Bringing Building Data on Construction Site for Virtual Renovation Works

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***Abstract*— In this study we aimed at evaluating the benefit of managing a digital mock-up for renovation operations in an ancient building. Focusing on thermal efficiency, the renovation proposal dealt with the great windows. We compared three methodologies dedicated to the project planning and management We first address the issue of the renovation of old buildings and come up with a workflow that connects the digital building to its lifecycle; then we focus on an instance of onsite handling of such data, in an augmented reality context, by elaborating the notion of "BIM in situ" as described in the papers of [3] as well as in [4]. Results reveal that handling BIM onsite through a mobile device is challenging but they also show that it brings more efficiency.**

***Keywords*— Mixed and Augmented Reality, AEC, heritage, BIM**

I. INTRODUCTION

Mobility has become a crucial need in today's society. This study aimed at evaluating the impact of mobility in the construction field, as far as renovation operations are concerned. The "Arts et Métiers Paris Tech" engineering school is located in former Cluniac abbey buildings. Dating back to the eighteenth century, the buildings are poorly insulated and this leads to dramatic thermal losses. The investigations suggest a renovation scenario on one of the hundreds of windows in the main building. Upon past studies [1] as well as on the advice of an architect, we chose to double the window's inner panel: The current woodwork being kept, the exterior aspect of the monument is unchanged. The inner configuration of the building remains consistent with the addition of a new partition wall mounted with a new window. Fig 1 illustrates the renovation project.

Fig. 1 Current configuration (left). Projected configuration

II. RELATED WORK

This section studies the evolution of the uses of BIM (Building Information Model) in a mixed and augmented reality context. The first sub-section is an overview of the added value of BIM. The second sub-section defines the concept of augmented reality. The third sub-section mentions a few past projects to expand the use of augmented reality in the field of AEC (Architecture Engineering Construction).

A. The Building Information Model to Warrant Efficient Building Management along its Lifecycle

Nowadays, innovation in AEC fields regarding the use of ICT has revolutionized building design. The use of a 3D model or digital mock-up has become a common practice in the design phase. The approach to building design is very different from the conventional use of CAD software known in the industry as the Building Information Modeling (BIM). BIM is an innovative approach to building design, construction and management that enables collaborative work between building agents throughout the project's lifecycle. What's more, the ever faster development of micro-technology enables to present and handle the digital mock-up directly on the construction site: Advanced mobile devices such as smartphones and digital touchpads can be operated to plan construction sequences; to monitor as-planned and as-built; to visualize the details of the shape of any specific 3D component; and to analyze the simulations needed before and during the construction process

The literature shows a progression in the use of Digital mock-ups to describe architectural projects throughout their lifecycle. Like the Digital model dedicated to automotive design and aeronautics, construction agents have considered the BIM as a powerful unifying tool which optimizes, upstream of its construction, the detailed definition of a building project. Simulations of various kinds (acoustic, thermal, sunshine…) are carried out so that the project may follow the latest designing specifications. This mock-up is implemented using an international standard format « .ifc » promoted by the Building SMART alliance. It consists in a geometric and parametric database embedding numerous associated metadata. This mock-up aims at gathering a meaningful set of data for understanding the architectural project (3D); it also targets proper critical path analysis, schedule management (4D BIM) and costs monitoring (also known as 5D BIM). Nowadays, this model proves to be powerful and cost effective in real estate management but also in managing large-scale construction projects. This concept is being adopted by the key-players in this field and also by local authorities. On this topic, the American company « McGraw Hill – construction » carried out a survey in 2009, advocating the full-adoption of the BIM concept in the AEC field [2]. This study outlines numerous financial benefits and it presents the most advanced projects.

However the Building Information Model is rarely used in managing the renovation of old buildings.

The AEC field involves various skilled agents and produces complex activity and technical knowledge. During the course of a project, the project team may generate multiple workflow models. Typically the architects generate an As-Designed model to depict the design intent of the building, and the contractor generates an As-Planned model to simulate the construction and analyze the constructability of the building. The construction team should provide input for the As-Designed, while the design team should provide input for the As-Built. While collaborating on the field these construction agents (from the architect to the site manager) commonly use paper to store, edit, and exchange data.

B. Computer Graphics to Enhance the Knowledge of one's Surroundings: Mixed and Augmented Reality –

The investigation explored through Milgram's Continuum (Fig 2). It also refers to the definition of augmented reality, meaning that they aim to enrich the user's knowledge of their surroundings through contextual virtual data. Virtual augmentation can be from various kinds. In this paper the focus is on visual and knowledge augmentation: Projected configuration (that means after the renovation works) is visually revealed. Moreover, data information (parameters) is retrieved so that the user upgrades his knowledge.

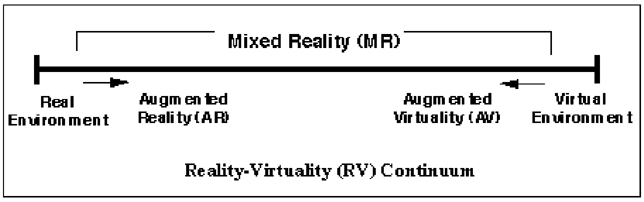

Fig. 2 Milgram's continuum [5]

Most of time augmented reality mixes live stream with virtual components. This study focused on fully virtual navigation into the mock-up.

C. Related Experiences Involving Augmented Reality in the Construction Field –

Augmented reality for building and construction (AR4BC) is a project led by the VTT research technical Centre between 2008 and 2010. The project explored the workflow of providing onsite BIM Digital mock-ups. It was focused on temporal aspects (4D mock-up) in order to compare scheduled tasks ("as planned") with actual advancement of construction works ("as built") [6]. Researchers developed their own software tools [7] enabling to geo-reference the mock-up of a building and to superimpose it onto a camera video stream. Research laboratories keep exploring [8] innovative applications in mobile computing with construction projects. Until now they have only focused on exterior applications on new construction. However the scope of this research mainly considers planning and monitoring of interior rehabilitation work. But those works were useful to build the workflow and advocate for the relevance of such a tool.

D4AR (4D Augmented reality): This partnership between the universities of Illinois and Michigan highlights the favourable contribution of taking into account temporal aspects in the definition of an architectural database (4D BIM). The referred article [9] describes the temporal monitoring of a construction project, by capitalizing daily automated geo-referenced shots of the "as-built" project. Collected pictures stand for a comparison-making tool of the "as-planned" and "as-built" states. Deviation in the schedule can be more easily detected.

The C2B (pronounced "see to be") project was carried out by Dutch organization for applied scientific research TNO [10]. This system brings a construction project on the field so that workers can have a clear overview of the work in progress. It mainly targets to avoid construction failure as well as to limit security risks. The system combines virtual elements with a real video stream. It provides an augmented jobsite. This project is really exciting but there is no mention of the Building Information Model.

Arviscope (University of Michigan). This thesis dissertation [11] proposes an approach which enables to visualize simulation through augmented reality. It deals with operation simulation on the jobsite. The recommended solution contains two main topics: Augmented reality and software development (Arviscope); Mobile computing (Rover) and related technological solutions. This approach limits CAD modeling to the project and reduces data collection tasks so that this gain can be reinvested in increasing the realism of the mock-up; with which it is easier to communicate with partners.

III. Scientific Questions

A. Research Issues

As illustrated in Fig 3, the latest information validation is processed through sequential steps: The architect designs a concept which is dimensioned by structural engineers. Mechanical, Electrical and Plumbing enrich the project with technical implementation. Then the onsite user gets information through printed paper documentation which is linked to an already expired release of the project (maturation state: t-1). This paradigm implies a long and critical path before the information, generally out of date, is supplied to the end user.

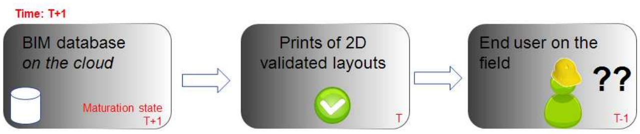

Fig. 3 Data maturation state at t=T+1 along the validation path

The following issues encountered with a paper-based process argue for novel work methods:

Data "out of/up to date" management: Data often change between agents, from minor (one note written on a layout on the field) to major revisions. Thus the challenge consists in optimizing the decision path.

Lack of flexibility: Data remains unknown if the request has not been anticipated (one detail on a drawing). Moreover, taking into account onsite revisions between agents is a long and tedious process. In 2004, the National Institute of Science and Technology (NIST) conducted a survey to analyze extra costs due to the lack of interoperability in a construction pipeline [16]. Their results argue for an alternative workflow, optimizing the exchanges between the partners in a project.

Sustainability of data throughout building lifecycle: The paper-based process does not warrant secure and rigorous information archiving. Dramatic consequences in construction/renovation works often occur: Imprecise data from the actual ground may lead to surprises (discovery of MEP networks)…

Related extra costs [16]. In addition to the management of releases of any document which dramatically increases weekly prints (up to 4000 printings per week according to the Bouygues Construction company, example being given for a 126k square meters project, priced at 260 million of euros), a noticeable amount of energy is spent to retrieving or (re)generating information, detecting and correcting mistakes, mediating according to each partner's prerogatives.

To conclude, the traditional paper-based methodology appears to be inadequate to obtain relevant contextual data as well as to access information. It raised the question of onsite collocation approach: Does it enhance building progress monitoring? This article aims to answer this question through the current case of the "renovation of an ancient building"

These statements account for novel paradigms. The workers in the field and the engineers in the office, require a work management tool which provides up-to-date data: Interaction and changes on the project has to be constantly updated during every construction steps. Providing onsite interaction on the 3D BIM (or 4D, 5D), the workers on the field are supported in conducting the project: up-to-date data management, lack of flexibility, and sustainability of data along the building lifecycle are overcome all at once. The principle of data access should be improved as it is shown in Figure 4.

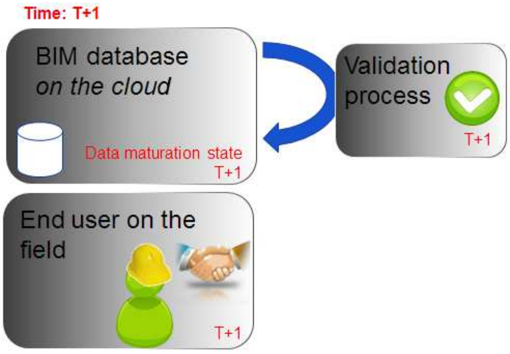

Fig. 4 Alternative proposal enabled by shared BIM management

The end user needs to get contextual and collocated information. Therefore, the geo-location system used to bridge the work process has to be focused on high accuracy. The device should enhance the user's mobility in a hostile environment. To conclude, the system should display information to the user directly and in an autonomous manner. Display should be updated according to user's posture (position and orientation). The interaction with data in this system requires an optimized Human Machine Interface. Compromises regarding the size, weight, and interaction principle on the device should be done. Considering the trends of technologies, the choice favored a touch-sensitive pad associated with an optical tracking system. 3D augmented reality glasses (such as see-through) and other self-supporting device could also be considered but this will be for future developments.

B. Boundaries that should be overcome

AEC are information intensive industries, and are increasingly dependent upon effective ICT. Various computer tools are used to support almost all AEC design and management tasks, and the information entered into all of these tools describes the same physical project. However, this information is passed from one tool to the next by producing paper-based or electronic documents which can only be interpreted by some building agents. This manual data re-interpretation and entry can often introduce errors into the project, and inhibits the use of better computational tools. To address this problem of information communication and exchange, a few challenges have been identified in these researches:

-The availability of all information, the data consistency and portability between the construction site and the engineering department office.
-To select the right tools (hardware solution and Human Machine Interface) to access and to interact with, throughout the generally tight work schedule.
-Ease of use taking into account the human factors.
-Ergonomics of the mobile device enabling onsite colocation of the digital mock-up

Moreover it raises some promising research topics related to dynamic project Management, virtual costing, delta management (which also means final discrepancy check, i.e. comparison between as-built and as-planned, for building acceptance [14], [15].) and time constraint management.

Handling a BIM is a challenge. But defining a consistent device and an intuitive interface is also an issue. The approach will be driven by these key-questions: Which level of detail for the data observed in situ? How represent non geometrical data? How designing an adaptive tool which would fit with the specific skills of each user? How to implement intuitive interactions between users and collocated data?

The work presented in this paper aims at evaluating new usage of augmented reality in the planning and monitoring of renovation works in ancient buildings. The challenge is to demonstrate the advantage of providing Building Information Modeling (BIM) onsite. Renovation works can be viewed as operations analogous to maintenance in manufacturing: it leads to changes in a product's lifecycle; it requires minimum knowledge of the current product. This investigation began with an augmented reality method dedicated to maintenance [12] [13].

IV. DESCRIPTION OF THE PIPELINE

A. Data Workflow from the Generation of Building Information Model

As shown in Fig 5 below, the CAD (Computer Aided Design) models (current and projected configurations) are designed in Autodesk Revit. It is exported in .fbx for operating the texturing steps in Autodesk 3DSmax. Finally the virtual mock-up is fed into a 3D engine enabling real time interaction with the geometry and embedded metadata (retrieved from the IFC digital mock-up). Thermal simulations have been computed, the results exported in TXT format were translated so that the 3D engine could interpret them in real time.

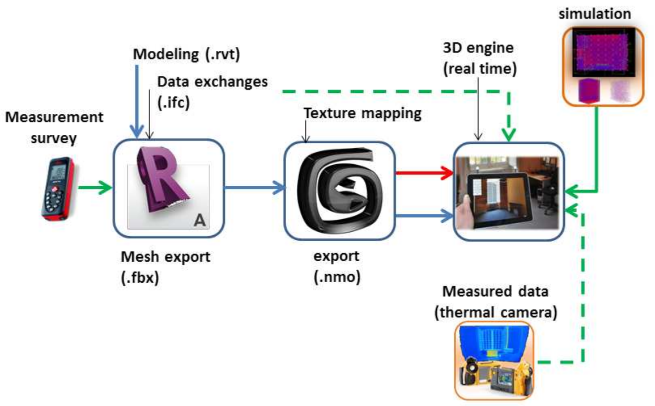

Fig. 5 Detailed view of the technical pipeline

B. *Hardware and Software Solutions*

Mapping textures aimed at enhancing realism in the 3D engine. Virtools 5 (Dassault Systèmes) was selected. This easy-to-use software appeared to be easy and practical to use for drafting virtual reality experiences. Virtools enables to connect motion-tracking devices: Collocated access to data is implemented through a real time tracking system, developed by ART (Advanced Real time Tracking) [17]. This system was chosen because the manufacturer ensures top-rated accuracy (0.04 pixels for each camera. With distances between cameras and the user reaching up to 4 meters, the theoretical accuracy of the setup is below one centimeter). In the field of indoor geo-location, the literature has widely experimented hybrid solutions which appear to be more efficient as well as to improve accuracy [18]: for instance, it would be possible to couple WIFI (or radio wave) systems to gyro sensors. The ART system was also selected because it was fully compatible with the Virtools environment: it implements intuitive and instantaneous outputs of the six degrees of freedom.

For the mobile device, the Ipad© (Apple) was chosen. An intuitive interface, a light weight and a multi touch pad argued for this device. Besides, on-board sensors (gyro) would enable future works dealing with coupling hybrid geo-location systems. The user handles, thanks to the Ipad, a slight window- like with “the planar” project [19]- towards the virtual mock-up of the renovation project. Furthermore, the principle of displaying on mobile device is enabled through a remote desktop access (Splashtop remote Desktop). Thus the real time rendering calculation is delegated to a workstation and the device is only a display. The pixels flow is WIFI-transferred via a dedicated access point, located in the room and wired to the local network. It allowed the system to reach an acceptable refresh rate and an average latency measured at 0,159s which did not disturb the users As for thermal calculation tool, Ecotect software (now included to Autodesk’s suite) was used.

C. *Hardware Configuration*

An Intel® Xeon® CPU E5420 (4 cores) @ 2,5 GHz processor is implemented in the workstation which was used for workshops B and C. It contained 8 GB of virtual memory (RAM). Regarding the GPU graphic card, it hosted an NVIDIA GeForce GTX 260 chipset. The operating system was Microsoft Windows XP Professional x64 edition Service Pack 2. Additionally, the hardware architecture featured a dedicated Linksys wireless-G model number WAP54G ver. 3.1 Wi-Fi emitter, connected to the local area network.

V. Experimental Studies

The scenario proposes to renovate a window by adding a double skin (windowed partition wall). It requires a set of tasks, scheduled on the virtual mock-up: Entities identification, measurements, analysis of thermal simulation results, etc. Two paradigms will be evaluated (desktop computer and mobile display) and compared to traditional paper-based work method.

A. *Hypotheses*

During the preparation of the workshops three hypotheses were stated:

(i) “Bringing the BIM onsite through a virtual environment (Workshop C) facilitates the overall project understanding and renders access to any contained information intuitive

(ii) “Bringing the BIM onsite enables to save time and to be more efficient in the execution of basic tasks”

(iii) “Bringing the BIM onsite allows easier detection of problems or inconsistencies”

B. *Three Workshops to be compared*

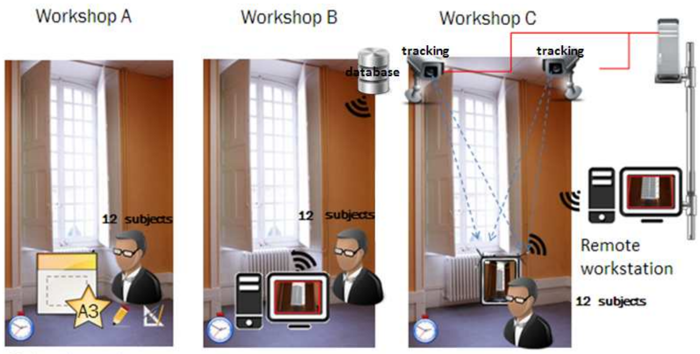

Fig. 6 Three workshops designed for the experimental study

The first workshop focuses on the common methodology consisting in the paper-based practice (see Fig 6).

TABLE I
Workshop “A” Definition

Data	Equipment/Tools
-Data sheet of all components of the virtual mock-up (with associated metadata -The macro-schedule for the renovation works -Data sheet of the results of the thermal simulation (current and projected states) -A financial proposal from a contractor -Mathematical formula (Pythagoras) -One description on the type of heater (projected state) -A general description of external joinery -4 layouts of the perspective/sectional views of current and projected states	-One multi-scale ruler (architect’s tool) -One calculator -One pen to complete answers to the questions

The second simulation provides a virtual reality application running on a desktop workstation. (See Fig 6)

TABLE II
WORKSHOP "B" DEFINITION

Data	Equipment/Tools
-Virtual reality environment with GUI (Graphic User Interface) -Data sheet to assist the user with the interface (main icons functions)	-Workstation with interaction devices (screen, keyboard and mouse) -One pen to answer the questions

The third workshop is an evolution of the previous one with collocation access to a digital mock-up on a digital tablet actively linked to the subject's behaviour. The digital tablet provided in this workshop has six degrees of freedom which are updated in real time. Therefore, the operator will be able to interact with the virtual model, in particular with the renovation project, just by moving the tablet like a mobile window. Displayed data are processed virtually and described by a virtual mock-up: the user's experience is enriched in the real world. (See Fig 6)

TABLE III
WORKSHOP "C" DEFINITION

Data	Equipment/Tools
-Virtual reality environment with GUI -Data sheet to assist the user with the interface (main icons functions)	-One pen to answer the questions -One touch pen to interact with the touchpad (the user may also use their finger)

To understand properly the setup of Workshop B and C, their fundamental differences are: the visualization mode (on a monitor for B; on a touchpad screen for C), the interaction techniques with the virtual mock-up (mouse/keyboard for B; motion tracking and touch/multi-touch for C). For this workshop, an onsite operator is given a touch screen. He can move within a perimeter laid out on the ground. The operator's movements are monitored by a real time optical tracking system thanks to passive targets placed on the iPad. Data are sent to the workstation through the local area network using a VRPN server. Under Virtools, a script creates a VRPN client. It receives motion data which operates a virtual camera (translation vectors and quaternion orientation). Real time calculations are carried out by the workstation. The rendered view is streamed to the iPad: Thus there is no rendering calculation.
Advanced functionalities to interact with the model are:
-Measure (Fig 7).

Fig. 7 Measurement tool

-Switch between current and as-planned configurations
-Access to metadata: A few attributes of the components of the digital mock-up were imported from the IFC file.
-Thermal data analysis: The user may retrieve information from simulation results through visualization metaphors.
-Animated view of scheduled tasks: It begins with the current configuration and ends with projected one. 3D components are shown or hidden along a timeline.

C. The Procedure for experiments

The experiment protocol consists first in forming three groups of ten to twelve candidates, which will each be assigned to a workshop. Each person performs the experiment individually, provided with a paper document which highlights the principles of the experiment.

In the first step, the person is asked to perform a time-limited set of tasks focused on accessing and reading information. The Multiple Choices Questions sheet (MCQ) contains ten questions whose topic is linked to common issues encountered in the traditional paper-based methodology. The idea is to evaluate the ability of subjects to interact with this new technology. In a second step, the subject is asked to answer a time-limited set of questions (twelve), dealing with measures. For workshops B and C the user uses a dedicated functionality in the application whereas in Workshop A the people use printed layouts. At the end of the experiment, the candidate is asked to fill in an electronic questionnaire (ten questions) to provide feedback from his involvement in the experiment.

The timer is launched once the MCQ is given to the person. He is allowed to browse all available data. Once the MCQ is completed, the timer is stopped. It is restarted when the second questionnaire is provided to the subject.

The tasks to execute are made of two sets of questions (10+12). These questions aim at evaluating the added value of bringing BIM onto the jobsite and whether this improves working conditions and enables agents to save time and to be more efficient in the execution of the usual basic tasks occurring on the field. The subject is asked to answer two types of questions. One type is related to simple access to the metadata of specific entities. The other type of questions involves measurements. Sometimes the answer is obtainable by both means. Volunteers were also asked to retrieve values from thermal simulation results, alternatively in the current or in the renovated state. The difficulty was then to select the correct configuration which allowed obtaining the relevant simulation results. Users from "workshop A" answered those questions better (success rate of 92.3%) than those in "workshop B" (success rate of 63.3%) and "workshop C" (72,2%)

The experiments involved up to 57 subjects. But only the last thirty-six were retained (twelve per workshop) because of beta-testing users or non-usable data. The tables below (Part VI) take into account 36 subjects only. The subjects who took part in the experimentation are mostly students (Bachelor's or Master's degree and PhD students). They represent more than 70% of the tested population. Other people are faculty or employees of the engineering school. Women represent 19% of all subjects. Regarding the age distribution, most subjects are aged between 20 and 24. Their backgrounds are divided into two domains: Social sciences and engineering. The percentages for workshops A, B and C are respectively: (social sciences: 8%; engineering: 92%), (social sciences: 0%; engineering: 100%), (social sciences: 45%; engineering: 55%). The gender distributions for workshops A, B and C are respectively: (female: 8%; male: 92%), (female: 33%; male: 67%), (female: 17%; male: 83%). Left(or right)-handed distributions for workshops A, B and C are respectively: (left-handed: 0%; right-handed: 100%), (left-handed: 25%; right-handed: 75%), (left-handed: 17%; right-handed: 83%).

D. *Factors and Metrics*

The parameters consist in the different modes of access to any piece of data. Whatever the workshop, the paradigm of interaction with the project representation differs. But the scope of this research is beyond the comparison of "digital content" versus "non-digital content". The research works go further in defining the potential uses of those data-management strategies in AEC practices.

The research work wishes to delineate a first indicator of the relevance of new technologies in this kind of operations. parameters in relation with hypotheses (V-A) and research questions, will be monitored, evaluated and compared: Regarding hypothesis (i), the rate of correct answer according to type of question and for each workshop, analysis of subjective evaluation (ergonomics, comfort, immersive aspect…); differences between recorded measure and reference value will also be rated.
Regarding hypothesis (ii), the duration of completion of each questionnaire, for each workshop as well as the duration of answering each question will be measured, according to its type and for each workshop.
Regarding hypothesis (iii), one indicator will consist in the rate of traps detection
These parameters will help to highlight the advantages of collocated access to a virtual mock-up for a construction/renovation project. The analysis will confirm (or not) the hypothesis.

VI. Data Collection and Analysis

A. *Data Analysis and Results*

Subjective evaluation questionnaire: 60% of the population estimates the provided material is relevant for the required tasks. Disparities appear among the workshops. Regarding the provided data, apart from the highest score (5) which favor Workshop C, scores are similar for each workshop. Workshop C seems to make questions easier to answer as well as to facilitate the access to information. Subjects report homogeneous scores about the ease to remain concentrated. A slight advantage for Workshop A may be reported. However there is a balanced distribution regarding general feelings (Apart from score « 2 »). Regarding the last chart, unless the item "stability" is considered, Workshop B has the highest scores (i.e. those closest to the center).
See Appendix 1 for result charts

The questions of the MCQ are listed bellow:
-Q1: According to given documentation, what is theoretical cost of the works; Q2: what should be the overall duration of the renovation?
-Q3: What is the name in the database of the new heating system?
-Q4: Choose between three proposed window the one which has been selected for the project
-Q5-6-7-8: What is the maximum/minimum temperature in the current/projected configuration simulated in April/October/February/December?
-Q9: What is the reference of the wall named Basic Wall : GZ-Cloison?
-Q10: Give the manufacturer of the light in the room.

Results from the MCQ are reported on Fig 8 : The rate of correct answers promotes Workshop C, as well as Workshop A, only once; whereas Workshop B is favored three times ; Two questions lead to equality: The second question with Workshops A and B; The third question with A and C. Nota: Questions 1 and 2 have a very low rate of success because of intentional input traps. Most of them have not been detected regardless of the workshop. Either users were not concentrated enough or the traps were too difficult to identify. Besides Q5 to Q8 are similar; thus their results were merged in the chart below.

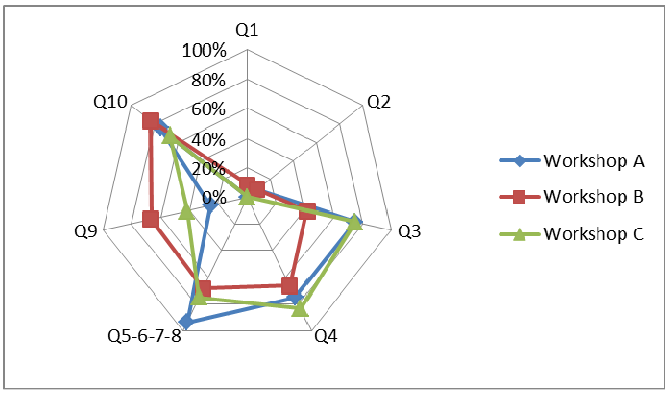

Fig. 8 Rate (%) of correct answer to the ten MCQ questions

B. *Running Anova Analysis*

For full results see appendix 1. The table below sums up the rank of each workshop.

TABLE IV
Rank of Each Workshop According to Anova Evaluation

	MCQ duration	Duration for set of measurement tasks	Deviance1 (D1)	D2	D3	D4	D5
A	3	2	3	2	2	3	3
B	2	1	1	1	1	1	1
C	1	3	2	3	3	2	2

C. Discussion

The results show that workshop B ranks first in most respects. Is it because desktop computer practice is more widespread than working on a mobile device, which would explain these results? However working on the field with a computer has no future: On a real jobsite, there is no way to set up a computer (mobility issues, power limitations…). Users mostly feel comfortable with both Workshops B and C (Fig 11). Up to half of them report a boring aspect in the practice of Workshop A. Most of the subjects of workshop C report exhaustion due to the handling of the touchpad during the test sessions (up to 35 minutes.). Thus the user interface and ergonomics should be improved. Moreover the constitution of the groups doesn't seem to be balanced: Unfortunately taking into account characteristics such as "gender", "background", "left-handed or not" and "age" lead to generally heterogeneous groups. Also, Workshop B and C put right-handed people at a disadvantage: Indeed, as the mouse features right-hand manipulation the user is unable to simultaneously manipulate it and write. Besides the virtual buttons are on the left-hand side of the Ipad screen which is not ideal for right-handed people. For this experiment, each subject tested only one workshop

VII. CONCLUSION AND PERSPECTIVES

This article described an experiment aimed at evaluating the appropriateness of using an augmented reality device dedicated to the AEC field. The elaborated prototype enables users to access a collocated virtual mock-up of a Building Information Model (BIM) on a touchpad. The application study focuses in this paper on renovation works on an ancient building. Two avenues are explored and compared to traditional work method: Access to project data through 2D layouts and documentation versus access to a 3D collocated database on a workstation or a mobile device. The results show the significance of the ergonomics of the touch interface as well as the constraints due to the weight of the device. The objective of this experimentation is to optimize the concept of onsite access to the digital mock-up, especially in order to get information from the jobsite.

These experiments occurred in a controlled environment. Technical choices were made to address the very first issue: Bringing a proof of the concept that ICT might answer some AEC needs, as far as the renovation of an ancient building is concerned. The first phase of the experiments is over and the next investigations are to be planned according to the current conclusions. They demonstrated the need for improving the prototype. Disparities of the results might be overcome by making the subjects experiment all of the workshops, and that could be our next experiment.

Fig. 9 Scenario of a user holding the mobile display

To be consistent with modelling the current-state digital mock-up, it was decided to display the full virtual scene onto the Ipad screen. The system will be provided with a video stream (from a high definition webcam or from the onboard camera on newer-generations Ipads) so that the user can have real (current state) and virtual (projected state) views. The user's proper positioning in the virtual environment would be hidden. The virtual mock-up would only be used to give feedback (IFC attributes) when picking entities. This upgrade has two benefits: Texturing step in 3DS max would be useless and could then be discarded. Moreover it would increase the immersive feeling of the user since they would be interacting with real components. One issue would lie in aligning the webcam's real motion with the virtual camera's displacement, which relies on the output of the optical tracking system.

It is planned to include additional data to the virtual mock-up, from laser scanning or photogrammetry options. Indeed, by modelling Building Information, it is mainly the geometric aspect which is estimated (especially in cultural heritage). Thus it seems appropriate, notably in the case of measurements, to provide two information channels to the user: One rules BIM data and the other, unstructured set of polyhedral triangles is the support of actual and accurate measures

Potential end users of this system will eventually be construction agents who will own a tool specifically dedicated to their skillsets. Experiment will deal with such a tool for helping to manage the jobsite in real time, warranting the interoperability of available data. The final objective is to implement bidirectional schedule and related-costs management. It would take as input data from common project review software. It would be playable into a virtual reality application usable onsite.

The future experiment will focus on data representation comparison in virtual or mixed reality: thermal data representation in a virtual environment [11] (such as a CAVE) will be considered. Several modes of volume restitution (transparent cubes, particles, horizontal and vertical portions…) will be evaluated.

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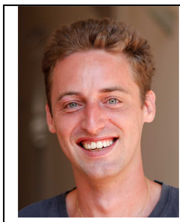	Jérémie Landrieu is a PhD candidate at Arts et Metiers Paristech, Laboratoire LE2I, UMR CNRS 6306, France. He received his Master in Computer Science from the Arts et Metiers Paristech engineer school in 2008. He has worked on 3D virtual restitution of the cluniac abbey church. The topic of his research deals with the implementation of digital mockup to enhance construction/renovation process in ancient buildings. His main research interests are digital design, scientific visualization, 3D, and AR/VR. Currently he is part of a project called "CoRDOBA".
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Appendix 1

- The table below reports the duration needed to complete the MCQ

Workshop A (in minutes)	Workshop B (in minutes)	Workshop C (in minutes)
21,25	12,17	8,77
11,7	12,33	8,25
22,82	14,63	8,9
16,38	16,33	14
18,35	17,17	16,95
12,02	11,38	12,23
10,58	15,2	13,83
11,87	17,33	14,5
15,6	21,82	7,75

15,8	9,35	7,87
12,88	9,3	13,33
18,58	8,47	

Table 1. Data collection for MCQ duration

F (2 ; 32)	p-value[1]
3,47	0,04

Table 2. Results of Anova Analysis

The « workshop » factor has a significant impact on the duration of the MCQ completion (task of accessing specific data)
One factor is leading the race. Newman-Keuls test will help to determine it by calculating w² value
To remind, w² formula is

$$\omega^2 = \frac{SCE_{inter} - (k-1) * (CM_{intra})}{SCE_{totale} + CM_{intra}}$$

$$\omega^2 = \frac{99{,}61 - (2) * (14{,}32)}{557{,}86 + 14{,}32} = 0{,}124$$

According to Keppler (1991) grid, the difference is estimated to "average"

$$0{,}06 < \omega^2 < 0{,}15$$

Average values for workshops A to C are, respectively: 15.54; 13.79; 11.2
Workshop C ranks first.

- The table below reports the duration needed to complete the second set of tasks (measures) (in minutes)

Workshop A (in minutes)	Workshop B (in minutes)	Workshop C (in minutes)
23	11,25	13,2
14,05	20,67	8,65
11,8	9,82	17,66
25,63	13,75	14,77
37,1	11,57	18,07
16,05	11,58	16,33
13,67	15,67	31,33
21,53	19	24,35
12,12	13,17	13,17
15,8	10,55	29,17
16,37	10,5	20,4
12,65	10,07	38

Table 3. Data collection for measurements duration

F(2 ; 33)	p-value
3,54	0,04

Table 4. Results of Anova Analysis

The « workshop » factor has a significant impact on the duration of the measurement tasks.
One factor is leading the race. Newman-Keuls test will help to determine it by calculating w² value

$$\omega^2 = \frac{337{,}86 - (2) * (47{,}64)}{1909{,}97 + 47{,}64} = 0{,}124$$

According to Keppler (1991) grid, the difference is estimated to "average"

$$0{,}06 < \omega^2 < 0{,}15$$

Average values for Workshops A, B and C are, respectively: 18,31; 13,13; 20,42
This analysis promotes Workshop B, i.e. working on a desktop workstation. Workshop C ranks last.

For the tables below, subjects were asked to obtain measurement data (second set of tasks). Each reported figure represents the absolute value of the subtraction between the given answer and the reference value.

- Height of the door

Workshop A (in meters)	Workshop B (in meters)	Workshop C (in meters)
0,079	0,030	0,084
0,09	0,030	0,016
0,060	0,075	0,004
0,211	0,010	0,030
0,09	0,030	0,002
0,09	0,030	0,09
0,010	0,020	8E-05
0,010	0,013	0,18
0,010	0,010	0,030
0,215	0,010	0,003
		0,010
		0,010

Table 5. Data collection for measurement deviance

F(2 ; 29)	p-value
3,52	0,04

Table 6. Tableau 1 Results of Anova analysis

The « workshop » factor has a significant impact on the measurement of the door (reference size: 1,91008)
One factor is leading the race. Newman-Keuls test will help to determine it by calculating w² value

$$\omega^2 = \frac{0{,}021 - (2) * (0{,}003)}{0{,}107 + 0{,}003} = 0{,}136$$

According to Keppler (1991) grid, the difference is estimated to "average"

$$0{,}06 < \omega^2 < 0{,}15$$

Average differences for Workshops A, B and C are respectively: 0,08 ; 0,027 ; 0,038
This analysis promotes Workshop B, i.e. working on a desktop workstation. Workshop C ranks second.

- Length of the room (in meters).

Workshop A (in meters)	Workshop B (in meters)	Workshop C (in meters)
0,009	0,002	0,028
0,424	0,024	0,003
0,509	0,03	0,039
0,081	0,03	0,02
0,009	0,029	0,014
0,03	0,002	0,031
0,009	0,022	0,104
0,009	0,03	0,011
0,03	7 E-04	0,061
0,557	7 E-04	0,002
0,03		0,021

Table 7. Data collection for measurement deviance

1 p-values were calculated online on these websites :
http://www.quantitativeskills.com/sisa/calculations/signif.htm
http://marne.u707.jussieu.fr/biostatgv/?module=tests/anova

F (2 ; 29)	p-value
3,54	0,04

Table 8. Results of Anova Analysis

The « workshop » factor has a significant impact on the measurement of the room's length (reference size: 4,49072)
One factor is leading the race. Newman-Keuls test will help to determine it by calculating w^2 value

$$\omega^2 = \frac{0{,}124 - (2) * (0{,}0175)}{0{,}63 + 0{,}0175} = 0{,}137$$

According to Keppler (1991) grid, the difference is estimated to "average"

$$0{,}06 < \omega^2 < 0{,}15$$

Average differences for Workshops A, B and C are respectively: 0,14 ; 0,029 ; 0,03
This analysis promotes Workshop B, i.e. working on a desktop workstation. Workshop C ranks second.

- Height of the wood pane (in meters)

Workshop A (in meters)	Workshop B (in meters)	Workshop C (in meters)

Workshop A (in meters)	Workshop B (in meters)	Workshop C (in meters)
0,191	0,018	0,067
1,21	0,091	0,083
1,32	0,035	0,19
0,033	0,016	0,2
1,18	0,008	0,03
0,04	0,015	0,035
0,02	0,059	0,024
0,08	0,025	0,357
0,031	0,044	0,28
0,442	0,034	0,08
0,22	0,038	0,016
0,031	0,029	0,03
0,053	0,045	0,004
0,073	0,018	0,08
0,027	0,02	0,328
0,027	0,026	0,052
0,033	0,016	0,007
0,027	0,087	0,173
0,033	3 E-04	0,004
0,043	0,005	0,114
0,027	0,003	0,023
0,027	0,091	0,083

Table 9. Data collection for measurement deviance

F (2 ; 27)	p-value
5,56	0,009[2]

Table 10. Tableau 2 Results of Anova Analysis

The « workshop » factor has a significant impact on the measurement of the pane's height (reference size: 2,97326)
One factor is leading the race. Newman-Keuls test will help to determine it by calculating w^2 value

$$\omega^2 = \frac{0{,}034 - (2) * (0{,}0031)}{0{,}117 + 0{,}0031} = 0{,}23$$

According to Keppler (1991) grid, the difference is estimated to "thin"

$$0{,}15 < \omega^2$$

Average deviations for Workshops A, B and C are respectively: 0,037; 0,031; 0,086
This analysis would promote Workshop B, i.e. working on a desktop workstation. Workshop C would rank last.

- One diagonal measurement (in meters)

Workshop A (in meters)	Workshop B (in meters)	Workshop C (in meters)
0,217	0,024	0,09
0,177	0,043	0,037
0,005	0,028	0,25
0,04	0,028	0,26
0,02	0,021	0,029
0,08	0,01	0,027
0,031	0,064	0,016
0,452	0,031	0,126
0,221	0,015	0,08
0,031	0,037	0,18
	0,016	0,014
	0,02	0,04

Table 11. Data collection for measurement deviance

F (2 ; 31)	p-value
3,35	0,04

Table 12. Results of Anova Analysis

The « workshop » factor has a significant impact on the measurement of a volumetric diagonal (reference size: 7,17955)
One factor is leading the race. Newman-Keuls test will help to determine it by calculating w^2 value

$$\omega^2 = \frac{0{,}058 - (2) * (0{,}0087)}{0{,}328 + 0{,}0087} = 0{,}12$$

According to Keppler (1991) grid, the difference is estimated to "average"

$$0{,}06 < \omega^2 < 0{,}15$$

Average deviations for Workshops A, B and C are respectively: 0,128; 0,03; 0,095
This analysis promotes Workshop B, i.e. working on a desktop workstation. Workshop C ranks second.

- Another diagonal measurement (in meters)

Table 13. Data collection for measurement analysis

F (2 ; 33)	p-value
4,68	0,016

Table 14. Results of Anova anlysis

[2] according to http://www.quantitativeskills.com/sisa/calculations/signif.htm

The « workshop » factor has a significant impact on the measurement of a volumetric diagonal (reference size: 7,17962)

One factor is leading the race. Newman-Keuls test will help to determine it by calculating w² value

$$\omega^2 = \frac{0{,}88 - (2) * (0{,}0945)}{4 + 0{,}0945} = 0{,}17$$

According to Keppler (1991) grid, the difference is estimated to "thin"

$$\omega^2 > 0{,}15$$

Average deviations for Workshops A, B and C are respectively: 0,399; 0,034; 0,115

This analysis would promote Workshop B, i.e. working on a desktop workstation. Workshop C would rank second.