the information to assess the item's TRL level. The first step of this strategy is based on their power position. Because of this, they took a passive role demanding information from contractors when applying for the provision of an item.

Several entities could be interested in using the proposed methodologies. However, the TRA process can be tedious. Moreover, not all the entities, in particular, small- and medium-sized enterprises (SMEs) [7], are capable of demanding information about their items of interest like the NASA or ESA easily can. Thus, entities from different economic sectors [16, 18, 20] claim that NASA's and ESA's methodologies must be simplified to make them affordable and accessible by "real-world" entities. Moreover, the existing methods must be extended to be able to use them with changing environment conditions, to adapt to specific sector requirements, in particular for ICT systems, which are composed of (sometimes) an unknown number of subsystems [21].

This motivated us to create an objective and simple TRA process for determining the TRL level of the technologies of interest for implementing the F4W Use Cases, using the definition of the levels provided in Table 2 as the foundation.

3 F4W HCI INDUSTRIAL READINESS ASSESSMENT

The results of our work for creating the F4W technology monitoring approach are the reports themselves, each of the versions of the HCI taxonomy and, more importantly, the methodology we followed to create the taxonomy of HCI technologies and to assess the TRL of their nodes as the basis of our approach.

Below, based on [22, 23], we present the methodology we followed to create the taxonomy and assess its TRL. In section 3.1, we introduce the process we followed and the decisions we made for selecting the HCI technology of interest of F4W and for representing them as a taxonomy. Once the guidelines for creating a taxonomy are defined, section 3.2 presents the rules we followed to assess the TRL levels of each of the taxonomy nodes. Finally, section 3.3 presents an overview of the process we followed to create and update our approach based on the updated taxonomy and on the TRL assessment of its nodes.

3.1 HCI Taxonomy Creation

The main structure of the taxonomy was created while writing the first release of our approach in [22].

First, we identified the technologies of interest for F4W. The process we followed is summarized below:

- i. The definition of HCI in the context of Industry 4.0 as vision of Internet of Things (IoT) from the manufacturing perspective;
- ii. The revision of the F4W project's objectives and industrial challenges to be faced;
- iii. The analysis of HCI technologies used by other Industry 4.0 projects;
- iv. The performance of a profound theoretical study on the background of HCI.

These steps can be used by other projects for creating a taxonomy of (HCI) technologies within the Industry 4.0 scope or in another one. The inclusion of the fourth step should be analyzed when projects require a TRL higher than 7 because it will provide lower TRL technologies.

Figure 1 is adapted from the one provided in [24]. The original figure shows that, from a manufacturing perspective, Industry 4.0 can be considered the equivalent to the IoT [25]. Therefore, the analysis of the HCI needs and solutions of IoT will help to determine (most of) the technologies to include in the taxonomy.

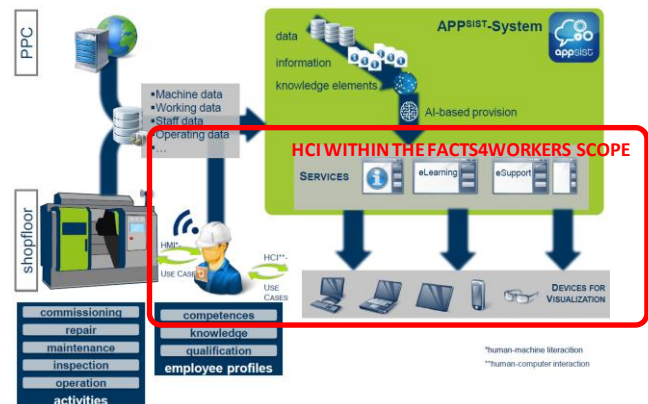


Figure 1. HCI within the F4W scope.

An interesting overview of IoT demands is provided in [26]. It highlights that for the IoT vision to be successful, the computing paradigm will need to go beyond traditional mobile computing scenarios that use smart phones and portable devices and evolve to connect everyday objects and embed intelligence in our environment. The authors of the paper suggested that, for technology to move from the user's consciousness to his or her sub-consciousness, between other factors the IoT needs to adhere to the following: 1) a shared understanding of the user's situation and appliances; 2) software architectures and pervasive communication networks that will process and convey the contextual information to where it is relevant; and 3) the analytics tools in the IoT that seek to secure autonomous and smart behavior. The authors based their conclusions on reviewing the concepts of calm computing [27], human-centric ubicomp [28] and ubicomp in general [29].

As a consequence, F4W HCI taxonomy needs to include any technology, software and hardware supporting and or developing of these concepts related with low intrusive contextualized ubiquitous computing, such as localization technologies, minimally intrusive interaction technologies, and

software development kits (SDKs) – considered integrators of software and hardware capabilities. The HCI technological F4W scope is represented by the red rectangle in Figure 1.

Because of the project requirement of providing SotA technologies and paradigms that can be of interest, we also performed a theoretical background study of HCI technologies and paradigms. This research has a second objective. Due to the educational nature of our approach, we want to include basic descriptions of the base technologies and paradigms that support current devices and interaction systems because these descriptions can contribute to a better understanding of the approach by the industrial partners of the projects and by the general audience.

After obtaining the list of desired technologies (software and hardware), we determined the best way to present them. We selected the taxonomy, a tree data structure, because it provides us with many valuable features; these include the following: 1) We want to provide more value than just putting together a set of tables showing available technologies (devices) and their technical features, as there are many of them on the Internet. The taxonomy structure, a tree, supports showing the technologies together with the relations between them, i.e., Table 2 shows the Augmented Reality (AR) node is composed of the AR tracking technologies, AR display technologies, the AR SDKs and the Interaction Techniques and User Interfaces nodes; 2) We used these relationships to subsume that the assessment of the intermediate nodes readiness can be based on their children’s assessment; 3) Finally, the tree structure provides high flexibility for updating the taxonomy, i.e., it is easy to add new branches, and for presenting the results of the TRL assessment, i.e. it is possible to present it on a high level of visualization as well as to browse the taxonomy to assess the leaves.

The creation of the F4W taxonomy followed a set of rules for classifying the technologies of interest into a hierarchy of technologies. First, all the technologies were classified as HCI-enabling technologies or as HCI systems. The latest version of F4W taxonomy is accessible in [29], and Table 2 shows an excerpt of the initial taxonomy and some sub-branches.

HCI-enabling technologies are those which, in most cases, are self-contained subsystems and usually appear embedded in other systems (such as the touch screen of a table). While they are not of interest for our approach, they help to identify some of the building blocks to be created within the HCI front end of F4W solutions. For example, by considering computer vision an enabling technology, we can classify the construction of a building block that implements the desired functionalities (text recognition, object recognition etc.) as a subsystem that can “easily” be ported into different, more complex systems (a smart phone, PC etc.) to achieve certain functionalities or implement different use cases. Moreover, their inclusion and the inclusion of their features contribute to a better understanding of the potential uses and risks of the HCI system embedding them and therefore of their TRL assessments.

The HCI system branch introduces the available technologies that offer an advance in ubiquitous computing, IoT or Industry 4.0 vision from the HCI perspective. This branch includes mobile devices, wearable devices, and augmented reality as whole

systems. A tablet or an augmented reality application is considered an HCI system, because it involves several technologies, e.g., identification/location and/or visualization technologies.

Table 2 shows that both HCI enabling technologies and HCI system branches are umbrellas covering other more specific sub-branches of technologies. These sub-branches can also group other more specific branches until we reach the leaves of the taxonomy. These leaves represent either specific kinds of technologies, such as the Reactive Touchscreen under the HCI enabling technologies branch or specific devices or SDK under mobile devices.

HCI Technologies		
Level 1	Level 2	Level 3
HCI Enabling Technologies	Conventional Technologies	
		Text Entry Display Devices Screen Positioning, Pointing and Drawing Technologies ...
	Touch-sensitive Screens (Touchscreens)	
		Resistive Touchscreen ...
	Image and Video Devices	
	Computer Vision Audio Input/ Output Technologies. Context Awareness Technologies	
		Positioning, Location and Identification Technologies. Qualified Self Emotion Detection, Affective Computing, Mood Recognition
	Haptic Interaction	
	Brain Computer Interaction	
	HCI Systems.	
	Mobile Devices	
		Mobile Devices Rugged Mobile Devices
	Wearable User Interfaces.	
		Smart Watches Smart Glasses ...
	Cross Platform (CP) Software Environments	
	Data Visualization Augmented Reality	
		Augmented Reality Tracking Techniques Interaction Techniques and User Interfaces Augmented Reality Display Technologies Augmented Reality SDKs

Table 2. Three higher levels of F4W HCI taxonomy.

In both cases they do not have child technologies because they represent technologies’ implementations and all the leaves having a common parent technology share a set of features that can be used for their comparison as well as for assessing their TRL, as we will explain below.

Because of the paper size restriction, we cannot provide a more detailed explanation of the composition of the F4W taxonomy. We recommend that interested readers refer to our reports [22, 23, 31] and the taxonomy versions [30] for a better understanding.

3.2 F4W TRL Assessment Approach

While the process for creating the taxonomy was introduced in [22] and this report also sketched the TRA procedures we present here, the TRA procedure was defined in [31].

Figure 2 presents a hypothetical taxonomy obtained after applying the process we introduced in previous paragraph. We use this figure for presenting our TRA procedure. Rectangles in the figure represent nodes of the taxonomy. The colors of these nodes, as we will explain after, are determined by the color associated to the node TRL in tables 2 and 3. These colors visually represent the assumed risk when using the technologies represented by the node and are used for provided a high level overview of the TRL of the technologies under analysis. Ellipses in figure 2 are used for identifying the node category which we will discuss in next paragraph.

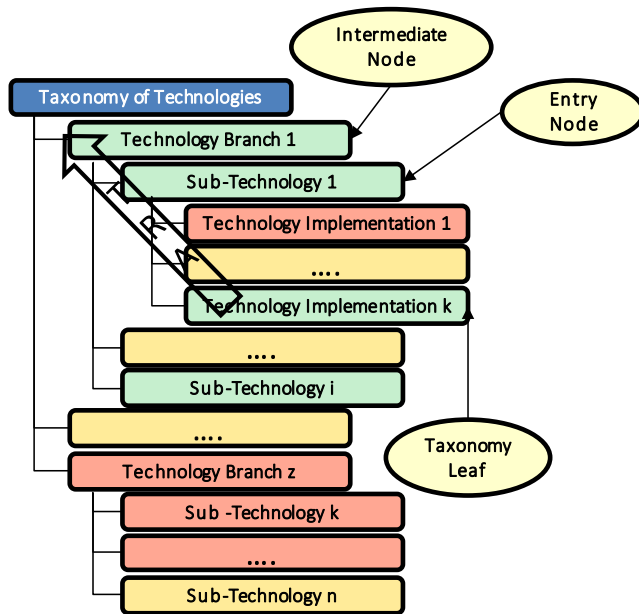


Figure 2. General Taxonomy Example.

The process we follow for assessing the nodes TRL considers that belong to one of three categories. The category of the node determines the method used for assessing its TRL.

As pointed by the TRA arrow in figure 2, our TRA procedure will follow a bottom-up approach, where we use the same approach for introducing the categories of nodes we consider. Starting from the down level of tree nodes, we first considered the taxonomy leaves category of nodes. As explained in section 3.1, there are specific implementations of a given technology. As devices, software products or any concrete technology (i.e. oled screens) all the technologies having a common parent node, will share a common set of features, for example, smart glasses are defined by their camera capabilities, their operating system, etc. This set of feature will be used when it is needed to select a specific implementation and also for assessing their TRL.

We call Entry Node to the category of nodes to which those nodes grouping Taxonomy Lead nodes having a common set of features, for example, augmented reality SDKs is an Entry Node (see table 2). If we consider the topology of the tree, Entry Nodes

also belongs to the Intermediate Node category. However, we differentiate both categories because they are used different methods for assessing their TR as discussed in paragraph.

Following the bottom-up approach we first introduce here the method we use for evaluating the TRL of leave nodes. The TRL assessment of these nodes is based on the adapted NASA/ESA TRA procedures. Both procedures follow the same schema: First gather information about the item under evaluation by answering a set of established questions including one for the lower development TRL; then use the information for assessing the item TRL level. The confidence in the TRL assessment can be compromised by several factors: there are a high number of questions; answers and their answers can be ambiguous [21]; it is difficult to transfer these TRL procedures to other sectors [17].

Table 3 provides the set of questions we use for assessing the TRL of the taxonomy leaves of a given taxonomy version. We created this question based on the ones used by NASA/ESA for TRA procedures. However, we reduce the number of questions in order to reduce the resources (time, people) required when executing our TRA procedure. Instead of requesting the providers to answer the questions we look for answers on public available information about the device, software, etc. of interest. We assume that none company is going to lay about the test cases of their products because doing it will affect its reputation.

Table 3 focuses in TRL from 5 to 9 due to the fact our project aims to develop solutions having a TRL level between 5 and 7 (or higher), and in consequence, we are not interested in technologies which are in a lower level of development. However this table can also be extended to technologies having a TRL lower than 5 and creating the set of questions for evaluation each given level.

TRL	Supporting Information
5	Does the public available information show the item was tested in laboratory?
6	Does the public available information show the item was tested in a real environment? Are the results of the test available?
7	Does the public available information show the item prototype was tested by an external entity in a real environment? Are the results of the test available?
8	Does the public available information give an idea of the integration of the item with other systems?
9	Does the public available information give example of real use case implementations? Are the performance, costs and determinant condition available?

Table 3. F4W Leaves TRL Evaluation Questions.

The answers to questions in table 3 will allow to determine the TRL of a given device or software. Since, we want to select a given set of technologies implementations for supporting

interaction between workers and F4W solutions; we also considered the specific features of the taxonomy leaves in our TRA procedure. The features of interest analyzed are dependent on the technology under assessment. They include physical dimensions (size, weight), prize, compatible software (S.O, SDKs) or included technologies (Wifi, Bluetooth, touch-pad) between others. However, for HCI devices, which have to be operated in extremely harsh environments and conditions, a really important issue to consider is if the device meets a rugged standard such as IP-xx [32] or MIL-STD-810G [33].

When assessing the TRL of leave nodes it is necessary to consider that: 1) the TRL level of a technology depends on the scenario of use; 2) technology readiness does not mean commercial readiness. When we consider it in the F4W scope, we can translate it to HCI consumer market technology usually has a higher TRL than industrial market technology. It is due to the fact the use environment requires different features, i.e. having a given rugged level, but also to the fact of the stronger restrictions that security and legal regulations they have to match. Smart glasses are an example. While there are many devices in the consumer market, there are not in industrial one because of the restrictions of the shop floor use. In [31], it is proposed to introduce what they called Commercial Readiness Level. We take a similar approach. But, instead of defining a new scale of values and guidelines for their assessment, we reuse the TRL scale and guideline but we assess the evaluated technologies in both scenarios consumer and industrial. We try to keep our TRA procedure simple, but it also allows us to compare consumer and industrial TRL. We think it will help to interpret the results as they can provide an idea of the expected development of the technology for industrial use in near future.

Once the TRL of the Taxonomy Leaves are assessed, it is possible to determine the TRL of the Entry Node they belong to. It is calculated as the maximum level of the nodes it contains respectively in the Consumer or the Industrial market. By considering the maximum function, we show the biggest expectation to be made on the represented technologies.

A similar approach is considered when assessing the TRL of intermediate nodes. They can be considered as systems composed or using the technologies of the children technologies. In [2] the author purposes the use of the minimum function in order to determine the TRL of system technologies. However, we use the truncated geometrical media of the TRL of each sub-tree. On the one hand, using the geometrical media allows all the children nodes to contribute the evaluation of the Intermediate Node level. In the other hand, by truncating the obtained value we give a bit more importance to the children having lower TRL level evaluation, in other words we take a more conservative point of view. It must be remarked, in order to correctly interpret the results for Entry Nodes and Intermediate Nodes, that once we move up from the TRL assessment of the leaves of the taxonomies, we are not evaluating a concrete product or technology; we are evaluating the set of products or technologies included as a whole.

Finally, as we made when we introduce the taxonomy creation process we recommend the interested readers to take a look to the second version of our approach [23] and to the last available version of our taxonomy [30]. The first will provide details of the

TRA procedure definition. The second will provide information about the features considered for subsuming the TRL assessment from taxonomy leaves to HCI-enabling technologies node and to the HCI systems nodes respectively.

3.3 Overview of the Methodology

The methodology we followed for creating the HCI technologies taxonomy and for assessing the TRL levels of its nodes is briefly presented in this section and Figure 3. The iterative process is very similar to those described in [9, 14, 16, 20], but it simplifies them. By presenting the process in these steps, we aim to allow the use, adaptation, or improvement of the methodology and the resulting taxonomies both within F4W and other projects.

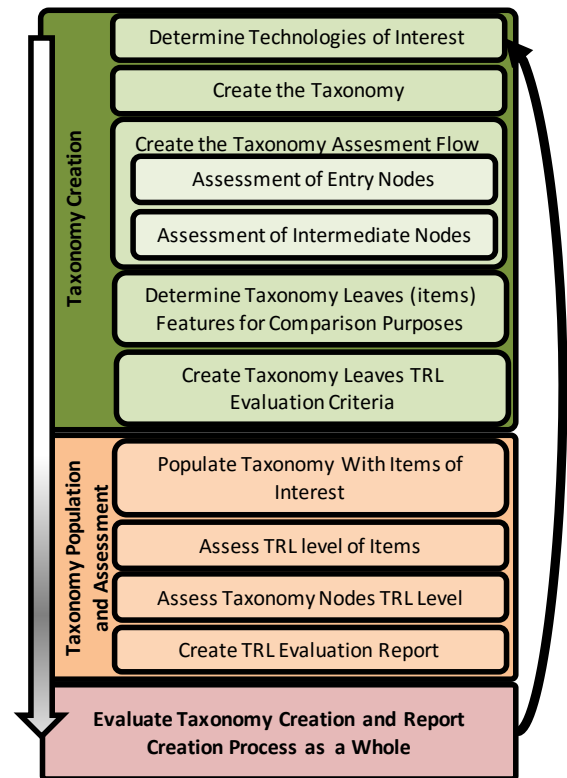


Figure 3. F4W TRL Evaluation Methodology.

An initial steps are under the *Taxonomy Creation* box. Their result is the (re)definition of the taxonomy as a tree structure, for defining the features of the leaves (devices, software, etc.) allowing their comparison, and for defining the set of TRL evaluation rules of each taxonomy node.

The first of these steps was determining the enabling technologies of interest based on other worker-centered Industry 4.0 projects, Use Case requirements (as they were available) and the experience of the F4W members. After determining the technologies of interest, as second step, they were classified by creating the taxonomy. While the taxonomy released with project deliverable in [22] was a pure tree (vertical relations), the further releases also identified horizontal relations reflecting more complex relations included in [23, 30]

The third step was the definition of the taxonomy evaluation flow. As detailed in subsequent sections, we used two rules: The first was to determine the impact of the taxonomy leaves evaluations within the entry node ones. We considered the maximum function for assessing an entry node TRL base on the leaves one; The second was to subsume the intermediate nodes' evaluation based on the evaluation of their children. We used the truncated geometric mean function.

Once we identified the entry nodes to the taxonomy, the “enabling technologies of interest,” we defined a common feature set for evaluating a particular item (an implementation of the technology) and making all the items under an entry node comparable. Finally, we created a set of rules for applying the TRL model for assessing the technologies items (devices, SDKs) based on their features and the information reported by their producers.

After creating the taxonomy and populating it, we evaluated the leaves and subsumed the evaluation to the root of the main two branches: HCI enabling technologies and HCI systems. Figure 3 shows the detailed steps in the Taxonomy Population and Evaluation box.

First, we populated the taxonomy with items of interest: we searched for existing items (devices, SDKs, etc.) that are considered to belong to the categories identified by the entry nodes. We saved the search engine queries for clarity and reproducibility reasons. Second, once we populated the taxonomy, we evaluated the items independently using the rules we introduced in section 3.2. Then, we automatically subsumed the evaluation to the higher level using the tool we developed [36]. Finally, we created our reports [22, 23, 31] based on the evaluation.

Figure 3 presents an additional step: *Evaluate Taxonomy Creation and Report Creation Process as a Whole*. It was created under the perpetual beta philosophy of the F4W project. The aim is clear: trying to improve the taxonomy definition and the process of assessment, i.e. by including new features to consider for evaluating the TRL of the leaves.

4 TRL HCI TAXONOMY

Table 4 presents the HCI system branch of the taxonomy of HCI technologies we included in our last report [31]. We focused on this branch because these technologies are the most emerging, they are in their infancy of application and, likely due to their immaturity they are passing the “*Through of Disillusionment*” of the Hype Cycle of Gartner [34], while the rest of the HCI enabling technologies and systems are mature enough to only experience new improvements in the specifications of the products but no real innovations that could be considered a decisive point to be included in the shop floor or to start new projects in this field.

It is also important to note that augmented reality (AR) solutions have not yet been introduced in the factories' shop floors, but it appears that the mainstream of AR may be coming much sooner, and its importance in the industry sector is predicted to be highly relevant. This prediction is based on the fact that in the reported period, AR experimented with significant technological

advancements, both at the device level and also providing new SDKs, which take advantage of the new implemented capabilities and increasingly powerful cameras. This will mean an acceleration of the process of delivering new AR experiences that will contribute to the effort of democratizing and extending this technology that is still in its infancy.

HCI Technologies			TRL Assessment	
Level 1	Level 2	Level 3	Consumer	Industrial
HCI Systems.			8	6
	Mobile Devices	Mobile Devices	9	7
		Rugged Mobile Devices.	9	9
	Wearable User Interfaces.		7	7
		Smart Watches	9	7
		Smart Glasses	9	9
		Hearables	9	7
		Smart Clothing	3	3
		Nearables	9	9
	Cross Platform (CP) Software Environments		9	7
		Smart Operating Systems.	9	5
		CP Development.	9	9
	Data Visualization		9	9
	Augmented Reality		6	5
		Augmented Reality Tracking Techniques	6	5
		Interaction Techniques and User Interfaces	6	5
		Augmented Reality Display Technologies	7	7
		Augmented Reality SDKs	7	5

Table 4. F4W HCI 3.0.

5 CONCLUSIONS AND FUTURE WORK

The study shows that the F4W HCI Taxonomy 3.0 [31] has demonstrable benefits, such as identifying the risk of the whole project as well as the limiting technologies just by going down the tree, while utilizing technologies such as mobile devices and wearable devices to support the realization of Industry 4.0 [34].

The combination of the relations between technologies, the taxonomy, and the assessment of their TRLs support us in tracking the evaluation of the F4W HCI technologies of interest. This combination is created by following the TRA methodology we present in this paper. We based the decision of creating this methodology on the reported need of more affordable and easier [7, 16, 18, 20] as well as, more objective TRA methodologies [21] than existing ones [9, 14].

While the methodology supports us in achieving the goals of F4W [22, 23, 29, 31], we believe that it can be used by other projects having different purposes. First, the taxonomy can be customized for other scenarios of application requiring other specific technologies. Second, the TRA processes we follow separate the assessment of the technologies' implementations of the (the leaves of the taxonomy) of the TRL assessment of entry nodes and intermediate nodes. It supports the adaptation of the assessment process to the specific technologies to be used by merely changing the taxonomy leaves criteria.

Moreover, the separation also allows the assessment criteria to be upgraded as the technology evolves. Khakurel et al. [4] noted that many challenges remain in HCI technologies for supporting

workers on the shop floor. They are related to technological (i.e., usability and security), social (i.e., privacy and adoption), wearability (i.e., devices worn on the body), policy-related, regulatory, economic, and data-related. Within this perspective, our future work will investigate ways to reduce such challenges and facilitate the adoption of the devices by identifying i) the essential device types using the evaluated F4W HCI 3.0; ii) which type of device categories are beneficial for specific utilization purposes to reduce the challenges, and facilitate the adoption of the devices using the categorization framework presented in [4].

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