



# A novel assembly process guidance using augmented reality for a standalone hybrid energy system

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## Abstract

The increase in the maturity level and the competitiveness of renewable energy systems, such as wind or solar-powered systems, is modifying the energy production market. Due to the possibility of decentralizing energy sources, standalone hybrid energy systems are those with the most promising potential. They generate a whole new electricity distribution network and new opportunities for socio-economic development in off-grid areas. However, several technical challenges are encountered during the deployment and operation of these systems, including transportation logistic costs, assembly, remote monitoring, performance evaluation, and real-time maintenance. Renewable energy systems must demonstrate a high degree of autonomy when operating without the supervision of an expert on-site. Furthermore, these systems must be able to communicate with their control center, sometimes located several hundreds of kilometers away. Once installed on-site, GreenCube (GC), a standalone hybrid energy technology, does not require specialized software or skilled user intervention to operate. Given the different versions of GC and the complexity of components, the assembly process plays a crucial role in the operational performance and durability of the equipment. This work applies the concept of augmented reality (AR) to provide assistance and guidance during assembly operations. It reviews the state of the art in hardware and software solutions based on AR to increase assembly precision, safety, and cadence in an industrial maintenance context. A real case scenario is described in which the user is guided step-by-step through sequences to deploy and assemble the components of a standalone hybrid energy system. Results suggest that the proposed paperless and AR-based method helps to reduce human errors during assembly operations, increase the health and safety of the assembly team, and provide insights on how to perform the tasks efficiently without the need for external documentation. The architecture can be implemented in any database management system to control relevant data generated from the assembly process and will be the basis for further research on remote maintenance approaches.

**Keywords** Augmented reality · Hybrid energy system · On-site assembly · Industrial maintenance · Industry 4.0

## 1 Introduction

Remote areas, such as isolated villages or mining sites, provide the world's important sources of raw materials and energy. In Canada, nearly 300 communities live in remote areas. The electricity produced to power these communities comes mainly from diesel generators. Although this is a safe source of energy, its use is not without consequences. One of them is the depletion of oil reserves, followed by the soaring price of fuel, given the direct relationship between distance and transportation logistic costs. With the emergence of Industry 4.0 and thanks to the implementation of new technologies, these costs can be avoided or considerably reduced, and the savings can be allocated to other projects in

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the community. Canada's economic and social development also depends on these fast-growing communities, so it is important to think of solutions to solve the problems related to the excessive use of diesel. The demand for electricity in remote areas has been increasing over the years. Knowing that these communities mainly use diesel for their electricity production, the impact on global warming is a direct consequence. Additionally, other kinds of installations, regardless of their size, require electrical power. These include telecommunication stations, weather stations, water pumping stations, mining sites, scientific and military bases, agricultural farms, and shelters, among others. Renewable energy has the advantage of combining different energy sources to improve the sustainability of electric power service, and thus guarantee a continuous supply of electricity despite weather variations during the year.

### 1.1 Standalone hybrid energy technology

Between 2010 and 2018, renewable electricity generation across Canada increased by 16%, with wind and solar having the largest growth [1]. Photovoltaic (PV) energy is the energy produced through the conversion of sunlight into electricity. More precisely, a PV cell is responsible for converting incident solar radiation into electrical energy. Thus, several PV cells form a photovoltaic panel; they can be arranged in series or parallel, or both types combined. This association allows for an increase in the size of the solar panels, and therefore the power. In 1985, solar power generation was estimated at 23 MW; however, 14 years later, a significant number of PV systems have been built in Canada, representing about 200 MW of installed capacity at an estimated cost of 3 billion dollars. PV systems have experienced technological advances in recent years; additionally, acquisition and investment costs have been decreasing from 1\$/kW to about 0.35\$/kW of installed capacity. According to the 2016 CANSIA report, the costs associated with PV systems will be cut in half by 2025. Wind energy is the kinetic energy associated with the movement of large masses of air around the globe. Wind turbines (WTs) exhibit their maximum potential when installed in open areas, such as coastal and offshore locations. Despite the need for cost-effective operation and maintenance strategies for WTs, electricity production from these energy sources has experienced strong growth over the recent years. In 2013, for example, the electricity production capacity from wind power reached 318 GW worldwide, noting an increase of 200 GW in 5 years (CDE March 2020). In 2014, installed wind power capacity was 50 GW, which was a record for a year in the world, or 40% more than in 2013.

The current market trend of renewable energy produced by WT is country-specific. China leads the list of countries with the strongest development, followed by the

USA, Germany, India, Spain, and the UK (CDE March 2020). Canada had the 9th largest installed onshore wind power capacity in the world (CDE March 2020). In northern regions, such as Nunavik, it is estimated that wind power can supply 40% of the electricity needed in Canada. According to the Canadian Wind Energy Association (CANWEA) [2], in 2019, the wind power sector in Canada directly benefited more than 299 communities in 12 provinces and territories, including involvement with more than 35 Indigenous communities. Standalone hybrid energy systems, such as Green Cube (GC) technology, are used to supply electricity in off-grid remote areas of Canada. The role of hybridization is to combine several energy sources in a way that strictly compensates for the lack of energy production that may come from other sources while optimizing the whole system from a financial and technical standpoint. The elements of a hybrid energy system are mainly based on WT, PV panels, and an energy storage system such as batteries, to balance power supply and load demand.

GC technology, in general, does not require specialized software installation to operate. Once installed on the site, it just needs to be activated to make it work in a plug-and-play manner. It has pre-installed equipment to enable assembling and mounting solar panels and wind turbines even during snowy winter climates. Five different versions of GC are already designed and manufactured wherein detailed on-site assembling plays a crucial role in the longevity of the system. This affects directly the maintenance activities required on an installed GC. Taking into consideration the distance and access limits to installed GCs in remote and isolated zones, reducing human interaction and periodic maintenance activities on GCs are recommended. Maintenance is one of the main lifetime costs associated with standalone hybrid systems. It continues to grow in importance as part of a technical and economic strategy aimed at promoting all actions to ensure the availability and reliability of any equipment throughout its life cycle while preserving the safety of personnel in all circumstances. Assembly is a process in which two or more mechanical parts are joined together to further the operational purpose of the equipment. It is the process by which the mechanical equipment, as well as equipment that controls the flow of electrical current needed to operate everyday mechanical equipment, is put together to fulfill the goal of the system. Assembly operations require detailed documentation of specific procedures and intervention methods to be applied to the target equipment. In addition, learning how to operate new equipment usually requires retraining of the workforce. As a result, companies must be prepared to meet changing work demands by creating and maintaining training programs that uncover and leverage employees' skills.

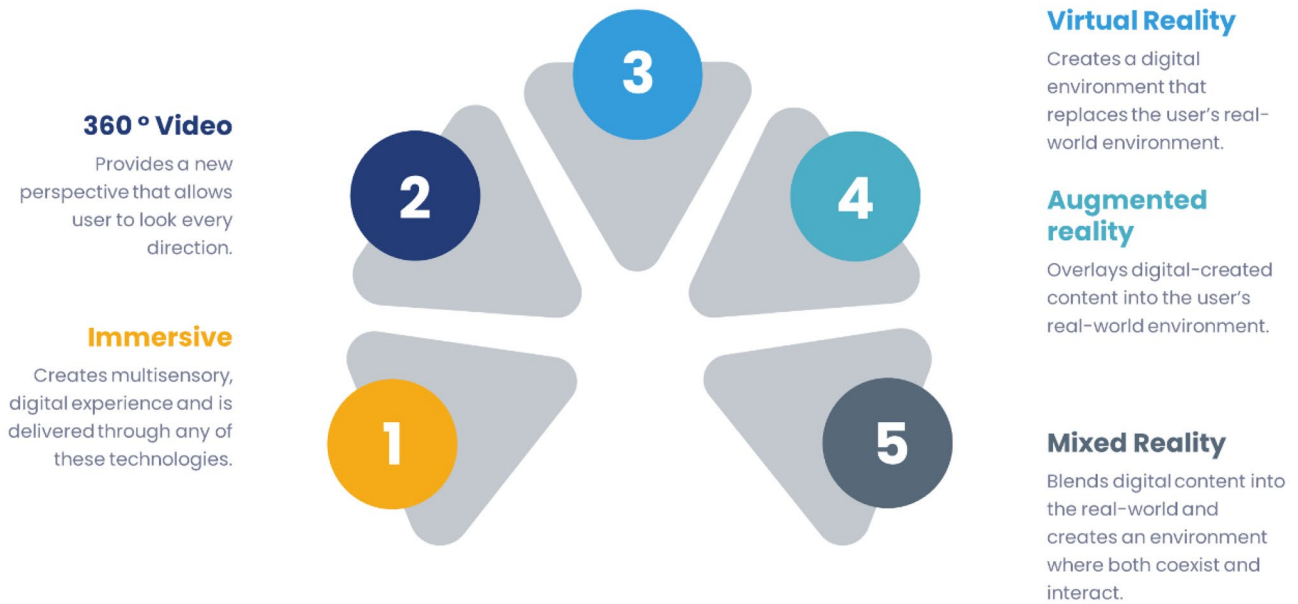


Fig. 1 The digital reality ecosystem [3]

### 1.2 Digital reality in the smart manufacturing era

Digital reality (DR) refers to a variety of technologies capable of partially or fully immersing users in a computer-generated virtual environment [3]. The schematic of the concept is presented in Fig. 1. DR is a framework of human–machine interfaces (HMIs), a group of Industry 4.0 applications including image processing, computer vision, and human–machine interaction. At the conceptual level, DR encompasses augmented reality (AR), virtual reality (VR), mixed reality (MR), 360° video, and other immersive experiences. The degree of immersion that the user experiences is based on an axis called the virtual-real spectrum proposed by Milgram and Kishino [4] and is illustrated in Fig. 2.

VR, the most immersive experience of the spectrum, does not combine real elements with the application. In contrast, AR superimposes information generated by a computer in a real scene while preserving a multi-sensory coherence with respect to the observed object [5, 6]. To understand the difference between VR and AR, it is essential to keep in mind that VR-based systems create a scenario with the help of a computer and give the user the feeling of being immersed in an artificial environment, while AR-based systems enhance the user's perception by overlying digital created content on their real-world environment. MR is an evolution of AR, as it also merges virtual elements into the real world. Unlike AR, MR produces new environments and visualizations that coexist and interact in real time [7–10].

Industrial applications can be developed within the entire virtual-real spectrum. For example, VR is suitable for certain situations requiring training in fine-tuning equipment

set-up. AR makes it possible to operate machines remotely, 24 h per day 7 days per week. Therefore, it could be advantageous to minimize displacement costs, reduce the risk of danger, or mitigate the exposure to harsh operating conditions. Moreover, AR applications have proven to be adaptable and highly scalable. However, they are often associated with technological drawbacks in terms of accuracy, robustness, tracking, and ergonomics [11–14]. The design of an AR-based architecture depends primarily on the choice of hardware, software, and HMI platform. At the hardware level, they can be equipped with hand-held displays (HHDs), head-mounted displays (HMDs), projectors, haptic elements, or sensors. The decision to use one device instead of another depends on the environmental conditions, the user, and the process requirements [15]. In the same way, the choice of software is made according to the information available and the compatibility with the industrial environment [16]. Lastly, the user interface must be chosen according to the feedback loop between the user and the system. It can be made of text, audio, 3D animation, or video.

This work proposes an AR-based methodology aiming to provide technical assistance for assembly operations of industrial equipment. In the present work, a standalone hybrid energy system, called GC, is used to demonstrate the

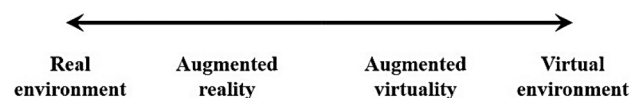


Fig. 2 Virtual-real spectrum [4]

application of our proposed AR platform in carrying out the assembly process. The remainder of the paper is structured as follows. Section 2 describes the literature review conducted to study the feasibility of AR integration. Section 3 presents the architecture and related methods for implementing AR technology. Section 4 presents the design and implementation of an AR-based architecture through a case study. In Sect. 5, the industrial challenges faced by current AR solutions are addressed. Section 6 discusses the conclusions derived from the present work and outlines future research directions.

## 2 Related works in the field of augmented reality

AR has gradually become part of our daily lives. It plays a role in a broad range of fields such as health, education, architecture, urban planning, marketing, and e-commerce applications, among others. Many works based on the principle of AR have been proposed since 1968, the date the first system was created. Although several works have been conducted on military applications in the early 1990s, the first major experiential prototypes emerged in the 2000s, particularly with educational and video game projects. Technological advancements in cameras and onboard systems have propelled the growth of AR applications since 2010, in part through the development of image recognition algorithms. Finally, since 2015, the number of manufacturers and new devices on the market has not stopped growing. The use of AR in industrial sectors has proven to be advantageous for part assembly, personnel training, and maintenance operations [17]. The application of AR in maintenance shows promising results by enhancing human performance when executing technical tasks, improving operations management, and supporting decision-making [6, 15]. Potential use cases for AR-based technology in industrial applications have been classified by Quandt et al. [18] into the following categories: product and plant design, training, production assistance, quality assurance, production logistics, and remote maintenance.

In [19], the authors assembling and maintaining machinery in a controlled multi-modal virtual environment is the main purpose of the industrial maintenance and assembly based on the augmented reality (IMA-VR) platform, which offers enactive training in a multi-modal virtual environment. By allowing multi-modal interaction (visual, audio, and haptic) with the virtual scenario, the system supports the active hands-on approach of “learning by doing.” This approach starts with a 3D graphical scene illustrating a maintenance task that appears on the screen. One haptic device is integrated, and a training program is used to teach and simulate assembly and disassembly. Then, by

manipulating the haptic device, trainees feel the contact between components allowing interaction with the tools and components of the virtual scene. In industrial maintenance and assembly based on AR (IMA-AR), the information is provided only on request via “virtual post-its” associated with tracked machine parts. If instructions are available for handling the part, an icon indicates that they can be selected. Selecting the icon brings up the instructions. Some examples in the literature [20–22] suggest that AR systems are suitable for industrial maintenance and assembly training programs.

Recently, Ishii et al. [23] created a VR-based training environment to construct maintenance training programs. Bhatti et al. [24] demonstrated the feasibility of using a VR system to recreate a physical training environment for people with visual impairments and physical limitations. The research described the uses of an interactive and immersive virtual environment to recreate a real physical training environment within the context of visual impairments and physical limitations. Moreover, a VR-based system for missile maintenance training was reported by Shu et al. [25]. Buriol et al. [26] consider VR as an effective way to perform real-time maintenance of power distribution networks describing VR as a way to perform real-time maintenance. Chang et al. [27] developed a simulation system for equipment maintenance training in substations presenting a training simulation system for electrical substations equipment maintenance. Contrary to VR-based systems, the trainee uses real instruments for interaction as part of an AR visualization and tactile feedback system [28].

Using a Product-Service System (PSS) approach, Moutzis et al. [29] presented an assistance application for preventive and unscheduled maintenance of manufacturing equipment. Industrial equipment maintenance involves a series of demanding tasks and is considered to be an essential activity during the lifetime of the product. This project is primarily focused on creating a tool that will enhance business-to-business (B2B) communication and will provide time and cost savings in maintenance procedures using smart devices. Specifically, an application is created, and it utilizes AR technology to detect and report malfunctions, define required tasks, and facilitate communication between all parties. A mold-making company is testing the developed application to digitize its production process. In terms of time, the first results showed that iterations with the customer were reduced, and maintenance lifecycles were also improved.

Martzis et al. [30] developed a cloud-based and mixed reality-based framework. Using MR graphical user interfaces (GUIs), the framework facilitates engineering team members during the design and manufacturing phase of new components. In addition to that, special emphasis is placed on how engineers can interact with holograms of components using simple hand gestures. This is done by taking



advantage of the advanced capabilities of MR devices. In computer-aided design (CAD) suites, 3D geometries could be imported for further development or production of parts. A laboratory-based machine shop is used to test and validate the applicability of the proposed framework.

According to Mohanty et al. [31], tracking accuracy and instability are among the biggest challenges to building effective AR systems, as they lead to registration and calibration errors. Studying AR applications in the fields of medical, engineering, simulation, route planning, entertainment, and military, they found that errors in registration and sensing are among the greatest challenges in building efficient augmented reality systems. In a popular study, Bellalouna [32] investigated the application of augmented reality technology in the industrial area. The article discusses the implementation of two AR applications and their potential to digitize product lifecycle processes by using industrial case studies. Case studies have been developed within cooperative projects between the University of Applied Sciences Karlsruhe and a fire truck manufacturer with the following topics in focus: product configuration management and assembly assistance. Using AR as technology for digital transformation along the product lifecycle, its potential applications in the manufacturing environment are explored. The authors presented their experiences with praxis-oriented AR technology on development and deployment in the engineering field, which can be adapted and utilized in future AR research. Mourtzis [33] discussed the major milestones in the evolution of manufacturing systems simulation technology. He also discussed the most recent industrial and research advances in key manufacturing fields. The article reviews the new approaches that have emerged in the literature as a result of the drive towards the digitalization of manufacturing. This is in the context of the 4th Industrial Revolution. The presentation focuses on advanced technologies that are gaining traction in industrial simulations based on digitalized factories, which offer multiple benefits.

Most related works have focused on specific areas such as assembly, installation, inspection routines, testing, overhaul, and repair. The work presented in [34] explores how AR can assist mechanics during maintenance and repair tasks in the military domain. The prototype developed reveals its usefulness when performing maintenance tasks, as it improves ergonomic maneuverability and reduces head movements compared to traditional approaches. Participants' responses confirmed the benefits of using the technology in terms of intuitiveness and comfort. Palmarini et al. [16] proposed a survey-based method to effectively guide users in identifying requirements and constraints derived from AR solutions to support maintenance tasks. Results are analyzed through graphs generated from the responses of the consulted experts and compared to the main trends found in the literature. However, the validation of the proposed methodology

has not been performed. Quandt et al. [18] discussed the general requirements for AR applications in an industrial context. The authors explored the potential benefits of this technology based on two case studies: an AR-based maintenance instruction for wind turbines (WTs) and an AR-based welding simulator developed for training and educational purposes.

Recently, Mourtzis et al. [35] developed an AR application to support remote maintenance operations in manufacturing industries. The main purpose was to establish communication between the on-site technician and the maintenance expert as soon as the presence of a malfunction in specific equipment was detected. The exchange of information between the two parties is enabled via a cloud-based platform. The results suggest that the developed application adequately meets the functional requirements in terms of cost and time savings for the given case study. Nuernberger et al. [36] presented a detailed work on AR technology applied to aerospace. The study aimed to evaluate the feasibility of using AR instructions for a daily maintenance procedure in an extreme environment. The authors focus primarily on assessing the crew's perceptions of using AR to help them execute maintenance operations. The analysis of the results demonstrates the relevance of the proposed approach. However, users suggest that substantial improvements need to be made, particularly concerning the navigability through all steps of the procedure in the user interface.

A proof of concept based on AR technology is developed in [37] as part of a strategy to assist users in the configuration and maintenance of various terminal regulators. The proposed platform is composed of two modules. The first one is the guidance module. It is responsible to configure the regulator model in real time. To do so, it creates a reference library based on the wiring diagram of each regulator model. The second is the maintenance module. It compares the configuration of the connected regulator with the reference model to verify and optimize the manufacturing operations. The results demonstrate that the developed AR application is suitable to guide both configuration and maintenance operations. However, further studies need to be conducted to test the transferability of the concept to larger industrial applications. AR-based applications have been gradually incorporated into maintenance strategies. Although, several factors may explain why companies have been cautious in adopting this technology into their processes. First, AR solutions are evolving to be suitable for industrial sectors, but their introduction to the industrial market is not competitive yet. There is also a natural reluctance among professionals to use tools that are often perceived as gadgets. This discrepancy may be explained by the lack of confidence in dealing with novelty, the fear to change, and even the generational gap. Finally, due to the lack of information and the fact that AR is a very recent technology, there is no exhaustive study

to prove that AR prototypes have significant gains for the industry in terms of investment costs, return on investment, and operational efficiency.

### 3 Materials and methods

This section presents the basic elements to build the AR architecture. It is intended to enable the collection, storage, retrieval, and transfer of information in a real-world environment to guide users during the assembly process. Thus, users can focus on the task at hand without alternating their attention between the equipment assembly and the instructions, which often happens using a paper file format. Figure 3 illustrates the flowchart of our proposed methodology. It consists of three main phases namely (i) geometric measurements, 3D modeling representation, and simulation; (ii) assembly sequence planning; and (iii) HMI creation for AR display.

Nowadays, software development kits (SDKs) are available for developers to create AR applications and experience them through smartphones, tablets, and smart glasses. Simultaneous localization and mapping (SLAM) and natural feature tracking (NFT) are tools used by these platforms to identify images and objects, as well as track them after identification. The development of these technologies enables the creation of digital content that can interact with the environment, inserted into the shooting scenes. Although most SDKs are intended for use in specific contexts and on particular hardware, the combination with AR-based technology has made them suitable for a broader spectrum of applications and enables more flexibility. AR applications could be divided into two groups. On the one hand, marker-based applications, where a camera is used to trigger digital content once a predetermined pattern is recognized. On the other hand, location-based applications rely on GPS and accelerometer data to determine the localization and orientation of the wearable AR device [28].

As a rule, the software for developing augmented reality applications is available free of charge or for a fee under a license, while open-source software is provided by Billingham et al. [38] and Syberfeldt et al. [39]. Despite this, we are inclined to use a licensed framework due to the features and support that it offers to develop a flexible and modular AR-based assembly tool. Additionally, there is the capability of comparing and contrasting the different SDKs according to the platforms supported by the devices and, more importantly, by the smart glasses supported. There is also no guarantee that every framework will support the development of applications for Android and IOS, and not every framework will support smart glasses. Based on existing literature, an assessment of the limitations and potential of augmented reality systems for managing and using content has been carried out. Miralupa Inc.'s MARGE™ platform is used in this project to design augmented reality experiences to span multiple device types and technologies across many different operating systems and technical standards, regardless of the venue or setting. An AR platform must connect devices and technology types across OS platforms and technical standards. It provides a robust, scalable, and customizable application providing full-spectrum analytics. It also provides quantitative and detailed results that assist users in understanding each step. The step-by-step AR-based assembly guidance process is presented utilizing a real case study on a GC and illustrated in Fig. 4; aspects arising from each step are discussed in the following sections.

#### 3.1 3D modeling representation and simulation

The first step involves the application of reverse engineering techniques to derive a 3D model of the equipment under consideration. It includes the sizing of each component to be computerized. This step is essential because a measurement error seriously affects the alignment between virtual and real-world objects when implementing AR technology

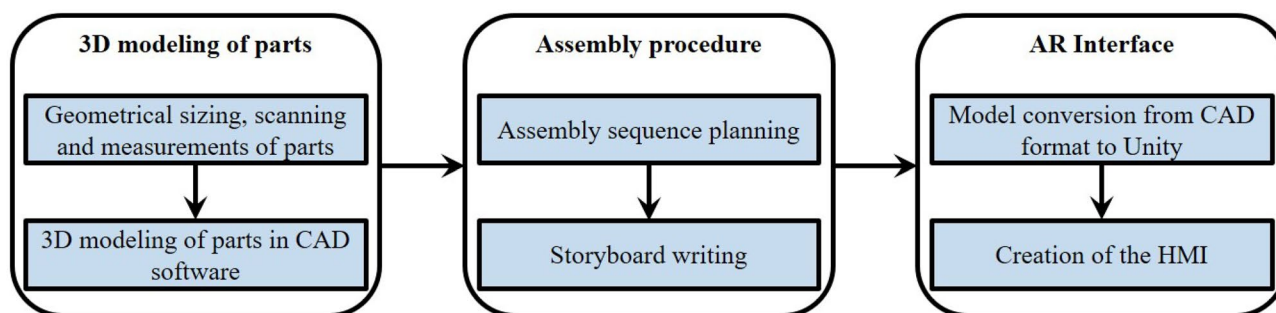


Fig. 3 Step-by-step representation of the proposed methodology

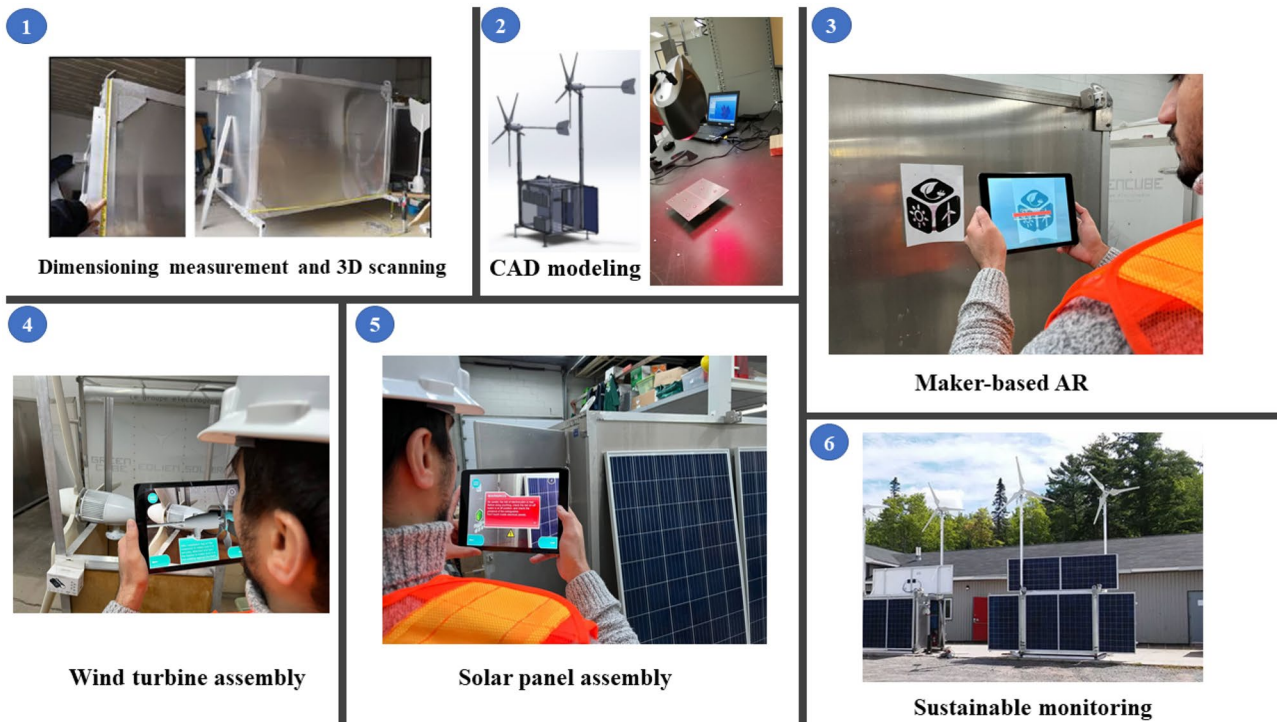


Fig. 4 Smart augmentation model

in the equipment. Thus, a 3D scanning method can also be considered. Assembly instructions can be augmented with a 3D representation of the equipment and a visual sequence of instructions [40]. 3D modeling is performed using computer-aided design (CAD) software in which the design criteria are verified using finite element analysis. This approach leads to the creation of files containing virtual models of each piece of equipment. The next step in the assembly process begins once all the details of the equipment are completed [41, 42].

### 3.2 Assembly sequence planning

This step consists in defining the requirements and the description of the scenario that will be used to assist the user during the assembly of the equipment. In this case, a sequence of instructions will be defined, and a list of objects to recognize will be deduced. Furthermore, a control history is recorded in real time and then reproduced by each user to give a clear vision of what remains to be done. A unique storyboard is used to visually describe the assembly sequence simply and intuitively. It details the actions to be performed such as assembly, alignment, and adjustment of parts. In addition, different sources of information such as texts, videos, 3D models, and the files contained therein can be consulted to troubleshoot problems related to handling and verification of the equipment. Finally, the process ends once all sequences are completed.

### 3.3 Hardware and software development process

This step consists in creating a communication link between 3D-modeled equipment and an AR development environment. Using a software development kit (SDK) or an application programming interface (API), information about the equipment (component, orientation, pose, etc.) is detected and highlighted, then the content is delivered in the form of video, audio, or text to describe the instruction to be done. Once the storyboard is written, the next step is to convert the CAD models into an environment that can handle the AR content using Unity technologies. In terms of algorithm development, the conversion involves four sequential steps:

- The 3D model used in our AR platform is prepared by extracting the geometry of parts and 3D objects in CAD models, using SolidWorks™, and converting them into triangulated facets presented in STL format. Then, these standard files are converted into a common exchange file format (e.g., FBX, 3ds, VRML, X3D) to enable their use in an animation environment (MARGE™ platform). This platform supports advanced user interaction capabilities for an AR experience. It allows visualizing the AR experience using ThruBox™ application, in which the modeled parts can be recognized. In this regard, a user can point to a marker through the AR hardware device to recognize a specific part of the equipment. The orienta-

tion and pose of each part can be manipulated to facilitate assembly operations. This also allows the experience to be shared and validated with any user.

- A unique fiducial marker is associated with the whole AR experience. Successful recognition triggers the delivery of the defined storyboard, including the 3D models of the equipment, each assembly scenario, and the actions to be executed.
- The 3D CAD models use a custom template to insert the fiducial marker associated with the AR experience. 3D representations are extracted from these files to provide information on each part of the equipment. Reducing the number of polygons in CAD models allows the size of a model to be reduced without losing geometric details. In cases where details of assembly methods are not included in the 3D models, such as small bolts and wiring, animations will have to be created from scratch in MARGE™.
- Files containing marker tracking settings, 3D models, and scenes are integrated through user experience design (UX). The experience is loaded automatically with a stop/continue mechanism or via pushbuttons used to advance the assembly process. The latter is illustrated in the storyboard. The instruction and the subsequent animation are expressed in each step/slide.

### 3.4 HMI creation for AR display

This step involves creating an interface that allows users to intuitively understand any instruction and safely interact with the equipment. It is composed of a set of graphical elements, and their appearance is defined by a command structure. The workflow guides the user through assembly instructions presented as a sequence of steps; each step

explains a single operation on a point-and-click basis. A button linked to the system allows the user to go to the next or previous step; the system then proceeds to recognize the next object in the assembly process. This step is completed once all assembly instructions have been processed. The interface should be as automatic as possible. The whole idea of a command-free interface is that it runs itself. AR experiences should be designed to require as little physical intervention from users as possible. This makes sense since users are looking through the device screen at an augmented picture, and it will be difficult for them to use gestures at the same time.

## 4 Implementation of the proposed framework

In this section, an AR-based platform is designed to guide an operator through the assembly process of a standalone hybrid energy system called Green Cube (GC). The GC shown in Fig. 5 combines wind and solar power as energy sources, a battery energy storage system, and a diesel generator. This innovative system represents a form of mobile microgrid capable of being easily deployed. It is a suitable system, capable of meeting the needs of sustainable energy production while remaining competitive in terms of fossil fuel consumption and CO<sub>2</sub> emissions. The application fields are also varied, ranging from the replacement of diesel generators in isolated and remote areas to temporary subsidization of energy supply in off-grid sectors of the population. However, there are major challenges associated with deploying this technology, including remote monitoring and maintenance, as well as performance evaluation to determine

**Fig. 5** 3D external view of a GC modeled in SolidWorks™: **a** front view and **b** rear view





if operational goals have been effectively achieved. The GC is a technology that does not require the installation of specialized software to operate, due to a handling error. Once installed on the site, you just need to activate it to make it work. It has another advantage of having pre-installed renewable energy systems; the PV mounting is done even during snowy periods. As mentioned before, there are five different versions of GC that are designed and manufactured. In the recent generation of GC, an augmented reality platform is developed to monitor in real time all the assembly processes and maintenance schedules.

The GC system must demonstrate a high degree of autonomy when operating without the supervision of an expert on-site. Furthermore, this system must be able to communicate with its control center, sometimes located several hundred kilometers away. In general, maintenance in a remote context is a critical issue for hybrid energy systems such as GC. The information, in the format of maintenance-related data, received at the control center may not only be used to detect patterns leading to failures in each of the units. It can also be used to determine, at the organizational level, the appropriate intervention scenarios in terms of reliability and cost-effectiveness. In Fig. 6, Ishikawa’s diagram is used to analyze the influence of the assembly process on equipment reliability.

Root cause analysis (RCA) is a step-by-step method for uncovering the cause of a failure. Ishikawa’s diagram or Fishbone diagram is one of the main tools used in RCA.

It provides an exhaustive list of possibilities causing variations or failures in a given problem. In general, RCA can be divided into four broad categories based on the field in which they are used: safety-based, production-based, process-based, and asset-based. Ishikawa’s diagram (fishbone or cause-and-effect diagram) provides a means of discovering the root causes of defects, variations, or failures in a process. Breaking down the root causes into successive layers helps to identify those that potentially contribute to a negative effect. In this work, materials, methods, environment, resources, and manpower were studied to determine the most important factors that cause costly and repetitive maintenance of the GC. Indeed, a proper and complete assembly of the parts reduces the need for maintenance and increases the level of safety and availability of the equipment [43].

In all maintenance planning, there is so much overlap with other separate and distinct functions. Fishbone diagrams, from the root cause analysis standpoint, are one method used in product design, quality defect avoidance or variation, as well as to identify factors that led to an event, hence their use in root cause analysis. Based on Fig. 6, the following categories are considered in our cause-and-effect analyses of GC reliability as a part of RCA investigation: materials, methods, machines, environment, means, and personnel.

The combination of these items results in some output or event. As an example, Maintenance Planning and Scheduling

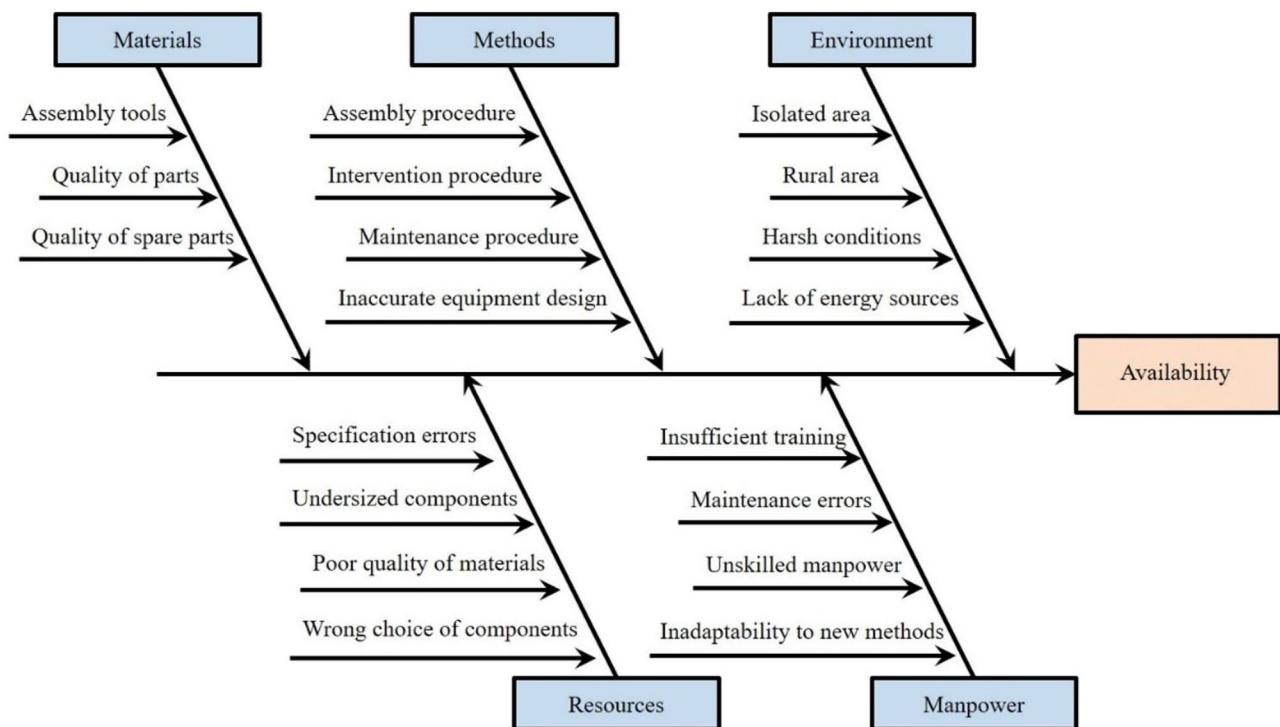


Fig. 6 Ishikawa’s diagram analyzes the most important parameters affecting the availability of GC

are hopefully combined to maintain or restore the reliability of equipment. In order to plan Maintenance Scheduling appropriately, we will need manpower estimates, estimated hours, and information regarding materials. In order to remain competitive, companies must constantly improve processes, reduce costs, and cut waste. Operation and maintenance (O&M) data must be analyzed with various tools and techniques to develop and implement effective plan strategies that lead to improvements in assets and processes. Recently, industry surveys have indicated that most organizations have begun to improve their processes, but they are still experiencing the same problems. Well-documented are the impacts on customers (internal and external), employees, profitability, and competitiveness of these problems. Formalized management systems such as ISO 9000, which guide management, contribute to a high level of visibility of such problems. Organizations are required to collect and analyze data on process performance by using audits, internal performance indicators, and customer feedback, as part of a new requirement of ISO 9001. Also, corrective action should be taken to prevent the recurrence of identified problems.

The Root Cause Failure Analysis (RCFA), also called RCA, is a method for uncovering the cause (root cause) of a failure step by step. It is imperative to address the root cause of a failure on time to prevent recurring failures, which cause loss of production and increase maintenance costs. To eliminate a problem, RCA must come to the root cause and not just treat the symptoms. An asset, component, or process may fail for a variety of reasons. A failure is typically the result of a series of actions and consequences. As a result of the failure, RCA analyzes the cause-and-effect chain to find its root cause. RCA's role is more akin to a detective at work solving a crime or to NTSB's role of making sense of evidence following a crash to determine what caused the wreck. It has been repeatedly proven by many organizations that 90% of unwanted situations caused by failures have to do with process problems, and only about 10% have to do with personnel problems. [44, 45]. Despite this, most organizations spend far more time searching for culprits than focusing on root causes. The result of this misdirected approach is that we miss the chance to find the root cause and eliminate the causes of unwanted failures. Materials, methods, environment, resources, and manpower are studied to determine the most important factors that cause costly and repetitive maintenance of the equipment. Indeed, a proper and complete assembly of the parts reduces the need for maintenance and increases the level of safety and availability of the equipment [43].

Given the complexity and the large number of components that constitute the GC, a sequence of assembly operations is required to reduce the time and effort spent to complete this process as safely and efficiently as possible. The developed

platform combines real objects with AR to perform elementary assembly and inspection of different components. For this purpose, step-by-step visual instruction is applied. Therefore, the user executes the instructions presented in 3D directly on the GC while looking through an HHD used as a hardware device. The AR experience is triggered and loaded by scanning a marker, as presented in Fig. 7.

#### 4.1 Pre-assembly

As shown in Fig. 8, the GC appears as “out of the box” or container. With the operator's safety in mind, the use of required personal protective equipment is reminded of employing the respective pictograms at the beginning of the AR experience. Before starting, the operator must ensure that the GC is correctly placed on the ground and horizontally aligned. To do so, two telescopic legs are disposed of on each side of GC to align the structure. It should also be verified that the GC door is locked and that the integrity of the equipment is maintained. When unlocking the door, make sure that the brake on the wind turbines (WTs) is in the OFF position. Before starting the assembly process, prepare the following tools: a 12-mm wrench or a torque wrench with a 12-mm socket, and two Philips screwdrivers with a size 2-point. In addition, make sure that the WT's masts (one 9-ft mast, and two 7-ft masts) and the lifting pole are located on the roof of the GC. The masts should be disassembled and placed on the ground as close as possible to the corresponding position on the GC.

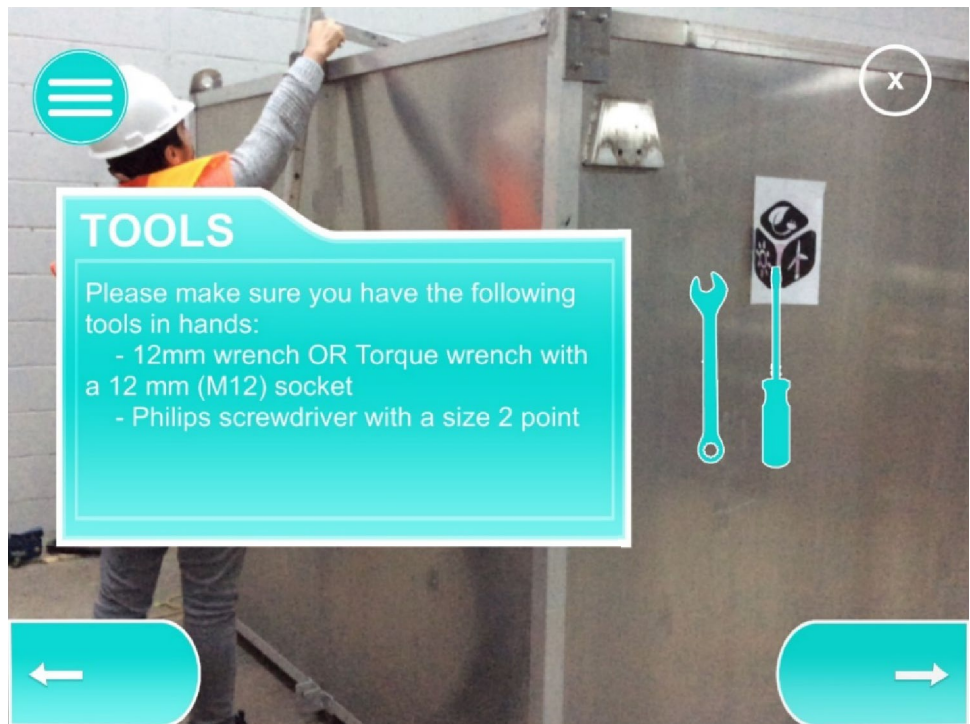
#### 4.2 Wind turbine installation

Wind turbines (WTs) are assembled in four main steps: mast structures, wind turbine core assembly, wind turbine, and mast lift. These steps are further explained in the following sections.

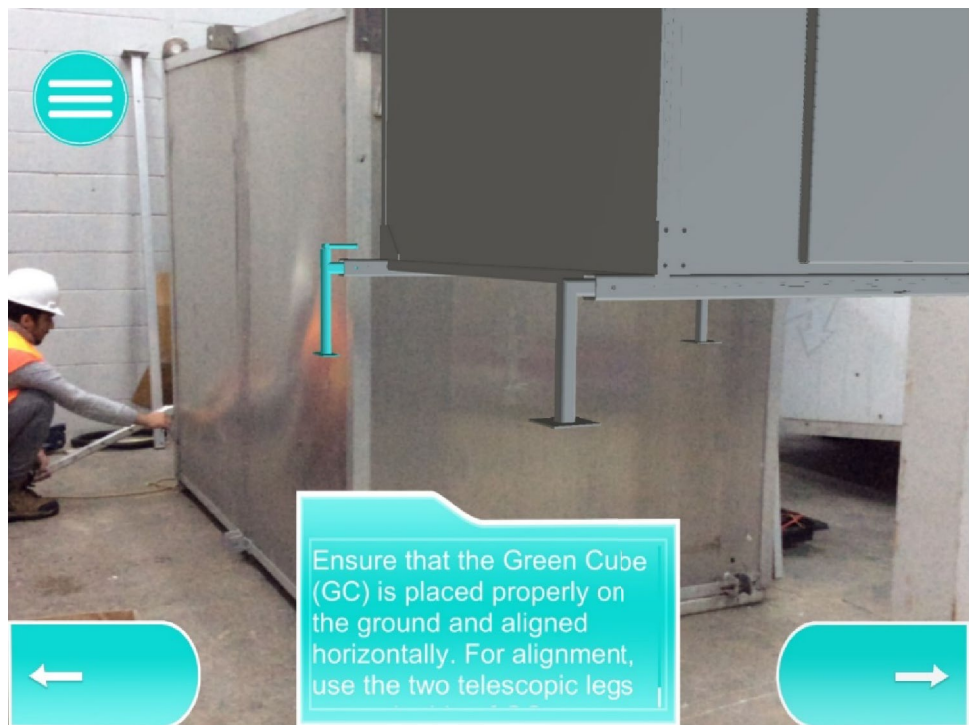


Fig. 7 Marker detection to trigger and load the AR experience

**Fig. 8** Pre-assembly of the GC: **a** required tools and **b** telescopic legs to support the GC



(a)



(b)

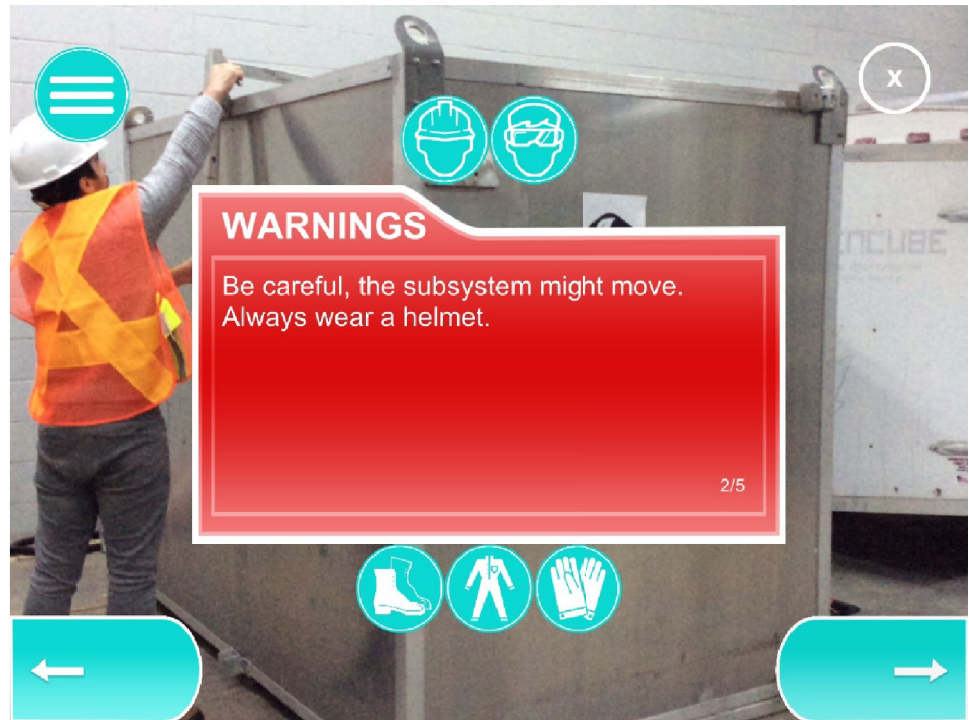
#### 4.2.1 Mast structures

Unlock the GC’s door with the key provided and remove the following components: a 4-ft mast, two mast connection pieces, ropes, screw bags, and cable bags. Keep the two WTs

and the four photovoltaic (PV) panels inside the equipment to protect them from any damage during the installation of the masts. Connect the 9-ft and 7-ft masts using the connection pieces and repeat the same process for the 7-ft and 4-ft masts. As shown in Fig. 9, use the appropriate mounting



**Fig. 9** Deployment of the mast structures to support the WTs: **a** assembly precautions and **b** mast structures' assembly



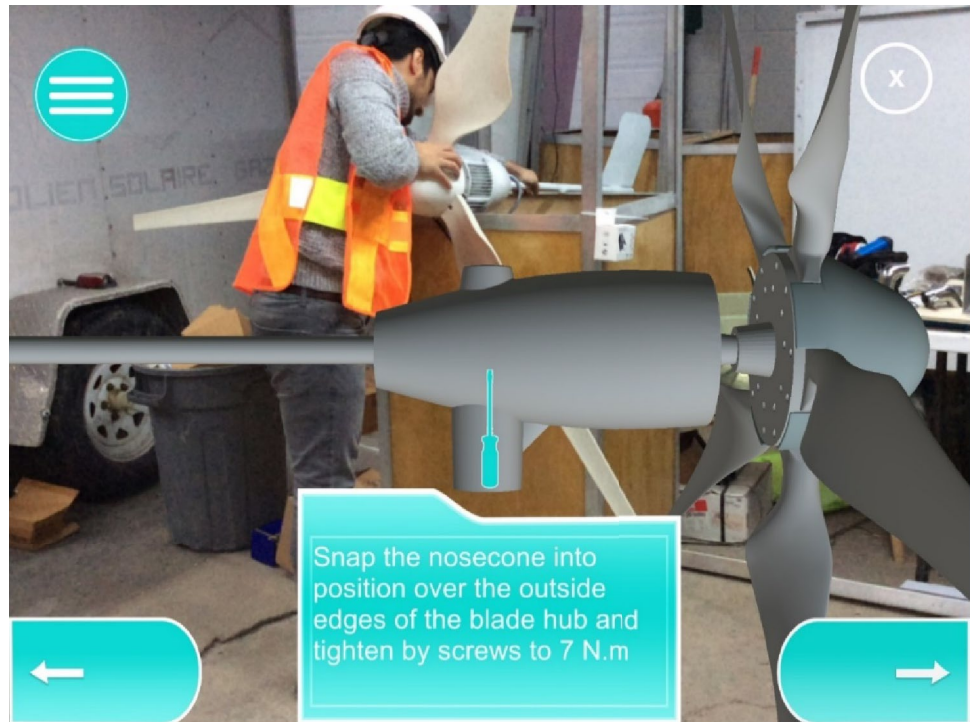
(a)



(b)



**Fig. 10** Deployment of the WTs: **a** Generator and tail vane assembly, **b** WT connection to the flanges



(a)



(b)

plates and bolts to join the two masts together. Once linked, set them aside near the connection points on the GC.

#### 4.2.2 Wind turbine core assembly

Figure 10 shows the deployment of WT components and their assembly. To do this, carefully remove the WT components from the GC and its packaging. First, connect the WT with the corresponding cable, then connect the WT body to the mast flange. The assembly of the generator and the tail vane is done by inserting the tail vane into the groove on the back of the generator; pay attention to the flange bore alignment with the back of the generator, then tighten the bolts to 35 Nm. Before connecting lead wires to the WT, unscrew the cable cover and pass the long wire through the cover to connect it to the main cable passing through the masts. Connect the three-phase lead wires to the terminals. Finally, screw on the cable cover and the waterproof cover. Pass the WT cable through the masts and mount the WT on the mast flange using bolts. Then, fit the flat washer, spring washer, and nut and tighten the nut to 60 Nm. Set the mast carefully to avoid damage to the generator and tail of the WT. Mount the blades to the hub by fixing the blades, flat washers, and locknuts and tighten them to 30 Nm. Repeat these steps for the second turbine.

#### 4.2.3 Wind turbine and mast lift

Mount and install the gin pole on the opposite side of the mast using bolts and nuts. Move the mast and WT assembly close to the GC connection point and connect it using bolts and nuts. Use a bracket to support the mast at an angle that permits the installation of the hub and blades. Partially raise the mast and WT body about 30° to the horizon. Connect the WT generator to the hub and nosecone. To do this, place the hub with the blades on the rotor shaft and rotate it fully onto the WT shaft, then place the flat washer, spring washer, and nut in sequence. Tighten the nut to 500 Nm. Snap the nosecone into position over the outer edges of the hub and tighten the bolts to 7 Nm. After installation, pull the nosecone to make sure it is securely attached and rotate the blades to make sure it is not rubbing against the front cover of the generator. Figure 11 shows the steps to lift the WT. Connect the winch cable (on the gin pole) to the mast eyelet and hoist it in place with the winch. Create two harness cables using the components provided. Secure the mast and WT with bolts, nuts, and securing cables and raise them to 90°. Repeat the mentioned steps for the second WT and mast.

#### 4.3 Solar panels

Figure 12 shows the deployment of solar panel components and their assembly. To do this, carefully remove the components from the GC and its packaging. Install the two middle

solar panels on the south-facing wall of the equipment and fix them with screws. Route the solar panel cables through the hole behind the solar panels and plug them into the electrical sockets of the GC. Install on both sides the fixing arms of the two side solar panels and secure them with support rods. Finally, connect the electrical cables from the side solar panels and WTs to the terminals on the outside of the GC.

#### 4.4 Plug and play

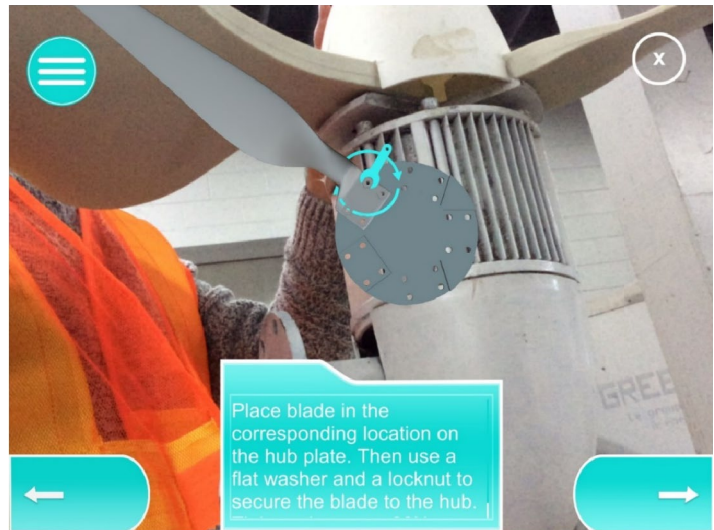
Before connecting the cables from the solar panels and the WTs to the GC terminals, verify that the circuit breakers in the control compartment and the main switch on the battery pack are turned OFF. Then, connect and turn on the battery pack. To do this, press and hold the right button on one of the batteries for 5 s. The other batteries will automatically light up. Turn the main switch of the battery pack to the ON position. Also, start up the four solar panels and both WT chargers by turning on their switches. Finally, be sure to close and padlock the GC door. There are three different ways to connect a GC: to power a device with an AC 110 V output, to connect it to another GC, and to connect it to the grid. At any time, the user can navigate through each one of the controllers to access system operating information. Figure 13 presents the GC fully assembled.

### 5 Results and discussion

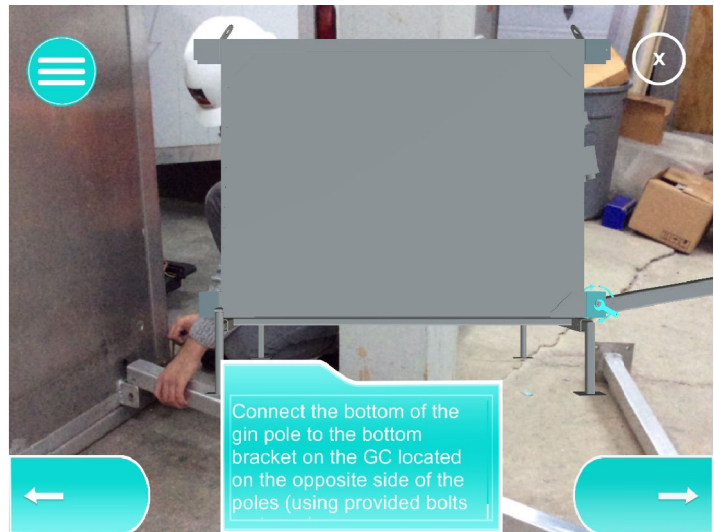
An interesting finding in this work concerns the adaptability of AR prototypes to different application contexts and operating modes. At this stage of technological development, AR systems cannot replace human expertise, but they can be very useful compared to paper-based materials and procedures [17]. AR can be integrated into the roadmap of any project in any organization. For instance, it can be used to train maintenance professionals and help them to achieve significant tasks accurately and efficiently. More precisely, when it comes to procedural guidance during assembly and performing quality compliance inspections, AR-based systems enable fast and accurate task execution. However, existing data on the use of AR for assembly guidance neither support nor refute the hypothesis that simultaneous mixing of 3D models with the physical world facilitates the understanding of technical concepts.

Data and object connectivity are the defining factors of Industry 4.0 technologies. This principle combined with the development of cyber-physical system platforms allows information from sensors or operational processes to be continuously obtained and securely transmitted to data centers. This massive production of data requires evaluation and subsequent analysis to establish the system's health state, predict future behavior, and propose optimal solutions

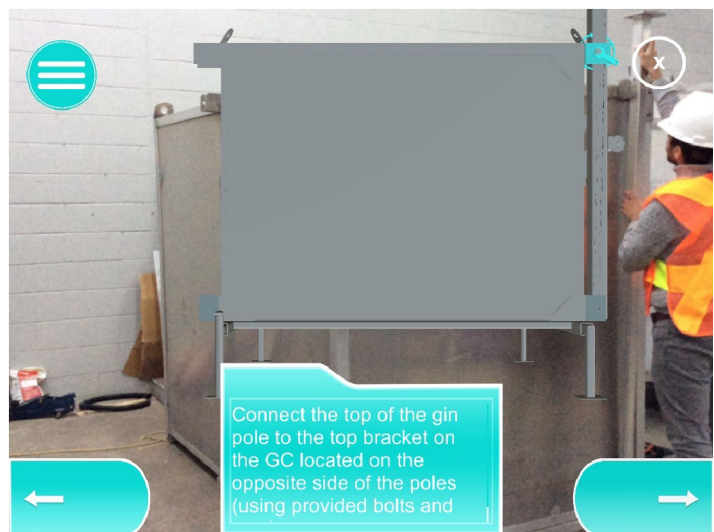
**Fig. 11** WTs lifting: **a** mounting blades on the hub, **b** mounting masts on the structure, and **c** lifting WT and mast in the vertical position



(a)



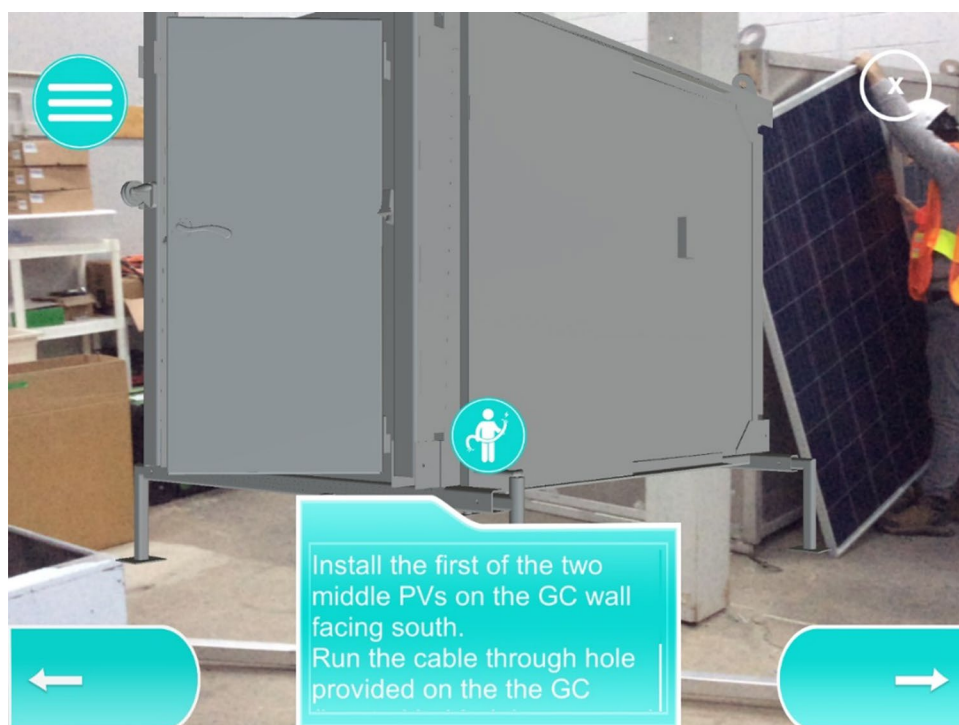
(b)



(c)



**Fig. 12** Deployment of the solar panels



concerning operational and maintenance processes. In complex equipment such as the GC, there are several operating modes including those associated with failures. The equipment is considered to be in failure when it is unable to perform the functions for which it was designed.

Traditional maintenance involves running the equipment until it fails. In general, this type of maintenance is unplanned: after a failure is detected, the damaged component is replaced or restored to a proper working condition [46]. Similarly, preventive maintenance is based on the evaluation of the physical condition of the equipment, which can be assessed by operator inspection, carried out according to a schedule, or by continuously monitoring performance parameters. These types of maintenance are expensive, and the useful life of the equipment is not optimized.

It is well known that a large number of catastrophic failures have occurred due to inadequate design, improper repairs, installation errors, and unnecessary preventive actions in equipment. For instance, in mechanical engineering, applications such as rotating machinery, shaft alignment, balancing of rotating components, lubrication fitting, calibration, and baseline measurements (vibration, temperature, torque, etc.) are key factors for safe and reliable operation. Contextualizing information and understanding why and how equipment fails, as well as the root causes, are essential in the decision-making process.

Generally, the design of a hybrid energy system depends on both the resources available and the load demand [47].

The GC is continuously monitored, and maintenance is carried out every 3 to 5 years, except in the case of WTs, which are inspected twice a year at 6-month intervals. Basic maintenance activities include lubrication and cleaning of moving parts, alignment, tightening of junctions, and control systems verification, among others. Hence, corrective and preventive maintenance are often costly and lead to undesired equipment downtime. AR is a suitable solution to explain and train personnel in the execution of repetitive instructions. It allows operators to stay connected to relevant digital information while moving within the physical space of a facility.

WT alignment requires a high level of precision [48]. The gearbox and blades are seen as one of the most critical components of WTs. Like all mechanical mechanisms, they are subjected to a wide variety of failures [49, 50]. In a wind turbine, diminishing dimension faults provide manufacturers with self-confidence in the precision of the data. Also, it allows the design of extra aerodynamically efficient and prototype blades accompanied by other large-scale manufacturing. In fact, shaft and blade alignments are the most critical objects in maintenance problems. In this regard, the accuracy of shaft alignments includes aligning the centerline of the shafts of one or more rotating machines.

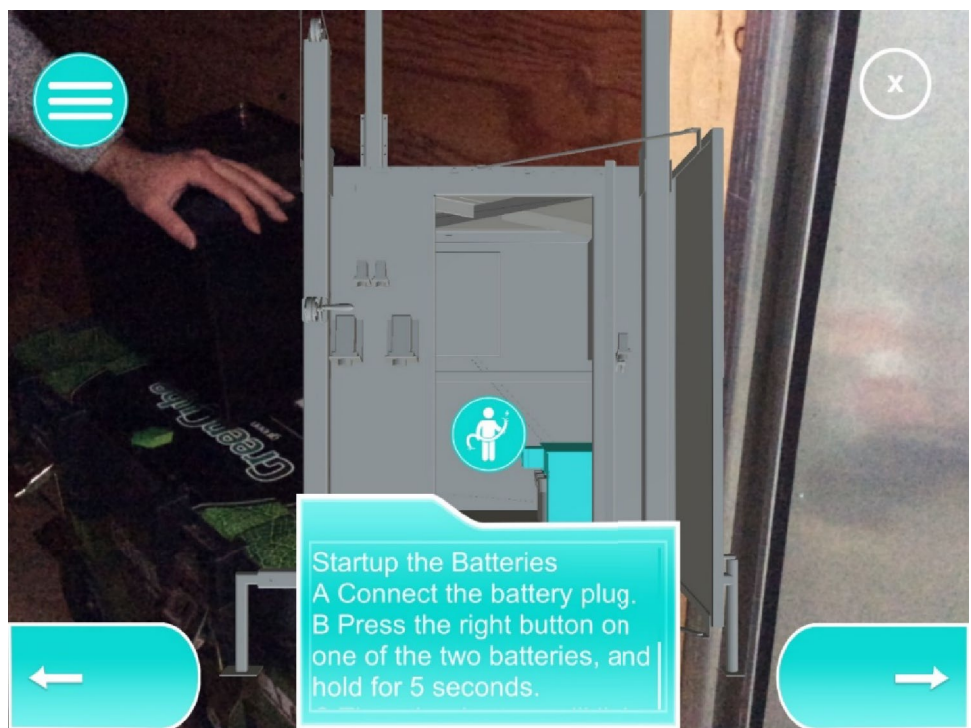
Meanwhile, the two turn freely, mitigating external forces that could destroy key components of the system once the shaft centerlines are co-linear, for example, bearings, seals, and couplings. To this end, AR proposed a safe procedure for installation in real time by inserting the tail vane into the



**Fig. 13** Plugging GC's components: **a** fully assembled GC and **b** battery pack, chargers, and controllers inside the GC



(a)



(b)

groove of the back of the generator. In this case, it should be noticed that the flange bore alignment with the back of the generator, and then tighten the bolts to 35 Nm, not more or less.

Primarily, WT maintenance is performed at an altitude of over 300 feet. Hence, the altitude restrictions impose new requirements in terms of accuracy, robustness, and ergonomics of the application. Robust and accurate camera attitude

constraints are a requirement for a diversity of requests such as interpretation, and dynamic scene analysis, 3D scene structure extraction, and video data compression would be a tough action.

Despite the growing number of applications found in the industry, there are still technological limitations to overcome among hardware, software, and user interfaces to select, integrate, develop, and query virtual content in AR systems. AR is a data and computationally intensive application where the challenges of computational capacity, data management, network access, compatibility, and interoperability must be addressed. Furthermore, both computational and rendering algorithm capabilities of mobile devices play an important role in the implementation of an efficient runtime environment for AR applications. Additional research is required to achieve more conclusive evidence to assess the cost-effectiveness of the implementation of the technology.

### 5.1 Accuracy

An AR application is considered accurate when it gives the illusion of a visual, haptic, or audible coexistence between the two worlds perceived by a user. Alignment between real and virtual objects requires a high level of precision in the acquisition, tracking, and superimposing of the augmented information [2, 10]. A major source of alignment errors comes from data transmission, synchronization, or computational delays between the time an observer moves and the time the image that corresponds to the observer's new position is displayed. This time difference is called end-to-end latency, which is important because movements such as head rotation can be very fast, and this would cause significant changes to the scene being observed.

### 5.2 Robustness

In computer vision, an optimal way to ensure robustness is to use recognition algorithms. The performance of the algorithms depends on the orientation of the camera and illumination conditions with respect to the object to be identified. For this purpose, taking into account the data from the relative position of the components on the equipment, shape, and colors resulting from the real scene in the virtual scene, a transformation of coordinates will partially correct the effects of misplacement. The chosen level of reality in virtual settings will determine AR quality with respect to the associated processing speed.

### 5.3 Ergonomics

A human-centered perspective is essential when developing AR applications. Their design and operation should be

optimized to maximize user experience and simultaneously meet comfort requirements [16]. Ergonomics is a key parameter in the design of the assembly process; its objective is to adapt equipment and workstations to the capabilities and needs of users. Indeed, rather than consider the individual design of each component of the equipment, attention should be directed towards the interaction of the components as a whole, especially when multiple, complex, and dynamic systems are interconnected.

Poor visibility and lack of knowledge of the location of the components on the equipment, coupled with uncertainty about the instructions or assembly/disassembly trajectories to be followed, are some of the constraints faced by the operators during maintenance activities. Including this analysis at the earliest stage of development of augmented reality applications facilitates detection and prevents unpleasant user experiences. However, this is not often adopted in the field of emerging technologies, where designers are mainly interested in technological advances, and the real needs of future users are left in the background.

Various industries need to train technicians to acquire updated assembly and maintenance skills. It can be extremely difficult to train technicians to perform new skills efficiently due to the complexity of maintenance and assembly tasks. Augmented reality can be used to support the training of this type in an industrial setting. This technology directly links instructions on how to perform the service tasks to the components that need to be serviced. It is not sufficient to train technicians in executing maintenance tasks due to the increasing complexity of maintenance. The underlying skills—sensorimotor and cognitive—that are necessary for technicians to carry out new maintenance operations efficiently must also be taught. A training system that enables technicians to quickly acquire new maintenance procedures must be implemented to enhance the training process for maintenance and assembly skills. As a result, these systems would make training more adaptable to a variety of training scenarios and would enable more reusing of existing training materials. Using augmented reality, we have developed a novel assembly guidance process for a stand-alone hybrid energy system in order to train assembly skills, including subskill training and evaluation of the training system. Therefore, this concept is being monitored over a long period of time to create a comprehensive dataset for the maintenance 4.0 structure. Maintenance and assembly operations require the most procedural skills, so we emphasize these skills and methods to improve them. Maintenance tasks performed using AR are included in the reliability maintenance operation characteristic. They are categorized into four groups: Dis/Assembly, Repair, Diagnosis, and Training.

As can be seen, these are the categories that were mentioned most frequently in the filtered list of papers identified

for two different assets including mechanical and electrical assembly. Almost every paper that discusses the development of an AR system describes how the technology developed can be used to support one or more maintenance operations. Moreover, the hardware characteristic consists of the devices utilized in the AR system. Regarding the development platform (Mid/Low-level languages, Libraries of functions, SDK (Software Development Kit), Game Engine, 3D modeling), SDK is implemented. Moreover, the tracking characteristic consists of the tracking technology or principle utilized in the AR system developed by the authors, and the Marker-based concept is carried out with Dynamic 2D/3D Interaction method characteristic. Overall, the aim of this research is the first step of maintenance 4.0 which is to start from the right electrical connection of the wind turbine and solar panel procedure.

## 6 Conclusion

In isolated communities, electricity is usually produced by diesel generators, as a connection to central distribution networks is difficult and expensive. Diesel generators whose operation requires the use of large quantities of fossil fuels pose serious environmental, social, and even economic problems. They contribute to greenhouse gas emissions and global warming. The solution proposed by the scientific community is the use of renewable energies, available free of charge, with a very low level of pollution compared to diesel generators. The installation of a renewable energy system (RES), especially in isolated sites, encounters problems of operation, maintenance, and diagnosis. Indeed, it is very important to know the potential of renewable energy to know how to make a compromise between the cost of the project and its financing. In this article, the assembly challenges of a hybrid renewable energy station are studied which powers a camp in an isolated area in northern Quebec; more specifically, we carried out a feasibility study for a renewable electrical energy supply to a base station in an isolated area with a combination of GreenCube (GC) modules and proposed energy-saving solutions to reduce the load and delay the use of generators, but have a high penetration of renewable energies and contribute to reducing the emission of greenhouse gases.

AR is considered an emerging technology in industrial applications. It represents a suitable mechanism for remote monitoring and helps users understand how to install, operate, and maintain equipment on-site. On the one hand, AR allows control center operators to assess the status of equipment by visualizing historical or real-time observations and providing technical support for troubleshooting. On the other

hand, it offers step-by-step guidance to unfamiliar users for the installation and maintenance of equipment. In this work, the feasibility of using AR in a real industrial environment was demonstrated by an application serving as proof of concept for assembly guidance. To this end, a 3D model representation of a standalone hybrid energy system is generated, and the assembly sequence process is animated in an AR platform. Then, the AR experience is validated on-site to ensure the recognition, traceability, and orientation of the parts to be assembled. The proposed work contributes to the emergence of new AR applications. However, further research is needed to fully address the accuracy, robustness, and ergonomics challenges outlined above, as well as to add troubleshooting capabilities to the assembly process. Future works can also take into consideration an exhaustive comparison of using AR-based assembly tools with respect to conventional assembly activities in terms of safety, precision, operation rate, reliability, etc.

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**Author contribution** The authors' contributions are as follows: SSK, RES, and HI conceived, planned, and carried out the experiments; SSK, RES, YCEO, AA, MD, and HI contributed to the measurement interpretation, visualization, and analyses of results. SSK and RES took the lead in writing the manuscript, and AA contributed actively in writing the manuscript; all the authors provided critical feedback and helped shape the research, analysis, and manuscript.

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**Availability of data and materials** All data, material, and codes used in this paper are available.

## Declarations

**Ethics approval** This article does not involve human or animal participation or data, therefore ethics approval is not applicable.

**Consent to participate** This article does not involve human or animal participation or data, therefore consent to participate is not applicable.

**Consent for publication** This article does not involve human or animal participation or data, therefore consent to publication is not applicable.

**Competing interests** The authors declare no competing interests.

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