Virtual, Augmented and Mixed Reality as Communication and Verification Tools in a Digitized Design and File-To-Factory Process for Temporary Housing in CFS

Monica Rossi-Schwarzenbeck and Giovangiuseppe Vannelli

Abstract This work presents a research project in which Cold-Formed Steel building components for temporary post-emergency housing are developed and realized with a digitalized workflow. This starts from early design ideas (peacetime), includes file-to-factory production and assembly processes (emergency relief/early recovery) and leads to the disassembly of building components and their reuse (reconstruction). The key element of the entire process is the Information Model. This is the place of the interoperability that, during the different stages, interfaces with different devices including Virtual, Augmented and Mixed Reality tools as well as file-to-factory processes for the industrial production. Aim of the paper is to show how visualization tools (like interactive Whiteboard, Tablet, Cardboard, Oculus Rift, Hololens 2, and Cave) can be used not only to realistically and immersively represent the project, but also to optimize design, production and construction processes. Indeed, these devices can also be used to improve the communication between the involved stakeholders, to enhance participatory processes, to help in decision-making, to verify a digitalized design and manufacturing process and to train workers. To achieve this goal, the innovative workflow is presented in chronological order, highlighting the purposes for which the selected tools were applied, analyzing their characteristics, potential, limits, software, interfaces, involved users and costs. The results comprise not only the application itself, but in particular the advantages and challenges evaluation of the use of the selected tools in a design project in order to improve future applications.

Keywords VR AR and MR · BIM and interoperability · File-to-factory · Cold-formed steel · Temporary housing

United Nations' Sustainable Development Goals 9. Industry Innovation and Infrastructure · 11. Sustainable Cities and Communities · 13. Climate Action

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1 Introduction and State-of-the-Art

1.1 Industry 4.0 and the Architecture, Engineering and Construction Sector

During the Hannover Fair in 2013, the German Federal Ministry for Economic Affairs and Climate Action and that one for Education and Research, together with other partners, established the Industry 4.0 platform to support industrial production with innovative information and communication techniques in order to make it faster, more efficient and more flexible [1, 2]. The platform has been a huge success and a driving force not only in Germany, but also in the rest of Europe, in the digitization also of sectors outside manufacturing. Industry 4.0 has now taken an important place in the economy. Companies see this as an opportunity to increase their competitiveness, drive technological development and, in particular, optimize production and business processes. On the contrary, in the AEC sector the digitization of building design, production, construction and more generally of processes is taking place in a slow and uneven manner [3]. This is attributable to several factors including two main ones: the high number of involved stakeholders (often characterized by different interests, applied workflows and used tools) and the fact that each building is a unique piece often made on site and with wet technologies, so that an industrial production (either serial or customized) is not always applicable. In order to reduce this gap, numerous initiatives such as Planen und Bauen 4.0, started in 2015, have been set up with the aim to introduce digital construction processes in the AEC, to consider the entire life cycle of buildings and transform new business models for real estate projects [4].

Therefore, the application of innovative paradigms and digitized processes has become more widespread in recent years. However, this is often done in a fragmented manner, only at certain stages of the process or by only some of the involved stakeholders. Industry 4.0 in AEC is a challenge, but also a big opportunity, which, in order to work efficiently, must cover with a collaborative and holistic approach the entire designing, construction and management process.

1.2 Digitization in the AEC: Challenge and Opportunity

Digitization in the AEC sector is taking shape particularly in the following applications: Building Information Modelling (BIM), digitized production (file-to-factory) and buildings project representation (Virtual, Augmented and Mixed Reality).

The use of BIM—consisting of an innovative collaborative method of design, construction and management that allows integrating all information about a building in one single three-dimensional digital model—is becoming increasingly widespread, particularly in complex and large-scale building projects for public clients [5, 6]. The creation of a digital twin of the to-be-built/built building facilitates communication between the involved stakeholders, reduces the possibility of design and construction mistakes, limits unforeseen cost increases, and can also be subsequently used for Facility Management [7, 8].

The digitized production of components using the file-to-factory method is nowadays customary in many sectors where the entire production takes place in the factory, such as the automotive industry. In the AEC, building realization mainly takes place on the construction site, and file-to-factory manufacturing is limited to components that can be produced in the factory and then assembled on the construction site. Not all building materials are suitable for this type of production, although interesting applications in concrete, steel, brick, plastic, wood and fiber materials have been realized in recent years [9, 10]. The most significant difference between this type of production and the traditional industrial one is the ease in making unique pieces. According to the 2030 Vision for Industry 4.0, digitized manufacturing is becoming increasingly more customized and less serial [11].

In recent years, the rapid spread of three-dimensional representation software and visualization tools has meant that these have reached the general public. Initially, users were almost exclusively video game players, now immersive representation tools are also routinely used in completely different sectors such as museums, education, medical, military, robotics, marketing, tourism, urban planning and civil engineering [12]. In the AEC these tools are generally applied for realistic, experimental and immersive visualization of urban, architectural or industrial design projects, although they have great potential in improving the design process by being applied in the stakeholder engagement, design support, design review, construction support, operation and management and workers training [13].

1.3 Virtual, Augmented Und Mixed Reality: Typologies and Characteristics

The above mentioned digital technologies for the representation of an architectural project are all based on a three-dimensional model of buildings and/or components. A 3D representation can take place on a two-dimensional medium (such as paper, tablet or screen) or the third dimension can be rendered more realistically with, for example, the aid of 3D glasses and the screen of a cinema or of a special television. When this third dimension comes to life, it becomes another type of representation such as Virtual, Augmented and Mixed Reality.

Virtual Reality (VR) is a technology that provides a 360-degree world in which the viewer can look in all directions and can also change his perspective by bending down or walking towards something. VR needs a tool (e.g. VR-glasses) and is immersive. This means that the user is totally immersed in the virtual world and perceives no other space outside this environment [14].

Augmented Reality (AR) is used to describe a combination of technologies that enable real-time mixing of computer-generated content with live video display. AR inserts additional objects or information into the real field of view and can be immersive (e.g. using Hololens 2) but also not (e.g. using a tablet or smart phone) [15].

Mixed Reality (MR) is an extension of the AR. The user is able to move and perform actions at the same time and in an integrated manner, in both the real and digital worlds, interacting and manipulating physical and virtual objects [16].

2 Research Purpose, Methodology and Case Study

2.1 Workflow Development: Information Model as Place of Interoperability

BIM, file-to factory production and VR, AR and MR are certainly important resources for the AEC, but at present, they are often used independently of each other, without exploiting their synergies. In order to better exploit the potential of these tools in the AEC sector, the aim of this paper is to specifically develop for a real case study an appropriate workflow able to improve the entire design, production, construction and management process using different types of representation tools as well as file-to factory production devices. A key element in digitized processes is the interoperability. In the glossary of the Industry 4.0 it is defined as the ability of different components, systems, technologies, or organizations to actively work together for a specific purpose [17]. In the proposed workflow, the place of interoperability is the Information Model. It is able to interface with different devices, it is the common element between representation tools and digitized production one (Fig. 1) and can be used by the different stakeholders, facilitating their communication and interaction. The Information Model is able to filter the information and provide the user with only the needed information for example, it provides the representation tools with information like form, materials, surfaces, colors, and the production one with information like processes, procedures, thicknesses [18].

2.2 Case Study: Design, Production, Construction and Implementation Process of Post-Disaster Temporary Housing in CFS

With the aim to develop and test a workflow that is capable of exploiting the full potential of the information model, of the various immersive and non-immersive visualization tools and of the file-to-factory production, a complex project is essential as case study. It must be characterized by a high level of complexity and a long time-span and in which interoperability and communication play an important role (because of the many stakeholders involved). Due to that the design of modular [19], incremental, flexible, dry-assembled, easily removable and reusable temporary

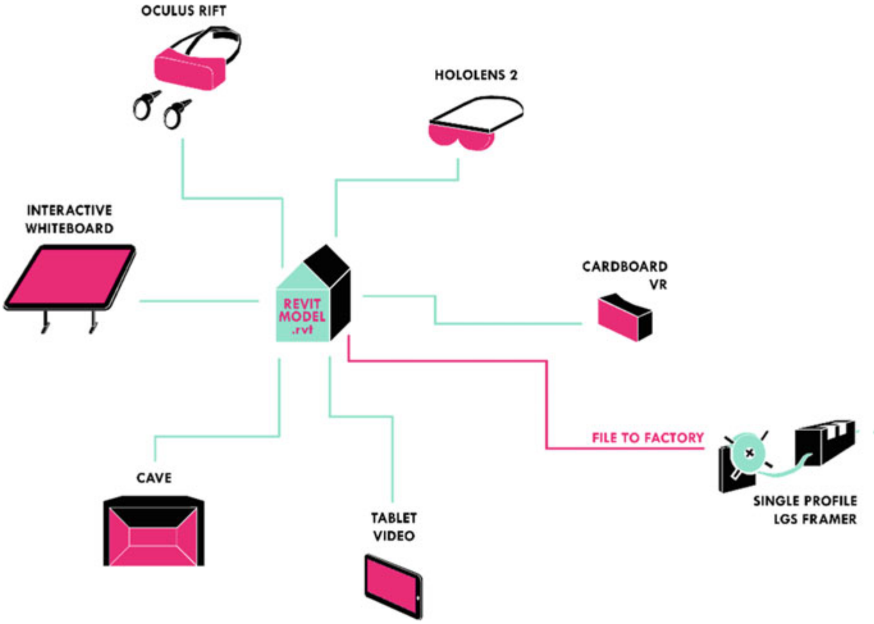


Fig. 1 Building information model as place of the interoperability. Visualization and file-to-factory tools that interface with the information model in the workflow developed

housing, using a construction system in Cold-Formed Steel (CFS) [20–22], for the construction of residential settlements to be built quickly following a disaster [23] (Fig. 2) was chosen as case study. These dwellings are conceived, according to the "building by layers" [24] logic, to be flexible and expandable over time, and at the end of their use, which is planned to be temporary, the wall-panels can be reused both to build new structures and to redevelop existing architecture by improving their seismic and energy performances [25].

The design of the housing units is part of a more complex process in which time plays an important role and is carried out in three phases: Peacetime (before the disaster, which as such is unpredictable), Emergency Relief/Early Recovery (following the disaster) and Reconstruction (Fig. 3).

The simulated process is characterized by a large number of involved stakeholders—that vary over time—and by different time phases whose duration is difficult to predict in advance as they are linked to unpredictable circumstances. In order to develop a workflow appropriate to the specific case study, it is necessary to analyze and predict the roles and relationships that stakeholders play during the process. These are the Italian Department of Civil Protection, designer (architects and engineers), university research centers, enterprises, local administrations, workers and inhabitants.

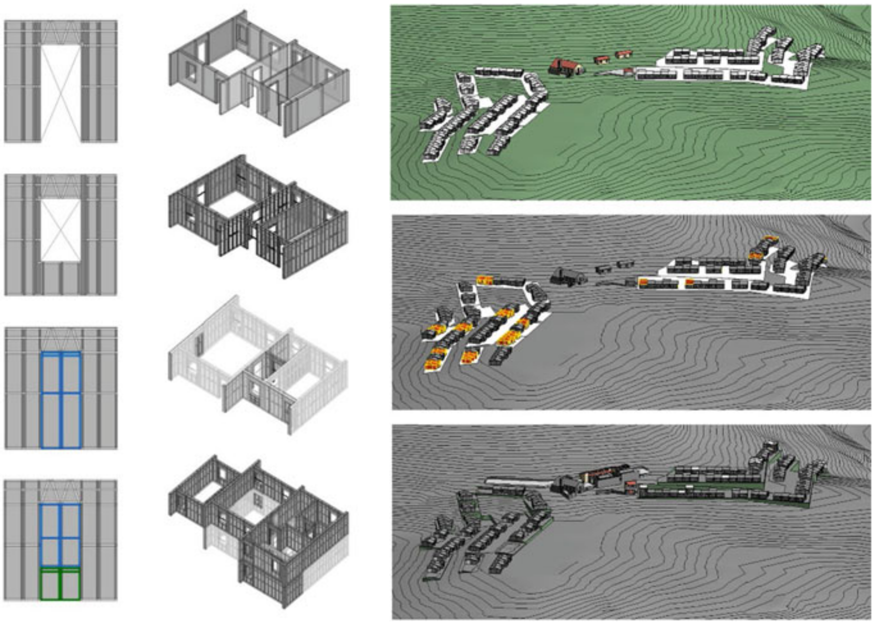


Fig. 2 Application case study. Design of the panel as building element, of the housing system and of the housing settlement in Sant'Eusanio Forconese (L'Aquila, Italy)

Fig. 3 Timeline of the design, production and implementation process: Peacetime, emergency relief/early recovery and reconstruction

3 Experimentation

3.1 Peacetime

In the first phase of the simulated process—called Peacetime, since it takes place in a timeframe prior to a possible emergency—the Italian Department of Civil Protection (DPC), supported by a university research center, is issuing a call for proposals for post emergency housing. The best proposal is chosen and optimized until it is ready to be manufactured and built immediately succeeding the emergency (see Fig. 4).

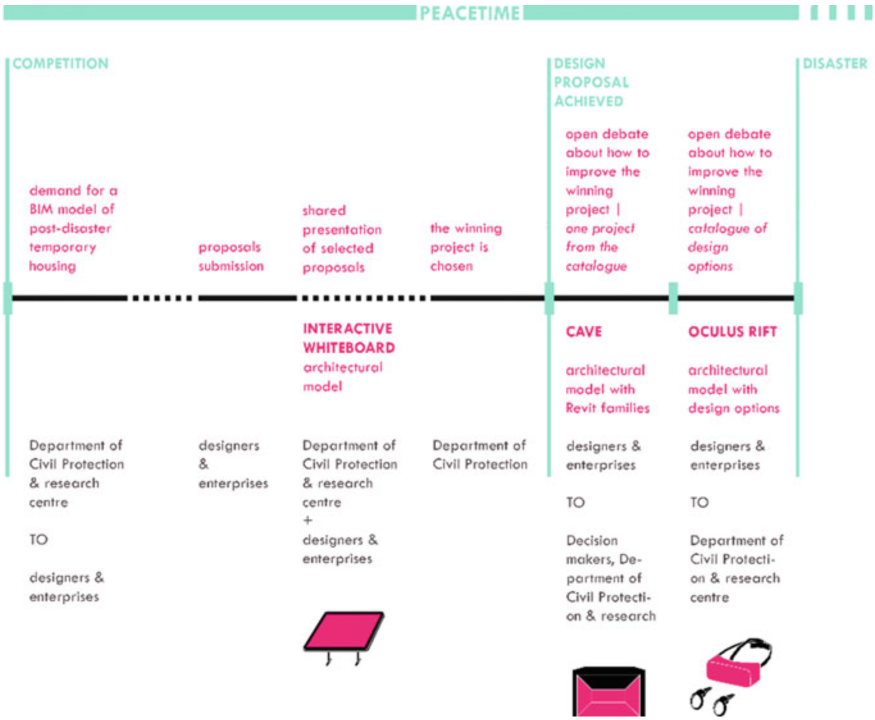


Fig. 4 Workflow and tools in the peacetime

The DPC is the national body that deals with post-disaster recovery and relief and in the simulated experimentation process constitutes the contracting and bidding body. The partner that could scientifically support the entire process should have a BIM laboratory equipped with the applied visualization tools, as it is the case for the Leipzig University of Applied Sciences (HTWK Leipzig, Germany). The call also requires that design proposals contain not only the project of modular dwellings, but also the design of dry-assembled and easily removable and reusable building components for their construction.

Then, design proposals must be submitted jointly by designers and enterprises that will be responsible for manufacturing the components. Additionally, the design must be presented in form of an Information Model able to be managed with a BIM working methodology. In this regard, the contracting authority also provides in the call an accurate Employer´s Information Requirement (EIR) [18] based on which the participants in the competition develop an appropriate Building Execution Plan (BEP).

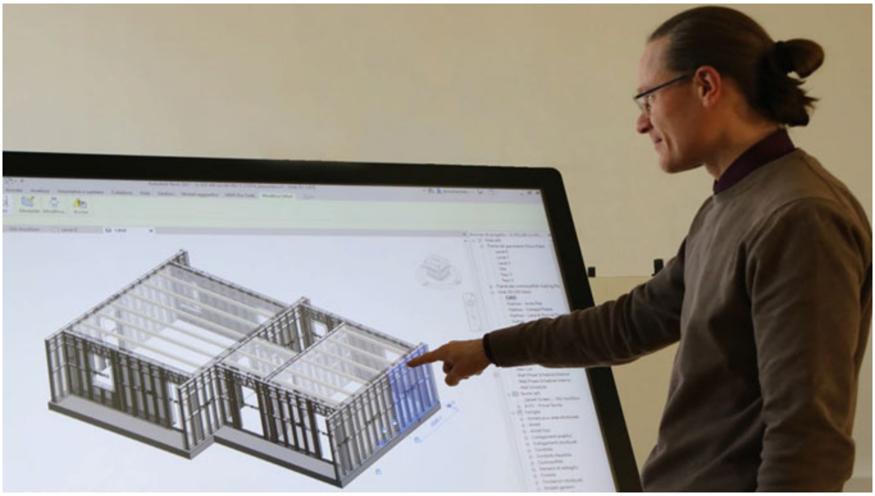


Fig. 5 Mobile interactive whiteboard with multi-touch display applied for the presentation as well as for the improvement of selected proposals (3D visualization)

After the submission of design proposals, designers and enterprises of the selected projects present their proposals to the principals with the support of a mobile interactive whiteboard with multi-touch display. This whiteboard constitutes a useful visualization tool for presenting the project to a small number of people, facilitating communication and interaction through the model (Fig. 5). The informative architecture model can be opened in the proprietary format in the modeling software (e.g. Revit or ArchiCAD) as well as Industry Foundation Classes (IFC) file in a checking software (e.g. Solibri Model Checker) and can be verified and superimposed on specialized models (e.g. technical building equipment or constructive model).

Following the selection of the winning project, open debates can be held in which the DPC, designers, enterprises, and decision makers participate. These meetings could take place at the university research center and aim at optimizing the winning design in order to make it executable. Therefore, following a disaster, the housing units to be built can be quickly chosen and/or adapted to the specific situation and the necessary building components can quickly go into production.

Then, the proposed experimentation simulates a possible process using a project developed as part of a doctoral thesis elaborated within a collaboration between the University of Naples “Federico II” and the HTWK Leipzig while Irondom srl—a CFS component producing company—has been the manufacturer enterprise partner.

Two representation tools could be used in the open debates: a Cave Automatic Virtual Environment and the Oculus rift. The Cave is a VR Space in which a discrete number of people (up to about 30) with the support of special 3D glasses can simultaneously immerse themselves in the virtual reality of the design proposal so that they can discuss it and possibly optimize it together (Figs. 6 and 7). The Oculus Rift is an immersive VR tool in which the moving around and interaction with the building elements (thanks to the two touch controllers) is greater. The model is editable and it is possible to write issues and to see model information. However, this is an experience that an individual performs alone and there is no interaction with the rest of the stakeholders, who see the model on the screen (Fig. 8).

Fig. 6 Cave automatic virtual environment and associated 3D glasses applied for the open debate between designers, enterprises and members of department of civil protection to improve the winning project (VR space)

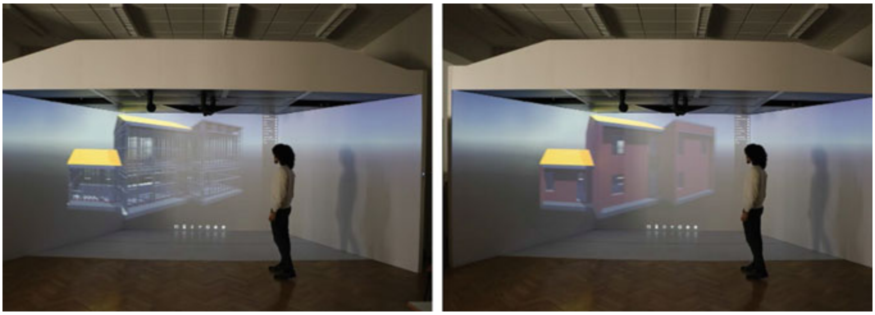


Fig. 7 Cave. View with and without building envelope

Fig. 8 Oculus rift (immersive VR). One person has a VR vision and people can see the 3D model on the screen

3.2 *Emergency Relief and Early Recovery*

Following the disaster—in case of the simulation an earthquake that occurred in central Italy (a seismic prone area, struck by several events in recent decades (1997, 2009 and 2016))—the process for the rapid construction of housing units starts (Fig. 9).

In the emergency relief phase, the site where the housing could be built is identified with the support of the local public administration. Within the experimentation an area located in the municipality of Sant'Eusanio Forconese (L'Aquila, Italy) was chosen. With the support of Hololens 2 it is possible to visualize the information model with different design options in the lot chosen for the settlement. DPC and the local government in order to define the exact placement of housing units in the lot can use this immersive AR tool, which can also be called MR as it allows interactions with both the real and virtual worlds (Fig. 10). At this stage, the quantity and types of housing units to be built and consequently the CFS building components to be produced are defined, based on number and needs of the future inhabitants.

A non-immersive AR visualization is also possible with the use of a tablet or iPad. This inexpensive tool, which even non-technicians often already have, can be used e.g. by workers (who may also be non-specialists and volunteers participating in the post-emergency construction) and future inhabitants to visualize the dwellings on the site. Unlike with the Hololens 2, the model is only partially editable with the tablet (Fig. 11).

In order to involve future inhabitants in the process and allow them to move virtually into their future homes, Cardboard VR glasses can be used. These are extremely inexpensive VR visualization tools that can be used with any type of smartphone,

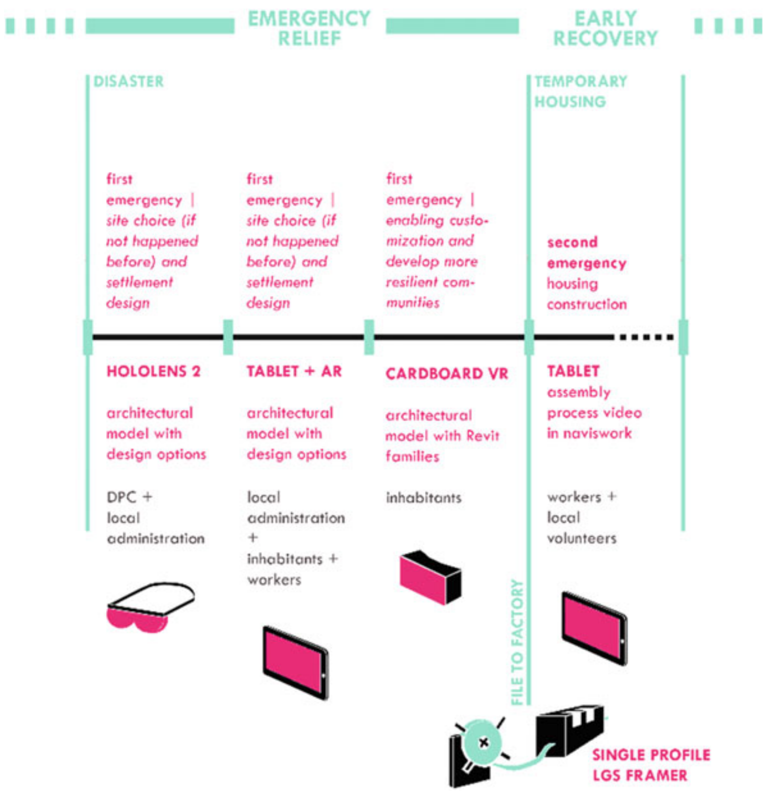


Fig. 9 Workflow and tools in the energy relief and early recovery

Fig. 10 Hololens 2 used to visualize the dwelling in the lot (immersive AR)

Fig. 11 Tablet used to visualize the dwelling in the lot (non-immersive AR)

a device currently owned by any type of user. This visualization is immersive but not interactive and does not allow you to edit the model, view information or write issues (Fig. 12).

As soon as the exact needs are defined, production based on file-to-factory processes can start. Panel-walls and other CFS elements can be produced by the enterprise—Irondom srl, in case of the simulated process—using a CNC machine (e.g. Arkitech AF I 200P Framer (Fig. 13)). This is a single profile LGS framer that is able to read the information of the building components from the information model and produce them through a digitized process based on customization and on-demand production (Fig. 14). Such a light production system opens the possibility of structuring flying factories [26] where to pre-assemble the building components. Moreover, this approach to the production process ensures—in accordance with Industry 4.0 goals—a high mass customization capability [27] and combines

Fig. 12 Cardboard VR-glasses used with the smartphone by future inhabitants

process flexibility, resource saving and high productivity. In post-disaster condition, also considering the amount and the variety of needs (variables over time) and of involved stakeholders, this is a meaningful workflow.

At this point, assembly and construction can begin on the construction site, carried out by skilled workers as well as volunteers. To assist the training of volunteers, videos made from the information model and viewable on a tablet or iPad can be prepared to illustrate the assembly of prefabricated elements (Fig. 15).

Fig. 13 Arkitech AF I 200P framer. Manufacturing process file to factory

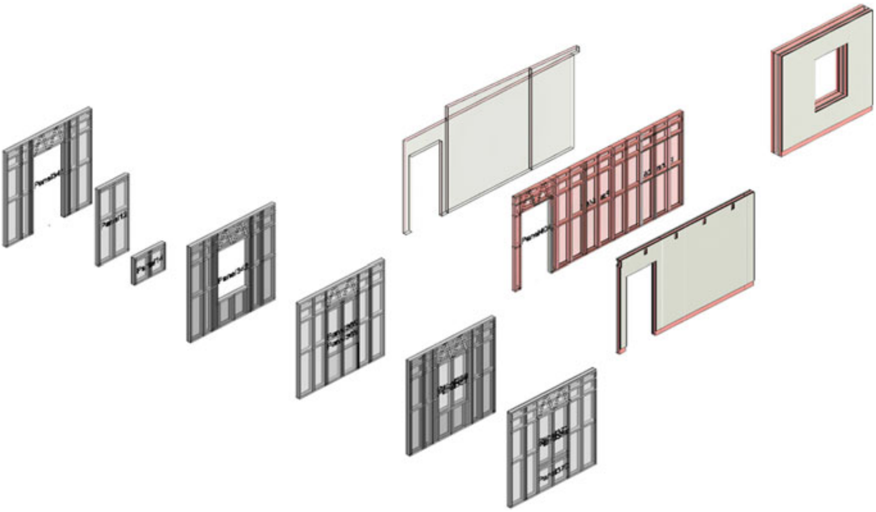


Fig. 14 Example of CFS customized panels/wall produced with a single profile lgs framer in a file-to-factory process

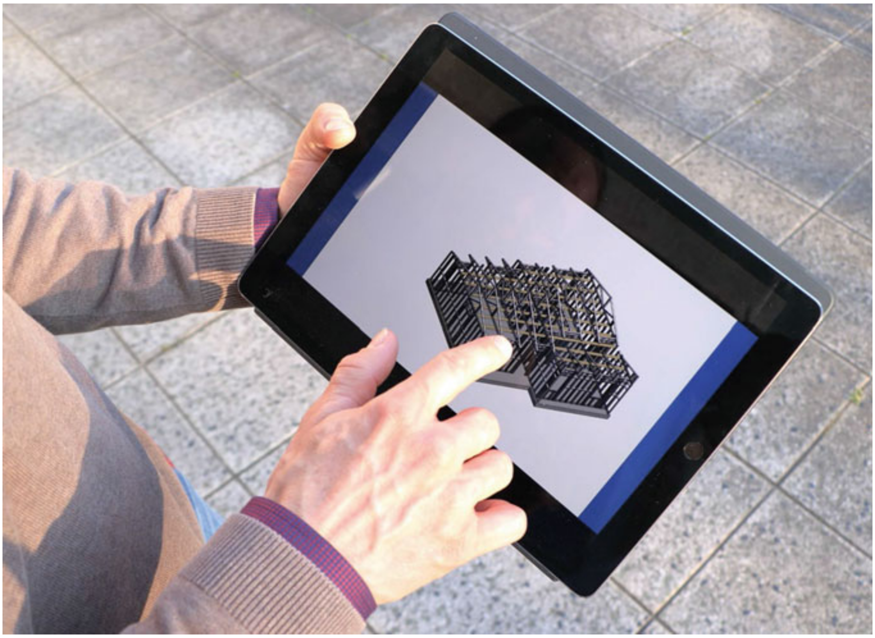


Fig. 15 Tablet displaying assembly process videos used by workers (3D visualization)

3.3 Reconstruction

While displaced communities are living in temporary housing, the reconstruction begins and includes rehabilitation and seismic improvement of lightly damaged buildings and demolition and reconstruction of severely damaged or collapsed buildings (Fig. 16).

At this stage, Virtual, Augmented and Mixed Reality tools (particularly the Cave and the Hololens 2) can be useful devices for stakeholders to jointly make decisions regarding future developments (Figs. 17 and 18).

The duration of this phase is difficult to predict as it depends widely on reconstruction policies and other external factors. Thus dwellings—which were intended to be temporary—are sometimes used for a longer period than expected and in the meantime the needs of the inhabitants may change (e.g. the number of members of a household increases). Otherwise, it may happen that two temporary housing units adjacent to each other, become vacant at different times, because inhabitants of different households may return to their permanent (redeveloped or reconstructed) home at different times. These changes in requirements over time may result in the need to expand one housing unit or to disassemble two adjacent ones at different times.

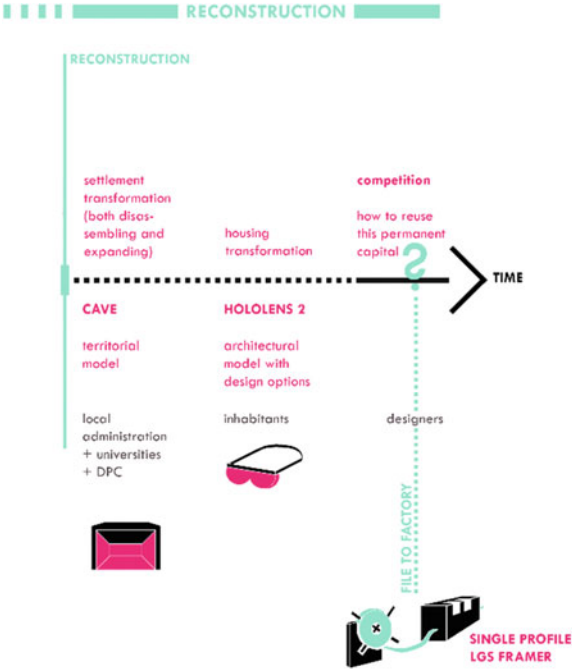


Fig. 16 Workflow and tools in the reconstruction

Fig. 17 Meeting in the cave using the urban model to identify housing units that need to be expanded, modified or disassembled/removed

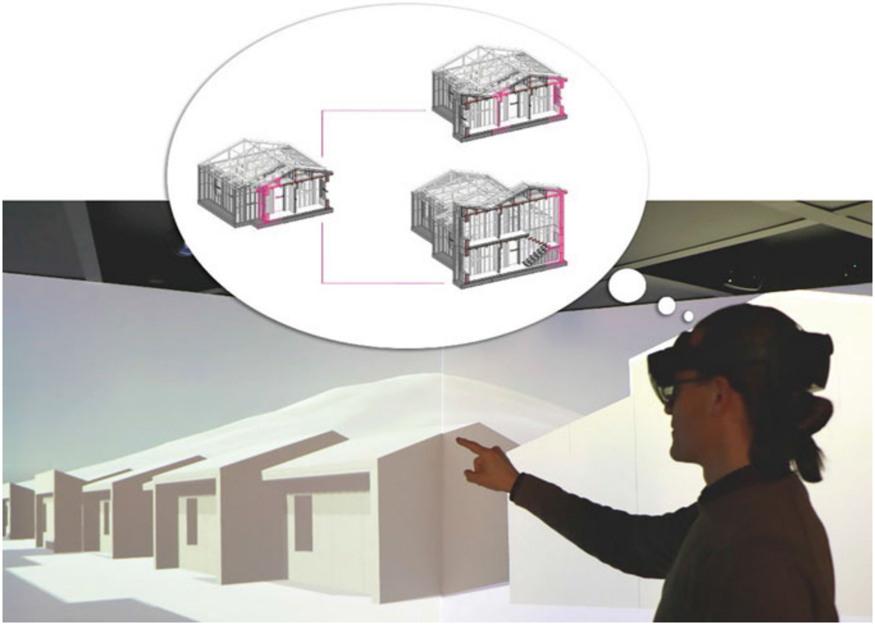


Fig. 18 Meeting in the cave. Evaluation of possible extensions of a housing unit

To respond quickly and easily to such needs, the housing units as well as the construction system in CFS components are designed with a high level of transformability and reversibility. Additionally, the reuse of CFS components, disassembled from temporary housings at the end of their use, for seismic improvement of pre-existing damaged buildings is conceivable. The reuse and recycling of materials and components makes the entire developed process part of a circular economy approach [28].

4 Results and Discussion

The outlined experimentation achieved several results on three different levels: process innovations (development of a digitized workflow that includes the use of VR, AR and MR tools and file-to-factory processes), design innovations (design of a catalogue of flexible, extendable, transformable and removable residential buildings) and product innovations (fine-tuning of different types of customized CFS panels, dry-assembled on site, removable and reusable).

In relation to the topic of this chapter, the development of the workflow is the most interesting result. Indeed, the case study demonstrated how it is possible to manage a complex, time-extensive process with numerous stakeholders based on an information model capable of interacting with different AR, VR and MR devices as well as with customized file-to-factory production tools. The application also showed that visualization devices could be used not only to realistically and immersively represent an architectural project, but also to optimize design, production and construction process.

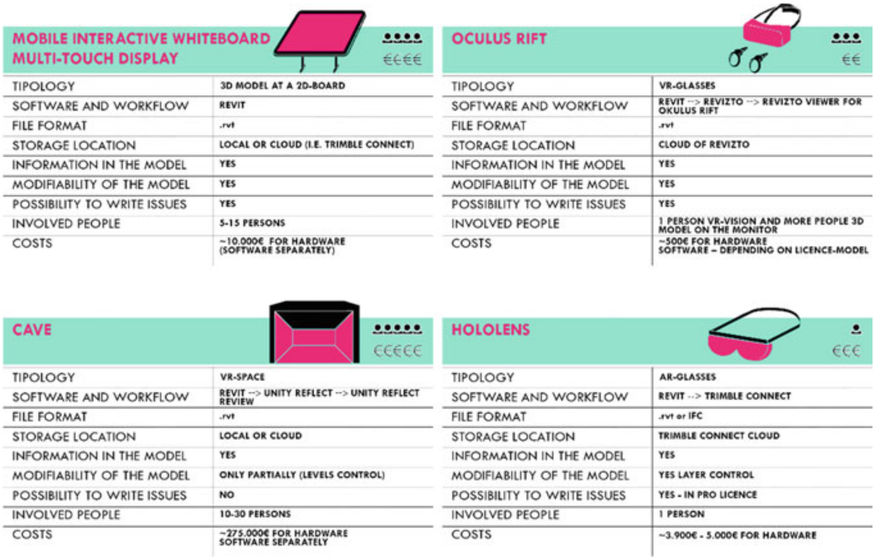
For this process to work best, it is necessary for the client to define the Employer´s Information Requirements (EIR) in detail, as well as for the designers to develop an appropriate Building Execution Plan (BEP). The Level of Definition (Level of Geometry and Level of Information), as well as the software and the exchange formats between them, are important points that must be defined in advance so that communication takes place without errors and the stakeholders receive only the information that is relevant to them.

The choice of which visualization tools to apply, at which stage, for which purpose and with which stakeholders must also be based on an understanding of their peculiarities. The tools used in the experimentation differ from each other in some fundamental characteristics such as typology, involved people (both in terms of amount and skills), possibility to check the model information, ability to modify the model, possibility to write issues, used software, formats and costs.

In particular, the number of users who can simultaneously use a device influences its application in a meeting among decision makers (even 20–30 people) or, for example, for solving a problem by an expert who is working alone. The ability to modify the model as well as the ability to write issues are key features at the stage in which the building system or design still need to be optimized, while they have no importance at the presentation stage of the project itself. Costs of the devices are also important: these range from €1.00 for Cardboard VR glasses to around €300,000 for the Cave. The Cardboard can be a gadget that can be distributed free of charge to residents; the cost of the Cave can be met by, for example, a university research center that rents it out to design groups to conduct their meetings or presentations. Other tools such as Hololens or Oculus Rift have costs that are also affordable for design firms or enterprises.

In fact, this research, in addition to testing, intends to analyze the potential and limitations of the visualization tools in order to facilitate their selection for possible future applications. To this end, their characteristics are presented in detail in Figs. 19 and 20.

In relation to design innovation and product innovation, it is possible to say that the use of a digitized workflow, in accordance with the principles of Industry 4.0, based on an information model, or rather on the overlay of specific information models (architectural model, structural model, plant engineering model, etc.) has certainly facilitated the development of a housing and a construction system capable of reacting to changing conditions and needs as well as a file-to-factory production. In fact, the use of the BIM methodology makes it possible to highlight any problems and collisions in advance. This is a fundamental requirement for a complex project such as the experiment performed, which has a high degree of flexibility and unpredictability due to a disaster event and uncertain development over time. On the production side, the information model also plays an important role by providing inputs to the CNC machine and allowing easy customization.



MOBILE INTERACTIVE WHITEBOARD MULTI-TOUCH DISPLAY	€€€€
TIPOLOGY	3D MODEL AT A 2D-BOARD
SOFTWARE AND WORKFLOW	REVIT
FILE FORMAT	.rvt
STORAGE LOCATION	LOCAL OR CLOUD (I.E. TRIMBLE CONNECT)
INFORMATION IN THE MODEL	YES
MODIFIABILITY OF THE MODEL	YES
POSSIBILITY TO WRITE ISSUES	YES
INVOLVED PEOPLE	5-15 PERSONS
COSTS	~10.000€ FOR HARDWARE (SOFTWARE SEPARATELY)

OCULUS RIFT	€€
TIPOLOGY	VR-GLASSES
SOFTWARE AND WORKFLOW	REVIT --> REVIZTO --> REVIZTO VIEWER FOR OKULUS RIFT
FILE FORMAT	.rvt
STORAGE LOCATION	CLOUD OF REVIZTO
INFORMATION IN THE MODEL	YES
MODIFIABILITY OF THE MODEL	YES
POSSIBILITY TO WRITE ISSUES	YES
INVOLVED PEOPLE	1 PERSON VR-VISION AND MORE PEOPLE 3D MODEL ON THE MONITOR
COSTS	~500€ FOR HARDWARE SOFTWARE – DEPENDING ON LICENCE-MODEL

CAVE	€€€€€
TIPOLOGY	VR-SPACE
SOFTWARE AND WORKFLOW	REVIT --> UNITY REFLECT --> UNITY REFLECT REVIEW
FILE FORMAT	.rvt
STORAGE LOCATION	LOCAL OR CLOUD
INFORMATION IN THE MODEL	YES
MODIFIABILITY OF THE MODEL	ONLY PARTIALLY (LEVELS CONTROL)
POSSIBILITY TO WRITE ISSUES	NO
INVOLVED PEOPLE	10-30 PERSONS
COSTS	~275.000€ FOR HARDWARE SOFTWARE SEPARATELY

HOLOLENS	€€€
TIPOLOGY	AR-GLASSES
SOFTWARE AND WORKFLOW	REVIT --> TRIMBLE CONNECT
FILE FORMAT	.rvt or IFC
STORAGE LOCATION	TRIMBLE CONNECT CLOUD
INFORMATION IN THE MODEL	YES
MODIFIABILITY OF THE MODEL	YES LAYER CONTROL
POSSIBILITY TO WRITE ISSUES	YES - IN PRO LICENCE
INVOLVED PEOPLE	1 PERSON
COSTS	~3.900€ - 5.000€ FOR HARDWARE

Fig. 19 Used visualization and production tools and their characteristics

CARDBOARD	€	
TIPOLOGY	VR-GLASSES	VR-GLASSES
SOFTWARE AND WORKFLOW	REVIT --> UNITY ENGINE (E-DITOR) --> GOOGLE VR SDK	REVIT --> ARCHICAD --> BIMX
FILE FORMAT	.rvt --> .fbx --> .exe	.rvt --> .ifc --> .pln --> .bimx
STORAGE LOCATION	LOCAL OR CLOUD	CLOUD
INFORMATION IN THE MODEL	NO	NO
MODIFIABILITY OF THE MODEL	NO	NO
POSSIBILITY TO WRITE ISSUES	NO	NO
INVOLVED PEOPLE	1 PERSON	1 PERSON
COSTS	1,00 – 3,00€ + SMART PHONE	1,00 – 3,00€ + SMART PHONE

iPAD OR TABLET (AR)	€€
TIPOLOGY	AR
SOFTWARE AND WORKFLOW	REVIT --> UNITY REFLECT --> UNITY REFLECT REVIEW
FILE FORMAT	.rvt
STORAGE LOCATION	LOCAL OR CLOUD
INFORMATION IN THE MODEL	YES
MODIFIABILITY OF THE MODEL	ONLY PARTIALLY (LEVELS CONTROL)
POSSIBILITY TO WRITE ISSUES	NO
INVOLVED PEOPLE	2-4 PERSONS
COSTS	~800€ FOR IPAD

iPAD OR TABLET (VIDEO)	€€
TIPOLOGY	VIDEO AT A IPAD OR TABLET
SOFTWARE AND WORKFLOW	REVIT --> NAVISWORK
FILE FORMAT	.rvt --> .nvs --> .mp4
STORAGE LOCATION	LOCAL OR CLOUD
INFORMATION IN THE MODEL	NO
MODIFIABILITY OF THE MODEL	NO
POSSIBILITY TO WRITE ISSUES	NO
INVOLVED PEOPLE	2-4 PERSONS
COSTS	~800€ FOR IPAD

ARKITECH AF1200P FRAMER	€€€€€
TIPOLOGY	SINGLE PROFILE LGS FRAMER
SOFTWARE AND WORKFLOW	REVIT --> MWF
FILE FORMAT	.rvt
STORAGE LOCATION	CLOUD
INFORMATION IN THE MODEL	YES
MODIFIABILITY OF THE MODEL	NO
POSSIBILITY TO WRITE ISSUES	NO
INVOLVED PEOPLE	1-3 PERSONS
COSTS	~10.000€ FOR MWF SOFTWARE ~160.000€ FOR ARKITECH FRAMER

Fig. 20 Used visualization and production tools and their characteristics

In conclusion, the developed workflow certainly yielded positive results that—after an appropriate adaptation to the specific situation as well as the needs of stakeholders and their relations—could be also applied to other complex projects. To this end, the digital information model becomes the place of interoperability and communication, while AR, VR and MR devices play an important role as facilitators for example in communication, in problem identification and resolution, in worker training, and in on-site assembly. Additionally, it is certainly desirable for future applications to extend the workflow of the digitized process to other phases such as facility management.

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