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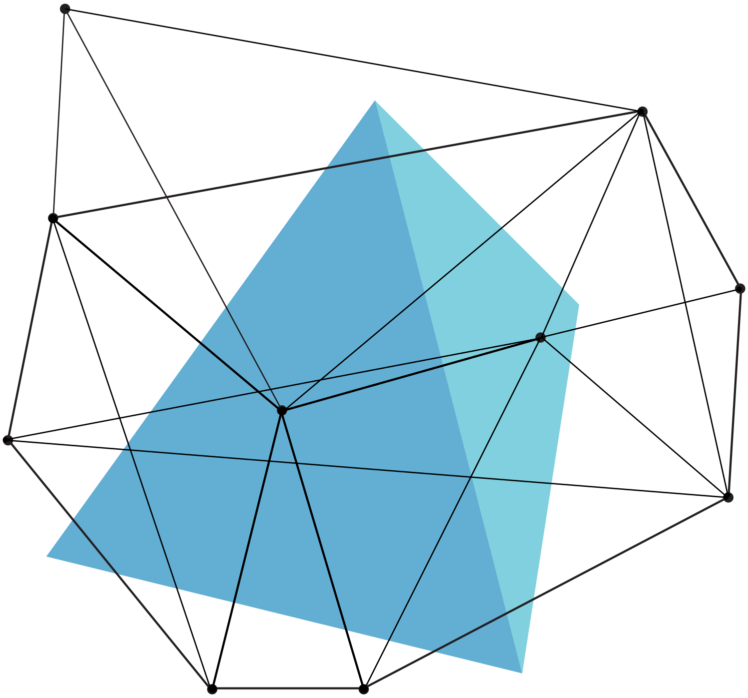

Cahiers édités par Elodie Hochscheid et Gilles Halin
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Sommaire

Préface

Le spectre des possibilités offertes par les technologies du numérique est en perpétuel accroissement. Acquérir, modéliser, représenter, visualiser, annoter, documenter, archiver, imprimer, fabriquer, virtualiser, interagir, échanger et partager sont autant de tâches qu'il est possible de réaliser avec des outils numériques spécialisés. Même si chacune de ces tâches, prise individuellement, demande une expertise spécifique des outils à utiliser, elle demeure appréhendable par tout expert qui souhaite la mettre en œuvre. En revanche, l'enchainement et la coordination d'une partie de ces tâches pour réaliser ou faire évoluer une pratique architecturale constituent un champ d'études particulier et essentiel.

En effet, une pratique architecturale devient une pratique architecturale numérique à partir du moment où chacun des usages numériques réalisés au sein de cette pratique apporte une valeur ajoutée identifiable et mesurable. De nombreux outils, modèles, méthodes, et approches sont mis en œuvre et expérimentés afin de déterminer la pertinence des usages, garantissant l'efficience et l'efficacité des pratiques numériques émergentes.

Les pratiques architecturales étudiées ici sont celles du projet d'architecture, de la conception à la fabrication, mais également celles de la gestion du patrimoine bâti, de la numérisation à la valorisation. Elles produisent chacune des modèles numériques qui s'inscrivent dans un continuum numérique, hybride et interactif qu'il est nécessaire d'appréhender d'une manière holistique et interdisciplinaire afin de proposer des approches (méthodes, modèles et outils) numériques pertinentes.

Ces recherches mêlant à la fois l'ingénierie, la sociologie, l'ergonomie, l'informatique, la psychologie cognitive mais également les sciences de l'architecture sont celles d'une communauté de chercheurs constituée autour d'une thématique commune identifiée sous l'appellation « architecture numérique ». Cette communauté scientifique communique, échange et partage des études, approches et expérimentations autour de l'usage du numérique dans ces pratiques architecturales.

Les membres du laboratoire MAP-CRAI de l'ENSA de Nancy, et plus globalement de l'UMR MAP, s'inscrivent dans cette communauté scientifique en alimentant régulièrement les connaissances sur le domaine par la publication de leurs travaux et leur participation à des conférences internationales sur l'architecture numérique ou des thèmes périphériques questionnés dans/par les approches proposées.

Cette deuxième édition des cahiers de recherche propose un échantillon représentatif de l'ensemble de ces travaux publiés entre 2013 et 2017. Ils ont été réalisés par les membres du MAP-CRAI dans le cadre de projets nationaux, régionaux ou de thèses financées par la France (MENR, MCC, Région Lorraine, ANR, ANRT) ou par un pays étranger (Belgique, Luxembourg, Tunisie, Algérie).

Six grands thèmes guident les travaux du laboratoire MAP-CRAI et structurent la présentation de cette deuxième édition des cahiers.

Dans le thème « Approches numériques pour le patrimoine », trois approches numériques sont présentées : la première compare les méthodes d'acquisition de modèles 3D dans le cadre de la numérisation de Plans-Reliefs, la seconde s'intéresse à la modélisation des structures maçonnées par une ingénierie inverse à base de connaissance, enfin la troisième approche porte sur une méthode de numérisation du plan-relief de la ville de Verdun à partir d'une exploitation de documents historiques.

Le deuxième thème « Conception, Matériaux, Environnement, Energie » s'intéresse aux approches dédiées à l'assistance numérique dans la phase de conception afin de proposer des méthodes et outils permettant la prise en compte des aspects caractérisant la notion de confort (lumière, thermique, acoustique, etc.) et ainsi d'évaluer les performances des projets afin de guider le concepteur dans ses décisions. Deux approches illustrent ce thème : la première propose une modélisation-optimisation de l'éclairage naturel d'un espace en utilisant un outil d'esquisse numérique, la seconde décrit un processus paramétrique permettant de concevoir des camps et abris d'urgence.

Le thème sur les « Approches collaboratives et maquette numérique » a pour objectif d'approfondir les liens entre pratiques collaboratives et la maquette BIM dans l'activité collective du projet de conception/construction architecturale et les pratiques métiers qui s'y déroulent. Trois articles illustrent ce thème : dans le premier la 4D est considérée comme un usage BIM afin d'identifier les niveaux de développement (LOD) qui la caractérisent, l'article suivant interroge les technologies du Big-Data pour l'étude des données générées par l'usage des outils BIM, enfin le dernier article propose une méthode permettant une prise en compte des espaces dans les pratiques BIM.

La « Modélisation et fabrication numérique multi-échelle » constitue le quatrième thème de ces cahiers où deux approches illustrant le continuum numérique et l'étude de la mise en œuvre de formes non standards sont présentées. La première, décrite par deux articles, est celle de la conception et de la mise en œuvre de structures plissées. La seconde s'intéresse aux parois cellulaires. Ces deux approches proposent un processus paramétrique guidant la conception/fabrication de ces types de structure.

Deux expériences pédagogiques et une expérience professionnelle font l'objet du thème 5 « Approches pédagogiques et professionnelles ». Elles illustrent le transfert permanent des connaissances du laboratoire vers la pédagogie ou la profession par la définition, la mise en œuvre et le suivi de pratiques pédagogiques et professionnelles adaptées.

Le dernier thème « Visualisation et interaction dans les espaces virtuels » s'intéressent aux dispositifs innovants (immersif, collaboratif, tangible, naturel) permettant d'interagir avec les modèles 3D. Le premier article présente un dispositif dédié à la collaboration synchrone dédié à la simulation 4D, le deuxième article propose différentes formes de valorisation numérique des modèles 3D issus de la numérisation des Plans-Reliefs, enfin le dernier article présente une navigation main libre permettant l'exploration d'un modèle numérique urbain.

Afin de permettre à tous d'appréhender plus facilement le contenu de ces recherches rédigées principalement en anglais, chaque thème est présenté par les résumés des articles écrits en français. Vous trouverez également la liste et la description des conférences dans lesquelles ces travaux ont été publiés à la fin de l'ouvrage. La forme éditoriale préconisée par les comités d'organisation de chacune des conférences a été gardée afin de préserver le caractère original de chacune des communications.

Ces cahiers s'adressent aux enseignants, chercheurs, architectes, ingénieurs ou étudiants, qui s'intéressent de loin ou de près aux recherches en architecture numérique et plus particulièrement aux contributions des membres du laboratoire MAP-CRAI.

Nancy, juin 2017

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de gauche à droite : Alain Fuchs, Henri-Jean Gless, Grégory Stocky, Benjamin Loillier, Gilles Halin, Elodie Hochscheid, Julien Meyer, Veronika Bolshakova, Manon Kern, Pascal Humbert, Vincent Marchal, Christophe Huon, Christine Chevrier, Jean-Claude Bignon.

THÈME 1

Approches numériques pour le patrimoine

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La numérisation et la restitution virtuelle des maquettes de la collection de Louis XIV (les plans-reliefs) sont un enjeu important pour la préservation et la valorisation numérique de ce patrimoine imposant, fragile et méconnu. Le travail présenté dans cet article compare différentes méthodes d'acquisition numérique de ces modèles physiques, par scanner ou photogrammétrie, permettant de produire un modèle 3D exploitable dans des applications numériques de valorisation.

Dans l'étude du patrimoine architectural, la maîtrise des données métriques est fondamentale. En effet, la définition des critères, l'interprétation des concepts géométriques et la mise en place de méthodes pour structurer l'information constituent la première étape pour modéliser et analyser des bâtiments anciens dans un objectif de conservation. Le principal obstacle est de passer de l'acquisition des données brutes à des modèles 3D compréhensibles. Pour surmonter ce problème, une approche basée sur la connaissance est proposée dans cet article pour réaliser une ingénierie inverse (ou rétro-conception) des structures maçonnées.

La numérisation et la restitution virtuelle des maquettes de la collection de Louis XIV (les Plans-Reliefs) sont un enjeu important pour la préservation et la valorisation numérique de ce patrimoine imposant, fragile et méconnu. Cet article présente une méthode réalisant une interprétation semi-automatique des documents historiques (plans, élévations, coupes) ayant servi à leur réalisation pour produire un modèle 3D sémantique en ajustant des modèles architecturaux paramétriques décrivant la morphologie des architectures civiles et militaires aux dimensions des objets présents dans les cahiers de développement.

ACQUIRE HIGH QUALITY MESHES OF SCALE MODELS FOR AN AUTOMATIC MODELLING PROCESS

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ABSTRACT:

Urban scale models depicting whole towns such as the hundred-scale model collection known as *plans-reliefs* are a valuable source of information of cities and their surroundings. These physical representations of French strongholds from the 17th through the 19th century suffer from many problems that are, among other things, wear and tear or the lack of visibility and accessibility. A virtual collection would allow remote accessibility for visitors as well as history researchers. Moreover, it may also be linked to other digital collections and therefore, promote the collection to make people come to the museums to see the physical scale models. We also work on other physical town scale models like Epinal for which the scale is a bit higher.

In a first part, we define a protocol for acquiring 3D meshes of town scale models from both photogrammetric and scanning methods. Then we compare the results of both methods The photogrammetric protocol has been elaborated by choosing the most accurate software, 123DCatch, which asks for about 60 pictures, and defining the settings needed to obtain exploitable photographs. In the same way, we defined the devices and settings needed for the laser scan acquisition method. In a second part, we segment the 3D meshes in planes by using Geomagic, which has been chosen between several programs, for its accurate resulting geometry.

1. INTRODUCTION

Urban scale models depicting whole towns such as the hundred-scale models collection known as plans-reliefs are a valuable source of information of cities and their surroundings. These physical representations of French strongholds from the 17th through the 19th century suffer from many problems that are, among other things, wear and tear or the lack of visibility and accessibility. Nevertheless, they are objects that come back with a new visibility to the public, with the apparition of the computer tools, and the new interest for city history. This can be seen by the new wave of copies of scale models, and the new exhibitions in which they are highlighted. To grant an access to a larger public, some researchers work on the possibilities to recreate them faithfully. A virtual collection would allow remote accessibility for visitors as well as history researchers. Moreover, it may also be linked to other digital collections and therefore, promote the collection to make people come to the museums to see the physical scale models.

In this paper, we focus on the very first steps in the 3D digitising/modelling pipeline that are the raw data acquisition and processing. 3D data acquisition from scale models is a challenging task for many reasons: the level of detail of the scale models, the high accuracy needed for modelling, the limited access to scale models, and the low luminous conditions in which they are exposed. We have been experimenting different acquisition methods, and we defined a full operation protocol, in order to automate the process. We will first introduce the town scale models, their specificities, and their complexities in comparison to the full-scale models (section 2). Then related works are presented (section 3), in terms of town scale model modelling, and comparisons between photogrammetrical and 3D laser scanning methods. Later, we will determinate the most appropriate software and method for high quality meshes acquisition, and define a protocol for each of these methods, by explaining our experiments (sections 4 and 5). One of these methods will be chosen (section 6). It will be followed by our experiments on segmentation of these meshes (section 7). And finally we will conclude with a presentation of our results (section 8).

2. SCALE MODELS

The town scale model tradition began in the 17th century. In France, a collection of 144 scale models has been initiated by Vauban, named “Plans-Reliefs”. They were made at a scale of 1/600, and their average size often approaches 50 square meters. Most of the old scale models are damaged by the time, and are difficult to move. In order to protect them and to grant a larger access to these pieces of history, there is a real interest to create 3D semantic models of the scale models that would be available for viewing by the public on the Internet. In parallel to these olds scale models and collections, a new wave of freshly realised scale models is actually coming. They sometimes have different scales, as Epinal’s one (1/300° scale).

In order to acquire their 3D meshes, there are many differences between a scale model and a full-scale object. The acquisition of a scale model needs much more precision than the full-scale object. Indeed, they have the same details of architectural complexity, only represented much smaller. 10 centimetres long in real life are represented by only a half-millimetre on the scale model. When the streets are 5 to 10 metres wide, they only measure 1 to 2 centimetres. The 3D acquisition of town scale models is much more difficult, and needs to be precise. The scale model reconstruction is a real difficult work. From this point of view, this operation needs some preparation, and a protocol must be defined in order to realise the acquisition in optimal conditions.

3. RELATED WORKS

3.1 Town scale model acquisition and modelling

Town scale model acquisition and remodelling has already been the subject of many studies. Most of these experiments use the scan data only as a support, to manually model the object. The

Project Relief Auguste Magnin (Geneva, 2013) is the project of reconstruction of the Geneva Plan-Relief. It has a high fidelity to the original, using a 3D scan, but has mainly been made manually. Rome Reborn (Dylla et al., 2010) is an interesting project of restitution of the Plastico Di Roma Antica that uses procedural modelling on the basis of scan data on certain areas: a program recreates plausible models, but not exact ones, in order to have the historic atmosphere of the city. It uses architectural rules from treatises translated to modelling language. Going further, a study on the automated generation of a Historical city Model of Hamburg has been done, including five different epochs (Kersten et al., 2012). It has been conceived by scanning acquisition on a scale model thanks to a robotic arm, and automation of reconstruction from maps. Finally, for the Plans-Reliefs exhibition in Paris in 2012, Google digitized many scale models in a short time, using pictures and laser scanning. Unfortunately, the laser scan data has only been used to verify buildings height, and pictures to create textures. Many graphic designers have modelled the Plans-Reliefs on SketchUp manually, with a loss of accuracy. Lastly, a PhD (Jacquot et al., 2013a) from our laboratory is being made on the plan-relief fortifications. The goal is to automate the adjustments of a parametric library of fortifications works thanks to reverse engineering process. In a previous paper (Chevrier et al., 2010), we explained how we managed to automate the modelling of the buildings from roof segments. However, these roof segments had been manually positioned with PhotoModeler, task that took a lot of time.

3.2 Comparison between photogrammetry and 3D laser scanning

As this paper is about 3D mesh acquisition from real models of cultural heritage, we had to care about the different technics of acquisition. Most of found studies are on real size objects. According to P. Grussenmeyer (Grussenmeyer et al., 2010) there are three methods: Laser Scanning, Photogrammetry, and Tacheometry. These methods have been tested on a full scale model: a castle. We can exclude tacheometry because of the small scale we are working on. Each of these has advantages and disadvantages: both capture heavy data with high precision; photogrammetry is easily textured and better detects edges. In the end, they seem complementary. Some researches insist on the fact that there is no method to be applied in every situation. They made some tests to select the most appropriate method and sometimes to combine them (Kadobayashi et al., 2004; Boehler et al., 2004; Skarlatos et al., 2012).

4. 3D ACQUISITION VIA PHOTOGRAMMETRY

In this part, we present experiments that have been made on a 3D printed replica of a city block of the Toul plan-relief. In section 4.1., we compare several photogrammetrical software. Then, in section 4.2, we defined a protocol to take pictures according to the recommended advices of the user manual software. Finally, in section 4.3, we define a protocol for the 3D mesh creation in order to obtain a high quality mesh.

4.1 Comparison of software

We have been looking for a tool that would automate to the maximum the meshing process. Previously, we used Photomodeler Scanner, software that used photogrammetric methods in manual ways. Now that the technologies have evolved in this field, many software programs exist. We have tested several photogrammetrical software that use different algorithms and different protocols for taking pictures, to select the most appropriate to our need. To do it wisely, we followed the main instructions for each software program to have a proper set of pictures, rather than providing an identical set for all software. Elements of comparison have already been made, on real buildings (Grussenmeyer et al., 2008). We considered these researches to make our experiments, but the tested software often ask for manual intervention. Also, others photogrammetric programs appeared recently.
Tested softwares are: Autodesk 123DCatch, Agisoft Photoscan, EOS System Photomodeler. Other softwares, as Pistou (a research program in MAP-Gamsau, or Topcon's Imagemaster Pro have been considered, but we excluded them for their apparent complexity. Here are the results of our comparison; each one tested on the 3D printed scale model of Toul:

	123DCatch	Photoscan	Photomodeler
Nb. Pict.	≈60	>100	2 to 10
Calc. time	≈30min	≈30hrs	Manual
Quality of the results	Good	Medium	Good
Price	Free	3500€	2500€

Table 1: Comparison of the different software.

As seen on table 1, 123DCatch asks for about 60 pictures, with a maximum of 80. Photoscan needs pictures as much as possible, the user manual mentioning 100 to 500. Photomodeler is mainly usable manually, but an automation exists, which demands for couples of pictures, to work with stereogrammetry. After experiments, the most appropriate software to acquire high quality 3D meshes from scale models using photogrammetry appeared to be Autodesk 123DCatch. It has the quality of being free, fast, and offers easily exploitable results. On the other side, it leaves a very limited control to the user for its parameterization, and does not display any preview before it is completely calculated. So you have to wait for the results before knowing if the model is usable or not.

4.2 Protocol for taking pictures

Fig. 1. Two printed city block from the Toul scale model.

To define the following protocol, we have tested different configurations in our laboratory. These tests were made on 3D printed city blocks of the Toul scale model, painted by hand and relying on a textured background (Fig. 1). The optimal configuration we found for taking pictures that are enough detailed and the most exploitable is a good single-lens reflex camera, equipped with a powerful flash device and its reflector. In the case of our study, we used a Canon EOS 6D, offering high quality pictures of 16 megapixels, equipped with a 24-70 lens. We had a laptop on the shooting place, to download and verify pictures. Also, we had the possibility to start a test with 123DCatch granting us a preview for exploitable results or not.

Have been tested aperture, sensibility, shutter speed settings and different lightning conditions, with some help from a professional photographer. This protocol was only applied and verified on the Autodesk 123DCatch software. It has been provided by our own tests, but also by following the user manual, the user experiences and previous related works on photogrammetry in the Digital Heritage domain.
The Single-Lens Reflex is set on manual mode, assembled with the flash device and its reflector. The flash device allows us to take pictures even in the low luminous condition on which the scale models are often exposed. Its shutter speed is set to 200 milliseconds. It is a very short shutter speed, which makes the ambient light shadows disappear when synchronized with the flash device. The aperture is set up to 11 to have a good depth of field. Its ISO Sensibility is set on 800, allowing us to take quite a lot of pictures without consuming too fastly the flash device battery (with a low quality loss compared to an ISO 100 setting). The Auto-focus is on, and the focal length is optimized according to the distance from the subject. The focal length has to remain the same for every picture on one unique subject.
The shooting conditions in which we work are not always great. Also, we tried to take pictures after verifying our own stability, and then to verify each picture. We have to choose parts of the subject of a reasonable size. The referent here is a city block and its near environment, as it can have in itself a real complexity. This represents an average surface of three square decimetres. Also, the distance to the subject has to be the shortest. In the first shoots, the subject must be entirely seen in every picture, and take the most of the area. Then, we can shoot scale model details. The nearest distance (30cm) the littlest focal length (24), and the furthest distance (1m) the largest focal length (70). We take two orbits of approximately 20 photos around the object. The first orbit at 30° from the ground, the second at 60° (Fig. 2). To complete this collection, we can add some photos orbiting around hidden areas. It will work better if there is a slight presence of volumes or a textured background all around the object instead of a solid colored one. We often arrive to a total of sixty pictures, which is generally enough to work with.
Furthermore, in order to have a spatial reference and scale for a future 3D mesh acquisition, it is advisable to place a small rule near the model. This will define a scale for it and make easier the following phases. After photographing the model following our protocol, we pass to the 3D acquisition phase with 123DCatch.

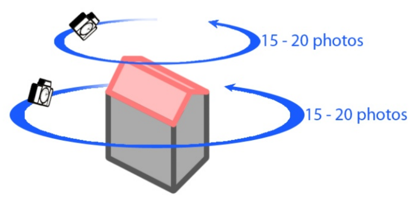

Fig. 2. Simple scheme for taking photos

4.3 Protocol for the 3D acquisition with 123DCatch

123DCatch is very simple to use. At the opening of the software, you only have to select the pictures you want to send. To simplify the computation, it can be useful to reorder the pictures by orbits. 123DCatch has a limit of upload of 80 pictures at a maximum resolution of 6 Megapixels. So we may have to resize the pictures before sending them. Then, we can send these pictures to the Autodesk cloud for calculation. During this phase, no user manipulation is allowed. 123DCatch keeps running in the background, you can also close the program, asking Autodesk to send an e-mail when the mesh has finished calculation. Whatever the size of the photographed area, the number of polygons in the mesh will remain the same. The more you photograph closely, the more the mesh is accurate. Once the pictures are sent, the mesh is computed and downloaded. This step can take several minutes (between 10 to 30 minutes). We have for the first time a good preview of the calculated object. If the result is satisfying, you can continue working on it, otherwise you have to restart with others settings.
At this stage, the program allows four different interventions:
-Define common points between unused pictures and the used ones to add them correctly to the calculation.
-Add new pictures to clarify complex areas, making possible round-trips between photo shoots and 123DCatch.
-Give a precise scale to the model for a future exportation, hence the importance of taking pictures with a ruler.
-And above all, recalculate a more precise model on a selected area of the mesh. This is highly recommended, because the first computing is generally inaccurate.
After these steps, the model is ready to be exported. 123Dcatch has the advantage of offering many export file formats: *.obj compatible with many programs (will be used to export to Geomagic), *.fbx compatible with Autodesk Maya to eventually modify the 3D, *.las which is a highly used point cloud file, and *.dwg compatible with AutoCAD.
Following this protocol, the acquired mesh quality is high and exploitable for next steps of treatment. Here are 123DCatch screenshots of these results on the Toul printed replica scale model (Fig. 3), and the real Epinal scale model (Fig. 4). As presented, meshes are well textured, and are accurate enough even in the centre courtyards. We always have small not captured details as they could not be seen from any point of view, as areas under the roof overhangs, small alleys (<2mm), and the smaller and deeper courtyards (1cm² in 2cm high courtyards).

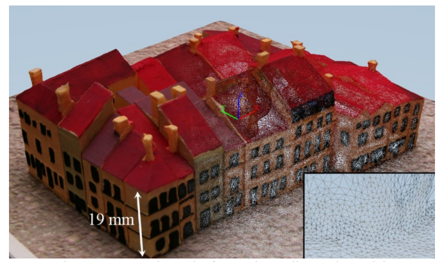

Fig. 3. 123DCatch results for Toul's replica scale model

Fig. 4. 123DCatch results for the Epinal scale model

5. 3D SCANNING ACQUISITION

5.1 Technical constraints

Technical constraints due to the scale models and plans-reliefs are almost the same for scanning and photo shooting. Then, the access to the scale model, often difficult, is even more important for the 3D scan because of the necessity to sweep the model from many directions. Moreover, the 3D scan needs to be wired to electric power, and to a laptop. It becomes much more difficult to use than the Single-Lens Reflex in almost every case. The use of our handyscan (Creaform EXAscan) is easier on little scale models. Also, the handyscan needs special reference points, which consists on a grid marked with many points, every 5 centimetres.

5.2 Tests

To define the following protocol, we made many experiments in laboratory, always on the same 3D printed scale model of Toul, and also in real conditions, on the Epinal scale model. Experiments on the printed Toul scale model have been useful to define every settings of the scan (luminosity, sensibility, precision), and the scanning time. These settings are related to each other: we had to make a compromise between precision, scan time, and size of the bounding box. These settings have been used on another experiment, on the real Epinal scale model, where we tried to define how to scan in real conditions of work..

All these tests have been influenced by previous experiments from our laboratory. In the first experiments (Chevrier et al., 2010), previous settings have been already defined and tested in real conditions. These experiments conducted on Toul plan-relief, have highlighted the difficulties to scan thin or damaged elements.

As special reference points, we suspended a wired doted grid over the scale model thanks to a portable scaffolding. This grid remains hardly installable over a massive scale model. We are not authorized to place pastilles on the model because it is forbidden by Cultural Heritage.

5.3 Protocol for the 3D scan acquisition

As the photogrammetry, 3D scanning needs some preparation. The device only scans what is in a radius of 30-45 cm from his sensors. Therefore, without an expensive robot arm to do this, the operator can only use his own arms, and count on the access he has to the scale model. As much as possible, it is recommended to study every access possibilities to the model, as if it is extremely rare to have a free access everywhere. The treated area by the scan is defined by its own acquisition quality settings. In the case of thin detailed scale models, the precision has to be high: one point each semi-millimetre. This setting limits the acquisition volume to a cube of 15cm side. The full acquisition time for this volume with an accurate precision is about one hour. To scan the full model, you have to sweep over the model from many different points of view. The software displays in real time every acquired point, which allows us to control the missing areas. If there are areas that are inaccessible to the scanner sensors, it will leave a hole in the final mesh, which can be difficult to fill. In the case of very dark painted surfaces, it is possible to change the light sensibility setting of the scanner to avoid other holes. The scanner cannot acquire areas painted that are near to the absolute black (in our case the openings of the buildings), which absorbs every light.

With laser scanning, we have been able to acquire high quality (0,2mm in our case) non-textured meshes, similar in quality to the photogrammetry. Each different acquisition is geo-referenced due to the dot grid, making easier the assemblage between them. Also, captured models are already at scale, which is a benefit for further operations.

We present the results of each scan on the Toul printed replica scale model (Fig. 5), and then on the real Epinal scale model (Fig. 6). The meshes are of good quality, but there are always some holes corresponding to parts that the scanner could not capture. But no textures are available. Earlier tests have been made with a textured scan, but results were not convincing. Textures are very rough, and they are not captured on the whole scale model, so they are not exploitable. For the Epinal acquisition, we focused on a part of the model that was easily accessible on the border.

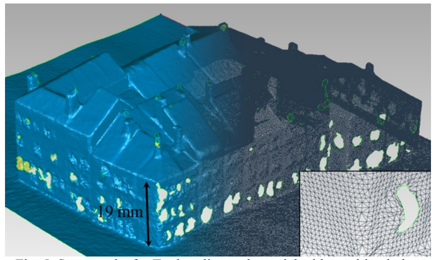

Fig. 5. Scan results for Toul replica scale model with resulting holes from non-captured black surfaces.

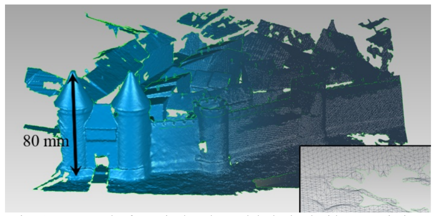

Fig. 6. Scan results for Epinal scale model: the back sides are missing because it is not accessible by the hand.

6. COMPARISON BETWEEN PHOTOGRAMMETRY AND 3D SCAN

In order to know which method is the most accurate in the case of city scale model, we compared each method results. We compared the mesh quality (section 6.1), the acquisition difficulty (section 6.2), the exploitability and the eventual extras that they offer (section 6.3).

6.1 Mesh quality

The mesh quality is important for us, as we need a high quality to exploit the model in order to segment it. Considering the amount of polygons as a part of a mesh quality, the results between photogrammetry and laser scan are similar (Fig. 3,4,5,6). In comparison, each scanned cubic areas (15x15cm) has 1.4 million polygons, whereas every 123DCatch mesh of the same size has up to 1.6 million polygons (depending on the number of pictures and their resolution). The mesh quality of the photogrammetry depends on the area we want to acquire and on the resolution of taken pictures, whereas the quality of the scan depends on the amount of defined sized cubic areas.

The mesh quality is not just about the polygons number. Others characteristics come into play: the accuracy of the acquired geometry, and the precision on details. On these criterions, laser scan has less noise on solid coloured parts, but photogrammetry is still enough for segmentation, and both cannot access in thin holes. Taking detailed pictures for the photogrammetry, we can improve geometry.

The available results in the fortified areas of the scale models are along the same line. Even if the photogrammetric mesh is more irregular than the laser results, the impact on the segmentation process remains invisible.

6.2 Difficulties of acquisition

Because of the size of scale models, we had to find the most convenient method to acquire its geometry. As a reminder, Epinal scale model, one of the smallest, is 3.3 x 1.8 m. The only city table of Toul is already 2.3 x 2.13m. So, some areas can be difficult to access (Fig. 7). Moreover, given the little control over the parameters of 123Dcatch, it is impossible to forbid its algorithms to create awkward geometries instead of trees and areas it could not capture properly. Therefore, photogrammetry is easier, thanks to the zoom and focal we can modify according to the distance we have to the subject. The Single Lens Reflex is also a lighter device than the Laser Scan. The Laser Scan has the disadvantage of needing a specific distance between it and the subject, which can often be difficult to access. This is resulting by holes and missing parts on the mesh (Fig. 6). This disadvantage could be bypassed by the use of a robotic arm or a bridge over the model, of a consequent price. The additional cost of these operations includes a truck, the equipment (the LaserScan we used costs about 55 000€, and the Single-Lens Reflex 3000€, which is much cheaper), and the loss of time from moving and installation.

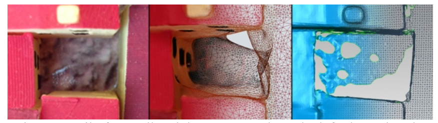

Fig. 7. Detail of a small and deep courtyard: on the left, the real scale model; in the middle, 123DCatch finds an average round geometry; on the right, the scan leaves holes instead of proposing a fake geometry.

6.3 Exploitation possibilities and extras

The exploitation possibilities offered by each method are similar. Thanks to the accuracy of the laser scan, segmentation part can be a bit easier than the photogrammetry, because of the slight noise on 123DCatch results. Scan reorganization is also easier thanks to the geo-referencing of each captured mesh, but it is also possible with photogrammetry in Geomagic Studio 12. In contrast, photogrammetry offers well textured meshes exploitable for the next steps.

6.4 Chosen method

After this comparison, we chose to give priority to the photogrammetry, because of its ease of use, its rapidity in situ, its price, and the needed capacity of texturing the models.

7. SEGMENTATION AND PLANES RECOGNITION IN THE 3D MESHES

After acquiring meshes from the whole scale model, we have many separated point clouds. These point clouds are heavy (about 1 million points per city block) and represents a very complex geometry composed of many polygons which are too heavy to be viewable online. So we have to treat this point cloud with respect to building shapes and roofs, in order to have a lighter model. The aim of plane recognition is to facilitate an automatic parametric modelling (that will be explained in a another paper). The texturing of the parametric model is automatically computed from the textured mesh.

In section 7.1, we compare software applications for segmentation. Then, in section 7.2, we define a protocol for this step. And finally, in section 7.3, we will see the final results of segmentation.

7.1 Comparison of software

In the domain of segmentation of 3D meshes, many software applications exists. We decided to test three software programs to evaluate which one is the most adapted to our needs. Many of these are commercial and expensive, because of their rarity and complexity. Tested software includes Geomagic Studio 12, Rapidform XOR3, EDF CloudCompare and Mesh2Surface 4 Rhino plug-in. EDF CloudCompare is free, it applies RANSAC algorithms with medium quality results, but it offers very low export possibilities. Mesh2Surface 4 Rhino is a Rhino plug-in that costs around 600€. It has been tested on its demo version, and did not offer exploitable results. Rapidform and Geomagic are recognized among the best point-cloud processing software. Their price is high (15 000 €) and their functionalities are very close to each other. However, Geomagic Studio 12 is an easy-to-use software that offers great exploitable results. It has many parameters that allow the refinement and the enhancement of the meshes, to prepare them to the phase of segmentation. Also, many of the operations are automated, and never ask to interfere directly on the mesh. That's why we decided to use Geomagic Studio 12.

7.2 Protocol for the segmentation

In order to segment the meshes, we will describe the use of Geomagic Studio 12, step by step. The general way to operate the mesh is: first, correction of the mesh, in order to avoid any calculation error, then optimization of the mesh, in order to simplify the computing in the following steps, and finally mesh segmentation. Each of these steps asks for many parameters, that we have to define. We have to find the optimal default values to have the best conditions to automate the process. Let us detail the three steps:

- Many functions help to correct the mesh. The first one is automatically proposed by the program, called the "Mesh Doctor". This operation reduces little spikes, holes, replaces the normal of false oriented triangles, and also improves the mesh quality in order to avoid any error on next steps. Others manual functions let the user complete the correction step, as hole filling, mesh trimming, etc. In the fortified areas, this process is a tedious task because of the vegetation cover which has to be removed. This operation can only be done manually given the proximity of the vegetation with the smallest details of the fortification works. Even with these precautions, the loss of information is inevitable and prejudicial for the segmentation step. Thus, it results in many program crashes delaying the segmentation process.
- Then, we prepare the mesh for the segmentation, by cleaning low curvature areas, reducing noise, and sharpening. These options are facultative, but they help to the segmentation, especially on imprecise meshes.
- Finally, the parametric surfacing / segmentation phase, finishes our process. This step passes by many actions. First, the region detection asks the user to enter sensibility parameters. Different parameters are asked at this time, as the separator and curvatory sensibility, and the minimum area to be computed.

Obviously, it often depends of the mesh quality, and the nature of the model. In the case of city blocks: sensibility must be high, and the minimum area is about a half square centimetre. Next, we define the type of geometrical shape we want to recognize (Planes for building reconstruction, Sphere for spherical trees, Freeform for ground). These regions are separated by their contours, which the user is able to modify and correct. In the fortified areas, manual interventions are always necessary as the fortified entities vary greatly in terms of size. The walls are usually correctly segmented depending of the amount of residual noise but smallest parts of fortification are nearly out of range even with a high sensibility and a minimum area about of a tenth of a millimetre.

Almost every face connection on scale models are edges, so we set the connexion type on “sharp”. Then comes the phase of surfaces and connections fitting. And finally the result computing, that offers a real segmentation, separated in trimmed primary surfaces. By following these steps and settings, we have a segmented model, approaching the real one, and allowing us further automatic treatments for the creation of the parametric models of the buildings (Fig. 8).

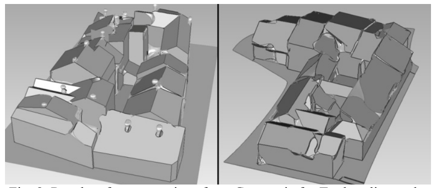

Fig. 8. Results of segmentations from Geomagic for Toul replica scale model, and for the real Epinal scale model

7.3 Results

Thanks to the plane recognition, the model becomes simpler, only composed of real plane polygons following their real edges. There are still some improvements to do, such as missing corners that needs even more precision, and the presence of chimneys that can be easily found (they are formed by spikes).

In the fortified part of scale models, the level of detail is higher than in the city area as the plans-reliefs were used above all as a military tool. Geomagic treatments and especially segmentation step are time consuming processes whose outcomes are far from being satisfactory. An alternative method is being tested right now. It uses Grasshopper plug-in for geometric and semantic segmentations and the early results are encouraging (Jacquot et al., 2013b).

8. CONCLUSION

This study about the use of photogrammetry and laser scanning on historical city scale model has revealed some important knowledge about the protocols for acquisition, and segmentation. From the different sizes of the scale models, compositions, and epochs, we could define a unique protocol to have the same quality of results. Tests have been focused on the city and fortifications, but they have to be extended to towers, vegetation, historical monuments, etc.

The next step of our researches is in progress: the automation of the creation of the building parametric models from the 3D segmented meshes. The texture of each building will be computed from the 3D textured mesh. The benefit of that kind of semantic and digitalized city model would be great: it will be accessible to the public; it will represent an information source useful for historians, patrimonial architects and town planners; it will promote the scale model collections to everyone.

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Knowledge-based approach for the 3D modeling of masonry structures

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Abstract— **In architectural heritage field, the control over metric data is fundamental. Indeed the interpretability of geometrical concepts, the criteria and methods to structure information are the first step for the analysis and simulation for the conservation of ancient buildings. The main barrier is to move from survey raw data to 3D models that are understandable. To overcome this issue a knowledge-based approach is developed to carry out a reverse engineering for digitised masonry structures.**

Index Terms**—Architectural knowledge, 3D semantic model, masonry structure, data post-processing, reverse-engineering**

I. Introduction

The Monumentum project aims at developing a software platform for the management of knowledge that enhances the comprehension and analysis of degradation phenomena affecting ancient buildings. Various disciplines are mobilized in order to define a prototype information processing workflow including spatial analysis of surfaces, geometric models of structures, heterogeneous documentary sources, etc. One of the issues of this project is related to 3D modeling and architectural strucuring based on digital surveys. 3D digitization techniques allow the creation of precise digital models of ancient buildings but whatever their accuracy or realism these models are not adapted to conservation analysis purposes. The specific objective of our task is to develop and experiment a process for the treatment of point clouds in order to create a computational model dedicated to mechanic behavior analysis. This article presents preliminary experiments to meet that objective. Following this introduction, the paper presents in part 2 a state of the art in reality-based semantic modeling applied to ancient architecture. Part 3 describes the method we are currently developing as well as the first experiments and results.

II. State of the art

Many methods can be considered to model semantic contents from 3D raw data. The required level of detail, the geometric complexity of the studied object or the quality of raw data are several criteria that may be used to determine what is often called “Scan-to-BIM” process [1]. In many case, the aim is not so much the creation of building information models but rather the parametric (and in some case the semantic) modeling of existing buildings [2]. The creation of such models is only one side of the BIM approach as it aims at overcoming geometrical issues regarding data size, gaps and accuracy. Indeed, acquired 3D data have to be processed in order to create geometric models based on parametric entities models which are accurate mathematical models that replaced approximate meshed representations. For this purpose, new tools and functionalities have been introduced in existing architecture software to read point-cloud files. In many projects, Autodesk Revit is used to perform reality-based modeling [3]–[6]. Even if the software is originally intended for computed aided design, a number of initiatives were developed in the reverse engineering field. A first example is the GreenSpider project of TC Labs [4]. This plug-in of Revit allows the conversion of point clouds into input parameters for the natives tools of the software. However, the points that are imported into Revit are already segmented. In 2012, Autodesk Labs presented Point Cloud Feature Extraction for Autodesk Revit technology: a prototype of a reverse engineering tool integrated into Revit 2012 software. It provided datum, building and floor extraction but also automatic straight wall extraction for the creation of basic parametric Revit elements [6]. Parametric modeling is the keystone of reverse engineering approaches. Textual programming languages were already used to create parametric models for the 3D modeling of ancient buildings. However, they required a significant learning period before achieving the implementation of algorithms. Since 2007 and the release of new parametric software like Grasshopper, the algorithms can be achieved through visual programming language thus decreasing the back and forth switching between the geometric shape and the algorithms, which in turn may allow the designers to focus their attention on design. Previous experiments were accomplished with Grasshopper for the architectural features extraction such as regulating lines, which are used to control the proportion and placement of elements in other proportioning systems as well [7]. Notable experiments of modeling based on the use of regulating lines include the military architecture features modeling such as bastioned fortification [8] and civil architecture features such as classical orders [9], [10] or gothic windows tracery [11], [12].

III. Knowledge-based modeling: initial experiments

The Monumentum project relies on a domain ontology that is developed from several reference materials including dictionaries [13] or stereotomy treatises [14], [15] to identify masonry structure architectural components. The latter are essential to model the vocabulary (i.e. all the terms describing the components of the domain) and the grammar (i.e. all the design rules fixing the constraints between components) of masonry structures. Based on the ontology, a library of parametric models containing architectural objects is implemented in Grasshopper. The library is made of parametric arch curves which can be used in turn to create most of the vault types. Once the point clouds are imported in Grasshopper, they must be manually segmented into smaller samples. Each of them has to contain a single arch or vault intrados. These samples are then used as input parameters in an automatic process that instantiated every arch curves of the library. The point clouds are projected onto the instances according to the shortest distance. The sum of the distances between the original and the projected points allows the identification of the arch type but also to position and to have dimensions attributed to the parametric arch by using directly the point clouds characteristics. The depth of arches or vaults is also automatically retrieved which allow the sweep of arch curves along a trajectory, thus resulting on the creation of intrados.

IV. Conclusion and futures works

Monumentum aims at the creation of an information system dedicated to ancient building degradation monitoring based on semantic annotation of photographs [16]. For that purpose, several tools have to be developed and especially a domain ontology describing the knowledge related to degradation phenomena and architectural morphology. The ontology is also used for the creation of specific 3D models. In this paper, we presented the very first experiments on the automation of the modeling of architecture masonry structures based on 3D surveys. Preliminary results are promising (fig. 1). In the long term, the resulting semantic curves are intended to be used in Revit for the making of the 3D models of the whole masonry structure. For that purpose, we can rely on the software library as well as a dedicated library that will use the segmented arches as input parameters. The low level of detail of the resulting 3D models should have little impact on their use. They will be converted to meet the requirements for the next step of Monumentum project, which is static behavior analysis.

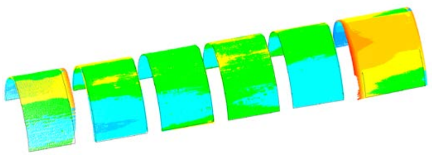

Fig. 1. Assessment of b-rep barrel vaults accuracy in Geomagic software. The average distance is 1cm and the standard deviation is 12cm.

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3D Semantic Modelling of Scale Models from 2D Historical Plans

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Abstract

The French collection of Plans-Reliefs, scale models of fortified towns, are an exceptional architectural heritage. Many cities, represented on these plans-reliefs, would like to expose, develop and exploit this historical knowledge. However, the fragility, the dimension of the supports and the exposure conditions make this acquisition difficult. Thus, the creation and the exploitation of a virtual model is an interesting alternative. This paper presents a new method exploiting historical documentary for the 3D semantic modelling of Plans-Reliefs as more than the half physical Plans-Reliefs are currently enclosed in containers in Paris. From 2D plans, ground outlines and facades of buildings are partially-automatically extracted to create automatically the 3D textured model of each building and ground elements (streets, rivers and courtyards). Another specificity of the method is the use of graphical schemes for the description of parametric objects.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: 3D modelling—cultural heritage

1. Introduction

The French collection of *Plans-Reliefs* are an exceptional architectural heritage (*Figure 1*). These scale models of fortified towns were built from the *17th* to the *19th* centuries. From an initial collection of 260 *plans-reliefs*, only one hundred models remain. Only 41 are exposed in two museums. The others are enclosed in containers in Paris. Many cities, represented on these *plans-reliefs*, would like to expose, develop and exploit this historical knowledge for tourism or urban issues. However, the fragility, the dimension of the supports and the conditions of their exposure make this acquisition very difficult and expensive. Thus, the creation and the exploitation of a virtual model is an interesting alternative for these cities. This creation of a digital model requires the availability of the town scale model as experiments led with Toul [CJP10], Aire sur la Lys [Ing13] and Saint-Omer [OnS14]. In this paper we present a new approach based on historical documentary resources. These historical documents bring together all the topographic surveys made on the ground by the engineers of the time and were used as specification for the construction of the physical *plans-reliefs*. Some of these documents have been digitised. Our method utilizes these documents as a data source for the reconstruction of a virtual historical city model similar to the original *plan-relief*. In a previous paper [Che15], the method was described for 3D textured meshes as input data. The same library of parametric objects is used but all the process of reconstruction is new and now specific to 2D plans. Another specificity of the new method is the use of graphical schemes for the description of parametric objects.

After an overview of the related works (section 2), a presentation of the historical documents is exposed (section 3), then our overall methodology is explained (section 4). Each step of the methodology is further exposed starting with the drawing of the polygons in the 2D plans (section 5), followed by the definition of relations between the ground polygons and their elevations (section 6) and the generation of realistic textures (section 7). The graphical schemes used for the description of the parametric models is then exposed (section 8), followed by the automatic generation of the 3D objects of the virtual version of the *plan-relief* (section 9.1). Finally results are detailed (section 10) and further enhancement discussed (section 11).

Figure 1: *Picture of the plan-relief of Verdun (currently stored in containers)*

2. Related works

For a couple of years, there are lots of ongoing works for the modelling of city scale models. In most projects, the 3D modelling is done without any automatic processes (Virtual Leodium [PCDB09], Pragues [Pra13]) or is not documented (Nantes [LKB08], Geneva [PRA11], Sarajevo [RPO15]) since the work is carried out by private companies. The focus is set to the outcome of the modelling rather than on the method used for the 3D modelling itself.

A first modelling project is the 3D modelling of Prague based on the scale model of Antonin Langweil realised between 1826 and 1837. More than a hundred people worked for the 3D model reconstruction step. The digitising was easy because the model could be divided into 52 parts (1.6 x 1m for the biggest with a scale of 1/480). The model was carried out thanks to the collaboration of Autodesk and the use of a photogrammetric software adapted and developed especially for this project [SZ09] [Pra13].

A second modelling project is the Rome reborn project [GFDs*05] [Rom13]. It aimed at illustrating the urban development of the Ancient Rome from 1000 BC to 500 AD thanks to the Plastico di Roma antica scale model. Because of the size of the model (280m^2), the accent was put on the 5% of well documented buildings (Circus Maximus, Colosseum, etc.), with a manual reconstruction. The remaining buildings (roughly 10,000) were modelled with CityEngine [Cit13], a procedural tool that creates credible but not necessarily true buildings [DMU*09].

A third project, the Hamburg project [KKSS12] was the only one in which automatic steps allow the modelling of the buildings. However lots of assumptions were made: saddle and symmetrical roofs, buildings with four sides. The scale of their physical model is 1:1000, so the geometry is simplified, most of the buildings respect the constraints (92%) and are correctly modelled.

Since our first experiments in 2010 [CJP10], other modelling projects of the *plans-reliefs* have been undertaken. The *plans-reliefs* of Marsal, Aire sur la Lys and Saint-Omer were digitised by private companies (3D textured mesh). In 2012, Google and the French Defense Ministry conducted the digitising of parts of 8 *plans-reliefs* for a visualisation in Google Earth [Alo11]. However the modelling was very disappointing: manual and inaccurate, as much for the geometry as for the photometry.

In computer vision, for full scale towns, extraction of segments or regions from images are also another research field of many teams [WZ02] [SV02] [JC08] [AF00] [TD04]. Other [HVF*97] [KD07] [MFVVG98] use geometrical properties to label each segment of a roof. [KD07] divide data into three layers: outline segments, every segment inside the outline and the roof slopes. They use TIN (Triangulated Irregular Network) algorithms to triangulate roofs but problems involving complex roofs still appears.

A visual programming language (VPL) is a programming language that lets users create programs by graphically manipulating program elements rather than by specifying them textually. Lots of VPL exist in various domains (education, games, multimedia (Quartz composer [Qua16]), simulation, automation... [vlp16] As far as 3D modelling is concerned we can cite Grasshopper [Gra17] a generative modelling interface for Rhinoceros 3D, Maya [AM13] or Blender [Ble16] software that include node editors to create shading programs as graphs. The aim of these VPL is to simplify the task of programming, making available the creation of software by non-specialists. Grasshopper is a visual programming language and runs within the Rhinoceros 3D CAD application. Programs are created by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components. Many of Grasshopper's components create 3D geometry. Non computer scientists can learn to develop with Grasshopper and create their own parametric objects as in [JCH13] but it requires nevertheless a long training period.

Revit software [Rev16] is specifically built for Building Information modelling (BIM). Revit allows a user to describe graphically new parametric elements from a 3D model by specifying parameters and constraints. In our method, we describe graphically the 3D parametric models of the buildings. The simplicity of the drawings allows a better reliability and fewer mistakes compared to the former method. These descriptions can be made by non-computer scientists with no training period which is important for us as we often work with non-scientist students.

3. Historical documents

In [CJH*15] is presented an overview of the project with possible applications. You can also find a presentation and characteristics of historical documents in [CJH*15]. In this paper we focus on the modelling process.

Problems of access to the physical scale models have led to the decision of using these documents to develop a new approach of 3D semantic modelling for the *plans-reliefs*.

4. Principles of the method

Our modelling process is explained in *Figure 2* and was implemented in our own software. It is a knowledge-based approach that consists of two steps: the first one is common to all projects, whereas the second one is specific to each scale model.

- Step 1: a knowledge model of the studied architectural elements (buildings and fortification works) is carried out (a) thanks to reference literature (e.g. classical and military treatises). Each kind of element is described in a library of parametric entities (b). This library can be enriched at anytime if required. For more details about the library, you can read [Che15].
- Step 2: the modelling process consists of:
  - Semi-automatic step (d): 2D drawing of polygons in the plans: ground outline of the buildings and elevations (Section 5).
  - Relations between the ground outline of buildings and their elevations are then manually specified. Each segment of the ground outline can be connected to a corresponding elevation (d) (Section 6).
  - More realistic textures are automatically computed from the 2D plans (Section 7).
  - Finally, from a ground outline and its corresponding elevations, we automatically compute the 3D textured model of the building (e) according to a given parametric object of the library (Section 9).

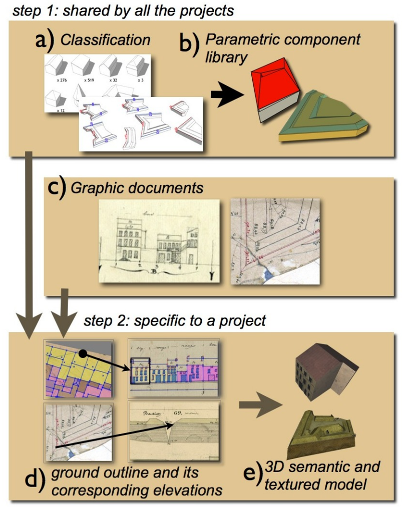

Figure 2: *Principle of the method*

5. 2D drawing of polygons in the plans

We developed a specific graphical user interface to capture polygons and segments. This step is manual for the ground plan (some tests carried out by specialists of this domain research did not produce exploitable results [Cha14]). For the elevations, simple algorithms allow us to automatically detect simple facades and their openings.

5.1. Ground plans

In the 2D ground plan of each city block the user draws points, lines and closed polygons corresponding to parametric entities of the library (*Figure 3*). The ground plan of the city block must be entirely covered by closed polygons in order to have no holes in the 3D model that will be computed from these polygons.

The following entities are drawn:

- *Buildings*: outline of each building is depicted as a closed polygon. The ridge, roof breaks, valleys and angles are represented by segments inside the outline.
- *Chimneys*: chimneys are represented by points inside the building outline.
- *Ground*: streets and courtyards are represented by polygons.
- *Walls*: outline of walls are represented by a thin polygon with parallel sides.
- *Stairs*: outline of stairs are represented by a polygon, the steps of the stairs are not drawn.
- *Vegetation*: vegetation is depicted as points and polylines.

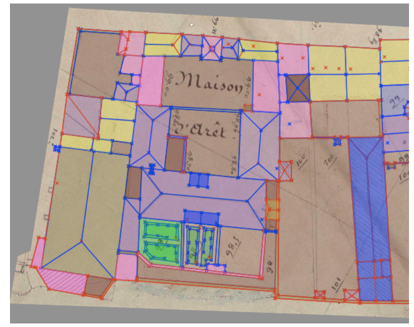

Figure 3: *sol*

For each element drawn on the plan, we must only indicate the type of parametric entity (building, walls, vegetation, stairs). The segments inside the building outline allow automatically the retrieval of the kind of building as explain in [Che15]. Similar rules for walls allow the retrieval of the kind of wall according to the outline. Polygons on the ground plans are used to define position, orientation and dimensions in x and z axis. Axis Y is the vertical axis.

5.2. Elevations

In the 2D elevation plans, must be drawn (*Figure 4*):

- closed polygons corresponding to facades with their openings and cornices, walls, stairs, chimneys. Openings are not used for the creation of the 3D model of the buildings but are used for the automatic process of creation of the textures (*Section 7*).
- lines corresponding to ridges.

A reference altitude is also chosen for each city block (the lowest altitude of the city block) and then on each elevation plan, a line corresponding to this reference altitude must be drawn. The 3D model will be then correctly build and positioned in height (altitude). Elements on the elevation plans are used to define dimensions in the vertical axis (y).

Automatic detection of facades produces good results with clear drawings (*Figure 4c*) but bad results with complex drawings (*Figure 6*). The algorithm detects first the outline of the facade (from a user picked point). Then it detects openings and cornices. Then ridge is detected and finally chimneys. Algorithms are simple and could be improved with better competence in image analysis process. The process is as follows (*Fig. 4 and 5* illustrate the process):

- A white and black picture is computed from the original plan with a threshold color of (160, 160, 160) for our plans.
- In this picture, dilatation process is computed from the picked point in white area (*Figure 5*) green color).

- close to the detected area, we look for vertical separation black segments that will be the limits of the facade: for each column of pixels inside de bounding box of the area (*Figure 5*) light blue box), near the right limit then near the left limit, we count the number of black pixels. The column with the maximum number is kept to be the searched segment.
- close to the detected area, we look for the bottom segment (not necessary horizontal) of the facade. We look for the longest segment near the bottom part of the bounding box.
- For the top part of the facade, we look for a flat segment. If no flat segment is found we look for a pinion composed of one or two inclined segments.
- then openings are searched inside the facade (lintel can be rounded), cornices are also sometimes detected (*Figure 5*) pink color).
- If the top of the facade is flat, we look for an horizontal segment above to detect the roof ridge. We also look for squares that represent chimneys. They are difficult to detect because features are not dark enough.

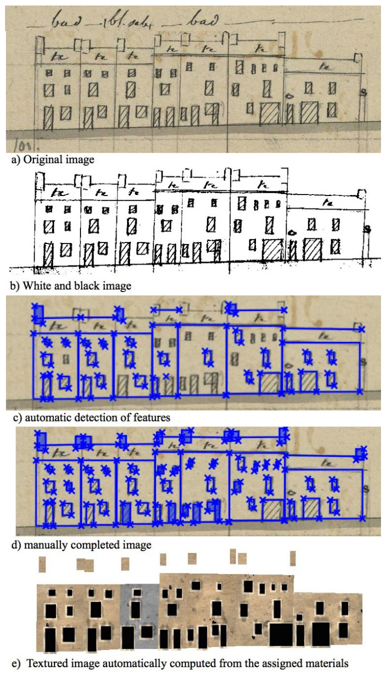

Figure 4: *Steps of feature detection process.*

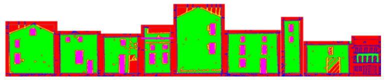

Figure 5: *examples of automatic detection with false colors for areas.*

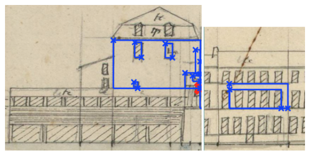

Figure 6: *Problems with automatic detection due to a large concentration of features. In some parts nothing is detected (hatching parts).*

6. Relations between the ground polygons and the elevations

Once the drawings are done, one must now define the relations between the ground outline of a building and its elevations (*Figure 7*). We develop a specific user interface allowing to specify which segment of the building outline corresponds to a facade. One can also have the drawing of only a part of a facade but not of the whole facade. We can then specify which part of the ground segment corresponds to the part of the facade. This will be taken into account in the automatic creation of the building.

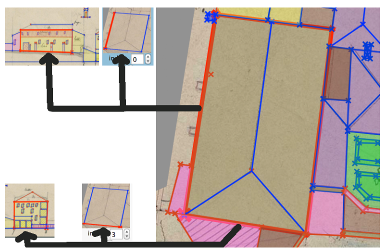

Figure 7: *Relations between the edge of the ground polygon with their corresponding facade.*

Interior segments require also relations with elevation features: the ridge segment on the ground plan must be related to the ridge segment on the elevation plan. Points corresponding to chimneys on the ground plans must be related to the corresponding polygon in the elevation plan.

Buildings and walls work in a same manner. Stairs can have one or two relations in the elevation plan. Vegetation has no relation because it is exceptionally represented in the elevation plans.

However, inconsistencies, errors and omissions are common and make it necessary to use *a priori* knowledge for addressing interpretation problems. Spending more time to understand and to interpret documents can sometimes solve this problem otherwise a solution is chosen between the various possible hypothesis. The most common problems we have encountered are:

- More or less facades between two numbers in the elevation plans than in the corresponding part in the ground plan.
- Lack of information about facades on small courtyards.
- Facades of a building are not consistent in height or for the roof ridge or for the kind of roof. They also can be incoherent with the roof building shape in the ground plan.
- Some corrections have been made several years later and modifications are difficult to understand or become inconsistent with facades. Crossing-out on the drawings are not clear (*Figure 8*).

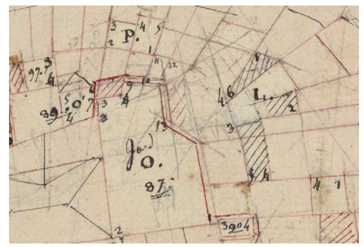

Figure 8: *Parasitic lines in the drawing make it no clear.*

7. Generating the textures from the 2D plans

In order to have more realistic textures for the 3D elements, we compute for each 2D plan a corresponding texture that will be used when creating the 3D models (*Figure 4e*).

7.1. Material assignment

Information about materials are written on the elevation plans for the material of the facades and for the kind of tiles (*Figure 4a* above the facades). We assign to polygons a material from a library. This library has been predefined with the most common materials encountered in the *plans-reliefs*. Transparency can be used for the materials. For ground plans, every polygon must have a material: grass, sand, soil, cobbled for ground / slate, terra cotta for tiles / ochre and other hues for walls. For elevation plans, all facades, cornices, walls and chimneys must have a material assignment. Every non material assigned polygon on elevation plans (like openings) will be black with white edges.

7.2. Automatic computing of the textures

From the material assignment, the texture image of the plan is computed by filling each polygon with the texture of the material (*Figure 9*). For elevation plans, the process begins with the polygons not enclosed in others (it means beginning with the facades and ending with the openings). For ground plans, textures of tiles are automatically oriented to follow the main sewer of the roof so that the tiles are correctly positioned. In courtyards, various polygons inside the outline of the courtyard allow to draw a composite texture (for example, brown soil and grass).

Along each edge of facades, the color of the textured polygon is automatically darkened. For each edge of openings, some dirt is automatically added to imitate the traces of glue of the physical scale models and add more realism (*Figure 4 e*).

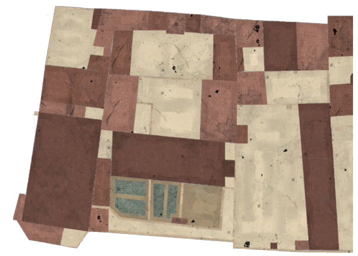

Figure 9: *Automatically textured ground plan*

We now have all required data to automatically compute the 3D parametric elements. Let's first see how we describe the parametric models with graphical scheme before computing the 3D elements.

8. Graphical schemes for the definition of parametric models

The shape of the bodies are mainly of four main types (I, L, U, T) but the roofs can present more variations. The openings are not modelled, they are present only on textures. So only the shape of the building is modelled, making quite simple the drawing of the ground outline, the facades and the roof pans. As explained in [Che15], we use parametric models for the buildings. However the description of the parameters and of the creation method is quite complex and especially for non-computer scientists. That's why we decided to simplify this task by using graphical schemes. The description had become then very simple. An exemple for the *I-shaped body two-slope roof* can be found in *Figure 10*. This section presents the graphical description of a parametric architectural element and algorithms for the automatic creation of the 3D models from these schemes.

After an overview of the kinds of buildings present on scale models (section 8.1), the various kinds of parameters we use to describe a building are then exposed (section 8.2). Section 8.3 allows the presentation of the various schemes we use to describe a parametric element and Section 8.4 details the algorithms to automatically create the 3D model from the parameters and to retrieve the value of the parameters from the 3D points present in the input data.

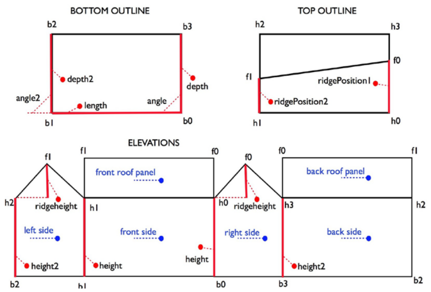

Figure 10: *Description scheme of the I-shaped body two-slope roof building.* b_i *is a bottom point,* h_j *is a point of the roof outline and* f_k *is a point inside the roof outline.*

8.1. Buildings on scale models

Buildings on scale models present few details as shown in *Figure 1*. Only the global shape of the building is represented. The openings and other facade features are only represented with textures. There is sometimes roof overhangs. The various shapes for the building bodies are I, L, U, T and O shape. More than 90 % of the buildings are of I shape. Most of the rest are of L shape. Shape for the roof pans can be more complicated with many unique case. Most of the cases are one or two pans with break or hip pans (*Figure 11*). See [Che15] for more details.

Some roof pan configurations may be found once or only several times in a scale model. However, with our method it is simple to describe them and fast to model as the process of reconstruction is quite automatic (full if we work with 3D textured meshes [Che15] and partially with 2D plans).

We currently have about sixty various parametric models for the buildings (found in the *plans-reliefs* of Toul and Verdun. The use of graphical schemes allow the creation of the 3D models from the parameters and also the determination of the parameters' value in a reserve process. We then do not need anymore the rules for the creation of the 3D parametric model of the buildings (*section 4.2.1 in [Che15]*) nor the rules for an automatic retrieval of the parameter values (*section 4.2.3 in [Che15]*). All the useful information for the creation of the 3D model or of the retrieval of the parameters' value are included in the schemes : points, facets, parameters and constraints. Some models have curved facets. We will explain how we handle this particular case also in the followings sections.

8.2. The various kind of parameters are:

- **lengths** (length, depth or other distance): to define a length parameter, two points are necessary. The second point will be computed from the first point.
- **heights** : to define a height parameter, two points are necessary. The second point will be computed from the first point.

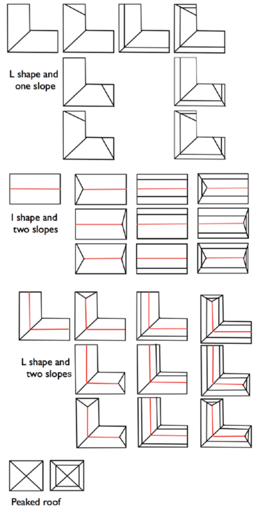

Figure 11: *The I and L types of roofs encountered in the scales models are mainly peaked, one-slope or two-slope roofs. They are combined with the body shapes and also with breaks and/or hips.*

- **angles**: to define a angle parameter, two points are necessary. The second point will be computed from the first point.
- **proportion** (of a segment relatively to another segment): three points are used to define a proportion parameter: *[*p_1,p_2*] = value * [*p_1,p_3*]*. Example *[*h_0,f_0*] = value * [*h_0,h_3*]* in *Figure 10*.
- **curvature** (for curved facet): to define a curvature parameter, two points are necessary. A list of points will then replace the segments to create a curved line.
- **parallelism constraints**: to define a parallelism constraint four points are necessary. The second point is placed according to the other points. $\overrightarrow{p_1,p_2}$ // $\overrightarrow{p_3,p_4}$.
- **alignment constraints**: to define an alignment constraint three points are necessary. The second point is placed according to the other points.

The **aim** is to position the parameters on the schemes in order to allow the computation of the 3D points that will compose the 3D model of the parametric object.

8.3. The various schemes

Three schemes are used : the bottom scheme (*Section 8.3.1*), the top scheme (*Section 8.3.2*), and the elevation scheme (*Section 8.3.3*). In the bottom and top schemes, the x and z coordinates of the 3D points can be computed from the parameters present in the

schemes. In the elevation scheme, the y coordinate of the 3D points can be computed from the parameters.

8.3.1. Bottom scheme (*Figure 12*a).

This scheme allows defining the kind of body: I, L, T, U, O or other configuration. On this scheme we have:

- A polygon representing the outline of the body.
- Each point of the polygon must have a name: we choose the following convention: b_i is a bottom point, h_j is a roof contour point and f_k is a point inside the roof contour.
- All the useful parameters for the creation of the outline of the body (y coordinates are null): lengths, angles and curvatures.
- If a segment of the polygon has a curvature parameter, the segment must also be named with a point list that will be used for the creation of the 3D model.
- Constraints (aligment or parallelism) can also be defined here.

The computation starts from the first point b_0 that is set to (0,0,0) at the beginning of the process. If there are some induced parameters, one can declare some additional variables with a computing expression and use these variables as supplementary parameters for the schemes. These additional variables are not considered as parameters for the parametric object, they are only variables for the computation.

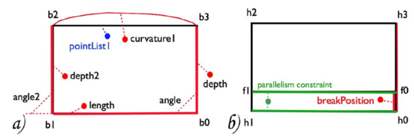

Figure 12: *a) Bottom scheme of a curved building. there is a curved facade between the point* b_2 *and the point* b_3*: parameter curvature1. The list of points used here is pointList1 in blue color. b) Top scheme of a I-Shape body break roof building. There is a proportion parameter breakPosition (in red color) from the segment [*$h_0$$f_0$*] relative to the segment [*$h_0$$h_3$*]. There is also a constraint parameter (parallelism in green color) between the segment [*$f_0$$f_1$*] and the segment [*$h_0$$h_1$*].*

8.3.2. Top scheme (*Figure 12*b).

On this scheme we have:

- A polygon representing the outline of the roof. The top outline is the same as in the bottom scheme.
- Segments representing ridge, roof breaks, valleys and angles.
- Each point of the scheme must have a name: h_j and f_k.
- All the parameters useful for the computation of the 3D points (y coordinates are null at this step): curvature and proportion parameters.
- Some constraints, if required (parallelism or alignment).

An example of the use of proportion and parallelism constraints can be seen in *Figure 12*b. The x and z coordinates of the h_j are the same as their corresponding b_j. The parameters on the top scheme allow the computation of the f_k points.

8.3.3. Elevation scheme (*Figure 10*).

The elevation scheme corresponds to the developed of the facades. This scheme allows also creating developed drawings of 3D models for paper toys for example. On this scheme we have:

- Points with a name corresponding to those given in the bottom and top schemes.
- Polygons corresponding to the facets of the building (facades and roof slopes) with a name. Each facade can be created in 3D thanks to the named points.
- All the parameters useful for the computation of the y coordinate of the 3D points: height (height between bottom points and top points, roofing height, break height, hip height), curvature and proportion parameters. A same parameter can appear several time in a scheme: each y-point has to be defined from another point (except for the bottom points that are set to 0 for y coordinate). These repetitions of parameters will also be useful for the reverse process in case of lack of information (for example, we do not dispose of all the facade drawings in the 2D plans).

8.4. Algorithms

Two algorithms are used to handle the 3D parametric models:

- The automatic creation of the 3D model from the parameter values and the schemes (*Section 8.4.1*)
- The automatic adjustment of the value of parameters from the points and the schemes (*Section 8.4.2*)

8.4.1. Automatic creation of the 3D model from the parameters and the schemes

The algorithm *1* allows the computation of the points of the 3D model from the parameters' value. The value of the parameters have been assigned by the user in the graphical user interface or assign automatically from the reverse process. Once the 3D points are computed, the 3D model can be created from these points and the graphical description. The process to compute the 3D points is: first, we compute x and z coordinates of the bottom points: *Algorithm1*(ground plan, bottom scheme). Then we compute x and z coordinates of the top points: *Algorithm1*(ground plan, top scheme) and finally we compute y coordinate of the points: *Algorithm 1*(elevation plan, elevation scheme).

8.4.2. Automatic adjustment of the value of parameters

We assume that points' coordinates are assigned from input data (2D plans (*section 9.1*) or 3D textured mesh) by the reverse process. Some points may not be assigned because of lack of information in the input data (facade not described in a 2D plan or not captured in a 3D mesh). The algorithm *2* allows now the computation of the parameters' value from the points' coordinates.

9. Automatic generation of the 3D parametric objects

First of all, we correctly position the 2D ground plans in 3D, the 3D objects will be superimposed on them. The ground plans allow determining the positions and dimensions in a horizontal plan, while the elevation plans allow determining the positions and dimensions along the vertical axis. On one side we have a ground outline and

Algorithm 1 Compute the points from the parameters

Input: *plan*: ground plan or elevation plan
Input: *scheme*: bottom, top or elevation scheme
p_1 *to* p_4: points in the parameter representation (b_i, h_j or f_k).
Put all the parameters of the *scheme* in an *array*
while there is parameter p in *array* **do**
  switch (p)
  case *length parameter***:**
    if p_1 coordinates are assigned (x and z if we treat the bottom or top plan, y if we handle the elevation plan) **then**
      Look for an *angle* parameter that uses p_1 and p_2
      Compute vecteur v from the *value of p* and the *angle*
      Compute $p_2 = p_1 + v$
    end if
  case *height parameter***:**
    if p_1 are assigned **then**
      $p_2.y = p_1.y +$ *value of p*
    end if
  case *proportion parameter***:**
    if parameter points p_1 *and* p_3 are assigned **then**
      Compute p_2 with the relation: $\overrightarrow{p_1,p_2} = value\ of\ p * \overrightarrow{p_1,p_3}$
    end if
  case *parallelism constraint***:**
    if parameter points p_1, p_3 *and* p_4 have their x and z coordinates assigned **then**
      Compute p_2 with the relation: $\overrightarrow{p_1,p_2} = k * \overrightarrow{p_3,p_4}$
    end if
  case *alignment constraint***:**
    if parameter points p_1 *and* p_3 have their x and z coordinates assigned **then**
      Compute p_2 with the relation: $\overrightarrow{p_1,p_2} = k * \overrightarrow{p_1,p_3}$
    end if
  end switch
  if a point has been computed, remove p (and *angle*) from *array*
end while
Create the curved segments:
for each segment s_{scheme} of the outline **do**
  Look for a *curvature* parameter associated to s_{scheme} and get the associated *pointList*
  Compute the list points by creating an arc with *curvature* from the first point to the second point of the segment..
end for

its relations (facades), on the other side we have the description of a parametric object. We have to create an instance of that object and to determine the parameters' value from the ground outline and its relations. We also have to place that objet correctly in 3D. The first step is to determine the coordinates of the 3D parametric object from the 2D plans (*Section 9.1*) and then we will be able to assign the values to the parameters (*Section 9.2*).

9.1. Determine the 3D object coordinates from the 2D plans.

We assume that the bottom outline on the 2D plan and the bottom outline on the scheme begin with the same point (b0) and turn in the same way. If not, we pre-treat the polygon in the ground plan as in [Che15]. The process is to compute:

Algorithm 2 Compute the parameters' value from the 3D points

p_1, p_2, p_3, *and* p_4 : points of the parameter
array : all parameters in the schemes (bottom, top and elevation)
while there is a parameter p in *array* **do**
  If required points for the computation are assigned the *value* of p is computed according to the parameter kind:
  value = distanceBetween(p_1, p_2) for a length
  value = angleBetween($\overrightarrow{p_1,p_2}$, $\overrightarrow{X\text{-}axis}$) for a angle
  value = $p_2.y$ - $p_1.y$ for a height
  value = lengthOf($\overrightarrow{p_1p_2}$) / lengthOf($\overrightarrow{p_1p_3}$) for a proportion
  if p is assigned **then**
    Remove it from the *array*
  end if
end while
create the curved segments (*algo 5*).

- the ground coordinates of the bottom and top points with *algo 3*,
- the y coordinate of the top points with *algo 4*,
- the coordinates of the points inside the roof outline with *algo 5*,
- the chimneys with *algo 6*.

Algorithm 3 Compute the x and z coordinates of the points

outline: bottom/top outline in the scheme
polyg: polygon in the 2D ground plan
p_{plan}: point in the 2D plan ; p_{scheme}: point in the scheme
p_{object}: point in the object (points we want to compute)
for i=1 to nbPointsInPolyg **do**
  p_{scheme} = outline.points[i] (for example b_0)
  p_{object}: point with the same name in the parametric object
  p_{plan} = polyg.points[i]
  $p_{object}.x = p_{plan}.x$ (affect the coordinate of the plan point to the object point)
  $p_{object}.z = p_{plan}.z$
end for

Algorithm 4 Compute the y coordinate of the top points

bottomOutline: bottom outline in the ground plan
for each *relation* in *bottomOutline*.relations **do**
  $facade_{plan}$ = facade of the *relation*
  $facade_{scheme}$: scheme facade with the same points (b_i, h_i or f_i)
  for i=1 to facade.numberOfPoints **do**
    $p_{scheme} = facade_{scheme}$.points[i] (for example h_1)
    $p_{object}[i]$: point with the same name in the object
    $p_{plan} = facade_{plan}$.points[i] no name for that point
    $p_{object}[i].y$ = height measured from the reference in the elevation plan of $facade_{plan}$.
    memorize the bottom-points' height to assign automatically the correct height to the street points.
  end for
end for

We now have computed the coordinates of all points represented the 3D parametric object. We must then determine the position, orientation and value of the parameters of the parametric object.

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Algorithm 5 Compute the inside points' coordinates

By comparing the drawings of $topOutline_{plan}$ and $topOutline_{scheme}$, we can assign the x and z coordinates of the inside points of the parametric object.
With the relations on the ground inside segments (ridges), we can compute the y coordinate of the inside points.

Algorithm 6 Compute the chimneys

Get non-connected points inside the outline in the ground plan.
Chimneys are rectangular boxes computed with the process of 9.1.
Cast a vertical ray in the building 3D model to find the intersection between the chimney and the house: the chimney can be correctly positioned in height.

9.2. Determining the parameters' value and computing the textures

Section 8.4.2 has presented the algorithm for the retrieval of the parameters' value from the 3D points. Adjustment in the parameters value or in the textures can be done in the user interface. Finally, we have to compute the textures from the facades and ground polygons in the 2D plans. Two kinds of texture are automatically computed: from the plans and more realistic textures with the images computed in *Section 7*. The case of the streets, rivers and courtyards is particular: these objects are created as 3D triangulated polygons. As there is no relations on the 2D polygons on the ground plans, only (*algo 3*) is processed. The height of each point was memorised during the computation of the buildings and they are used now to affect the points of the street, courtyard or river points.

10. Results and discussion

Results are shown in *Figures 13 and 14* for a city block and for a larger part in Unity game engine with the vegetation. For the vegetation, we process as in [CJP11]: the position and the kind of vegetation is given to Unity via files and the vegetation is planted with scripts from models in a library. Some indication is sometimes found on the 2D plans for the kind of vegetation: the kind of tree or the rough height of the trees are then assigned to their corresponding 3D models.

This method has been used for the 3D modelling of the *plan-relief* of Verdun [CJH*15] and produces good results. Monuments like churches, city halls are composed of several simple parametric elements. It is not necessary to describe them as a whole complex entity. The limits are for very complex buildings. In this case there are manually modelled. If a shape of the building is complex and unique in a scale model, one can wonder if it is worth to describe it with our method. Won't it be quicker to model it with a commercial software ? Based on our experience, we estimate the time each method will take and we decide for each case how we model it.

11. Conclusion and future work

In this paper, we have presented the method we have conceived and developed for the 3D semantic modellisation of old scale models

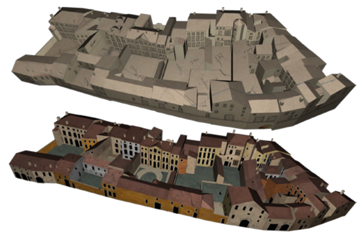

Figure 13: *Result of the 3D modelling on the number 22 city block of the plan-relief of Verdun.*

Figure 14: *Visualisation of the result for a large part of Verdun plan-relief with the vegetation.*

from their historical documents. This method could be improved by automating the drawing of the polygons in the 2D plans. It is currently the most manual time consuming task in the process.

We have also presented the new method for the graphical description of the parametric objects which is more simple and reliable. Our aim is now to describe composed objects (like monuments, churches or bridges) with relative positioning as simply as possible: an element is at the right (left / in front of / behind) of another element, is above or below, is anchored at a specified point of another element...

In our library, there are only several models with curved surfaces. Tests could be done with more complicated surfaces for body shapes but also for roof shapes. We just began to work with the *plan-relief* of Strasbourg which have other kinds of shape with bow windows and dormer windows. We would like also to extend the library with other kinds of parametric objects like the fortification works as studied in [JCH13]. Our method could also be tested with full scale models of town.

Acknowledgements

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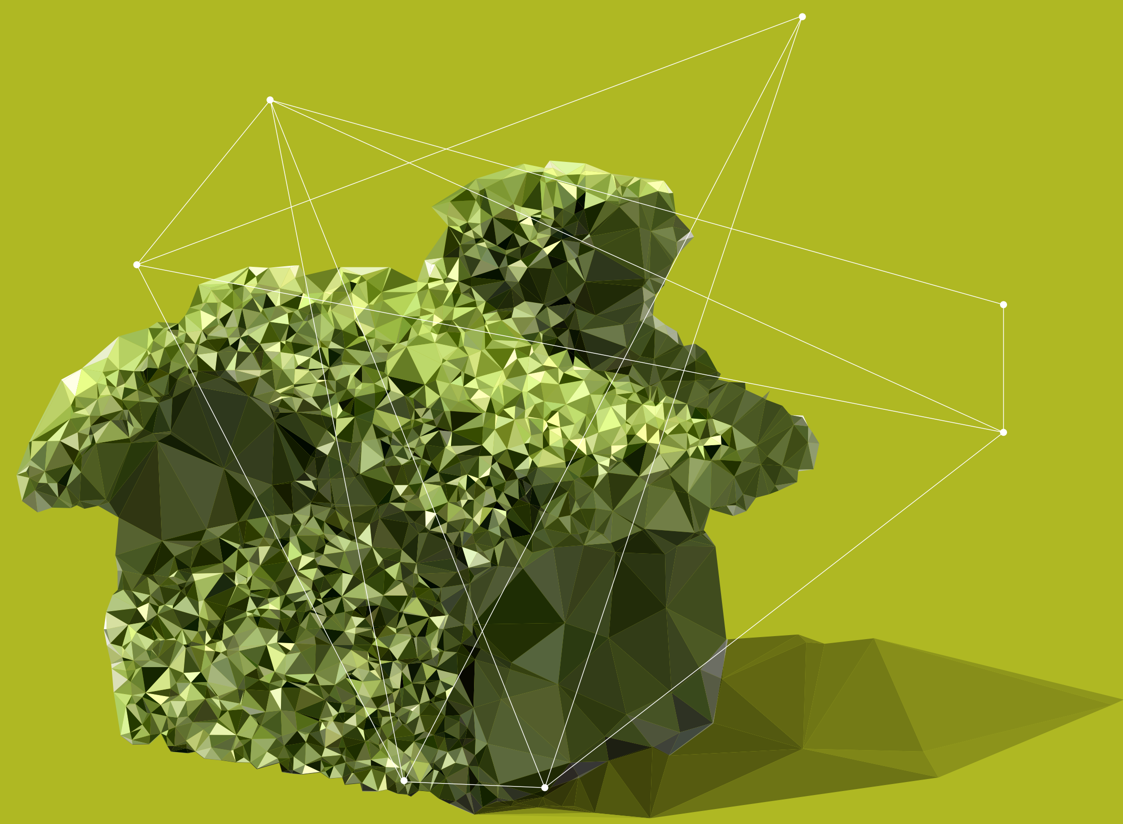

THÈME 2

Conception Matériaux Environnement Énergie

THÈME 2

Conception Matériaux Environnement Énergie

Ce travail cible les premières phases de conception architecturale, au cours desquelles le croquis est beaucoup utilisé et où la prise de décision a un impact important sur le projet. Cet article présente un outil numérique qui allie la liberté du dessin à la main avec la précision du numérique des évaluations afin de plonger le concepteur dans un processus de modélisation-optimisation de l'éclairage naturel dans un bâtiment dès les premières phases de projet.

La recherche décrite dans cet article propose une assistance à la conception d'abris et de camps d'urgence suite à une catastrophe naturelle où un conflit entraîne un déplacement temporaire de la population. La solution proposée tient compte des paramètres physiques, contextuels et climatiques par la manipulation d'un prototype paramétrique validé par une étude de cas.

Sketch-based and parametric modeling

Association of two externalization processes for early daylight optimization

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Abstract. This paper focuses on sketch-based and parametric modeling as two externalization devices used in architectural design practice. The first part of this paper addresses features and ability of these externalization tools to support design activities during the early design steps. The second part proposes an association process of a sketch-based modeling tool (*SketSha-Archi*®) and a parametric modeling tool (*Grasshopper*®) to create an advanced process for daylight optimization. The process aimed to associate the hand-sketching freedom with the precise exploration functions of digital tools (parametric modeling and evaluation tools).

Keywords: Sketch-based modeling; parametric modeling; early design stages; daylight simulation; optimization process.

1 Parametric modeling in architectural design

Parametric modeling is one of the digital modeling methods integrated in architectural design praxis. The generated models are controlled by parameters that characterize and control the most pertinent features of the modeled object and the design context. Parameters can describe geometric, performance, structural, material, social, urban and environmental features. The designer can generate different spatial and technical configurations based on the same parametric model. Parameters are instantiated by interchangeable values generating these objects.

The designer controls the value attribution process and try to find the best response to the design intentions and constraints. Optimization algorithms can be used to control the parameters instantiation process. The designer defines a target values describing his intentions (features, performance) translated in measurable values and optimization algorithms controls the value attribution process. These algorithms select the best parameters values generating the most pertinent configurations (verifying the target values). Evaluation devices linked to the parametric models to compute the performance level of the generated solutions [1], [2]. The evaluation devices concern sensitive features (atmosphere) and physical ones (daylighting, energetic and

Gabriela Celani, David M. Sperling and Juarez M.S. Franco (Eds.): The Next City: 16th International Conference CAAD Futures 2015, pp. 226-238, 2015. © Biblioteca Central Cesar Lattes 2015.

structural behavior). The association of parametric model, evaluation devices and optimization algorithms creates an iterative process that helps designers to operate complex research and exploration design activities. This kind of process contrasts with the static behavior of the classic modeling methods that are used to create one instantiated model. A fixed statement and a complex modification process characterize the modeled objects. In contrast, parametric modeling methods are used to define the structure of the designed object and the most pertinent controlling parameters in order to generate different configurations. In fact, the dynamic features of the parametric modeling methods offer more exploration potential than other digital modeling media [3].

As explained before, parametric modeling methods define the structure of the modeled object and not a fixed status. Object status will change depending on values attributed to parameters. A parametric model easily integrates transformation and evolution activities. During the early design steps, designers try to explore possibilities define the most important project features. At the beginnings, these features are fuzzy and hardy measurable due to the lack of design information. They progressively evolve to be more precise thanks to the iterative process of propose, evaluate and select activities. These features make parametric modeling methods more suitable for early design activities [4].

Parametric modeling is an evolutionary process. It can be transformed and enriched progressively as design process progresses. The designer can transform the parametric model structure by integrating new parameters, new features and more functions. The parametric model can be linked to more detailed ones adding new functions resulting from more advanced design steps. The following example shows how the designer used a parametric modeling tool (*Grasshopper*®) to design the lofted surface creating the outside skin of the project (early design steps) using simple curves. The model has been improved to integrate the skin materialization process using two modular components types (advanced design steps). The modular components are dispatched on the created surface through a distribution condition. The designer used the same model to integrate his early and advanced design intentions and constraints.

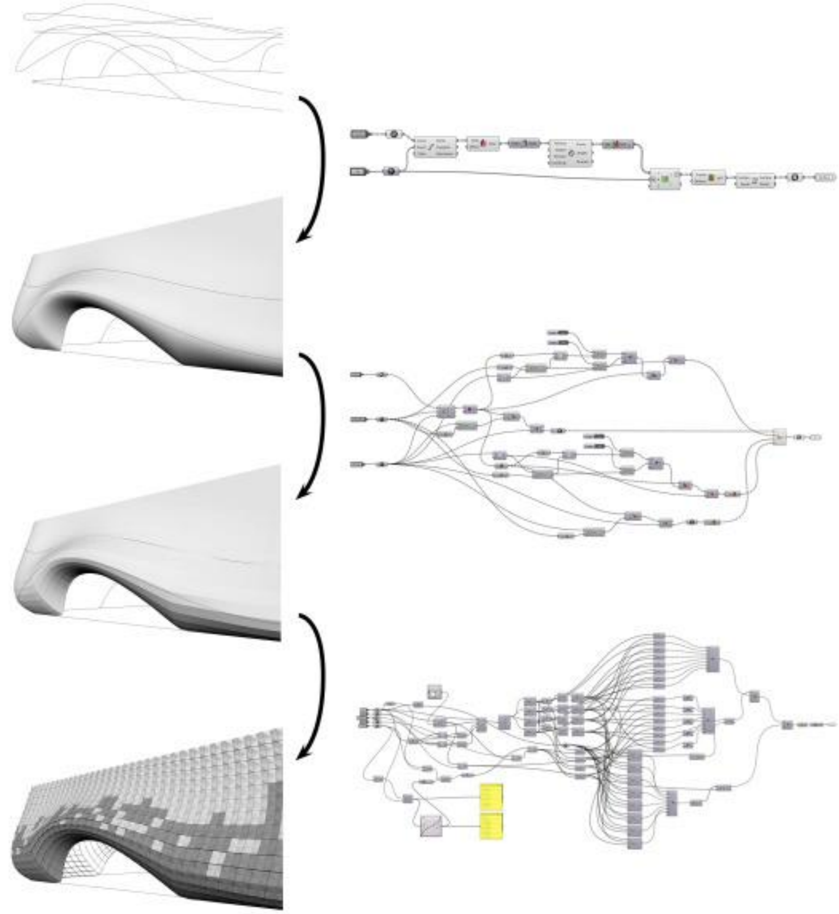

Fig. 1. Evolution of the parametric model [5]

During the early design steps, designers spend from 5% to 20% of their designing time to create the parametric model. The duration of the modeling and transformation time task depends on the knowledge level from of the parametric modeling tools. Expert users reduce duration required for the definition of their parametric model definition and allow more time to perform design activities. By contrast, novice users of parametric modeling tools consider modeling activity as an additive design constraint that constitutes an additive cognitive constraint. This constraint can delay the design task achievement.

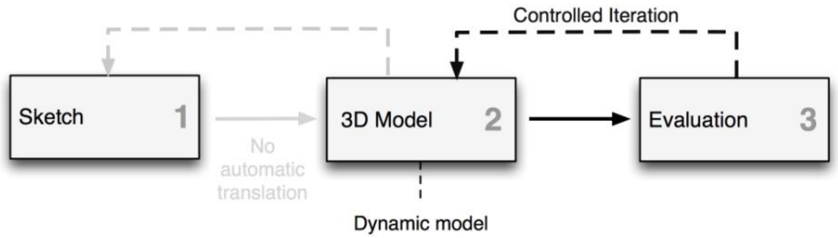

Fig. 2. Parametric modeling process

We consider parametric modeling as an advanced externalization activity that respects the early design steps features. This activity needs to be improved in order ease the parametric modeling activities. Parametric model creation must respect the designer's praxis by generating design media in few laps of time. Support design models (parametric models) must be easily transformable and particularly for conceptual steps.

2 Sketch based modeling in architectural design

2.1 Sketching in architecture

Sketching, as a representation tool, help designers to externalize their intentions and ideas and to address a first step of graphical conceptualization for architectural solution [6]. Sketching is considered as a tool to simplify reality, illustrate intentions and going to the most pertinent concepts [7]. They help the designer to progressively materialize design problems and reduce their complexity. Sketching helps designer to quickly produce and modify representation of the design problem and solutions [8], [9]. The use of sketching creates an iterative process of design integrating "propose", "evaluate" and "modify" activities. The iterative features of this process ensure the flexibility of the modification and appropriation activities characterizing early architectural design steps [10]. The flexible structure of sketching generates multiple interpretations of the externalized ideas and solutions through a continuous reflection process [8].

The precision level of the representations and the models increases and accompanies the evolution of the design activities. Written data and conceptual sketches and models are used during the early design steps characterized by the lack or the inaccuracy of the design information. Detailed representations, physical and digital models are usually used during the last steps of the design process where design information is available and precise. Representation tools like sketching used at the early design steps as sketching enhance the designer freedom. They allow many options and opportunities for how they can be read and understood [11].

By contrast, the use of digital modeling tools during conceptual design steps reduces the designer freedom. This limitation is due to the use of new artifacts (screen, mouse), new gestures, the need of detailed design information and a longer realization time. Despite this limitation, digital design tools, initially destined to production steps, are now used in the early steps. These steps are characterized by research and exploration design activities. The use of production design tools during early design steps tends to reduce the designer creativity and to impoverish the design. The designer is influenced by the tools functions during the decisive steps of the project elaboration [8]

2.2 Sketch-based modeling

This observation has led to update sketch-based modeling technics integrating gestures in modeling process. They associate free hand-sketching functions to digital modeling ones. This technic was initiated since the sixties by Ivan Sutherland that develop the Sketchpad device [12]. This device proposes a graphical freehand interface to draw geometries. It aims to associate the benefits of hand drawing to the digital tools functions.

Since 2007, the LUCID-ULg has been developing and using the *SketSha*® software (for Sketch Sharing) [13]. This application supports sketch-based, synchronous and distant collaboration. Based on the analogy of a real meeting, *SketSha*® offers a shared working space, where all participants can import and annotate any design documents (image, pdf, dxf or screen-captures). This application has been discussed in many articles [14],[15], [16]. The figure below shows an example of a *SketSha*® project.

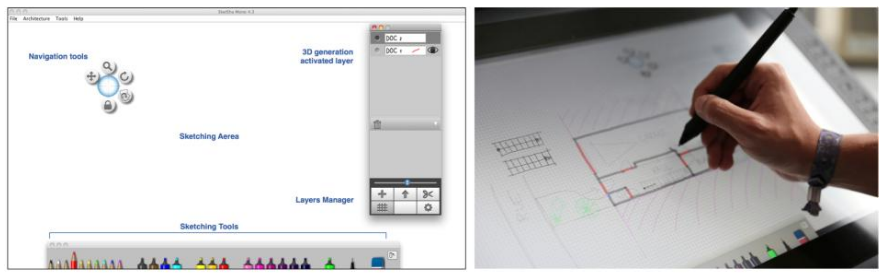

Fig. 3. *SketSha*® interface and use

Sketches are also used to generate 3D models. They are used as basic information for complex 3D modeling activities. They allow user to draw free hand sketches and to translate them to tangible 3D models using digital pens as communication and expression artifacts. The generated models can be used for representation purposes or can be integrated to the evaluation processes. The translation of 2D sketches to 3D models is achieved in three steps; a sketch analysis step, a synthesis step and an interpretation step. This process is limited by the need of precise knowledge about the design context and the used representation rules.

An alternative solution was integrated in *SketSha*®. An architecture-specific version has been developed. It allows the generation of an architectural 3D model, based on some explicit drawing conventions used in the sketches. It uses dedicated pens to describe walls, windows and doors. These elements will be extruded vertically in order to produce a 3D model. The figure below shows an example of some mix of interpreted and non-interpreted 2D layers and the resulting 3D model. Tagging the concerned layer (red tag on the layer name) activates the 3D interpretation process. We associate a semantic dimension to the sketching tools (pens) describing the most important parts of project as wall, bulkhead, windows and materials. We need also this information during the evaluation process of the project daylight behavior.
This process simplifies the analysis step and enhances the adaptation ability to different design context and users.

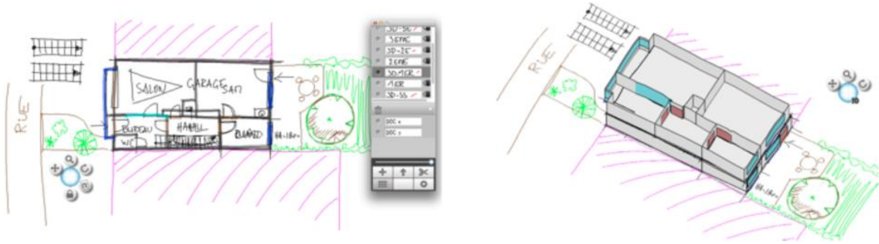

Fig. 4. Multiple layers of 2D sketches and the resulting 3D model

The tool supports multiple floors and the user can control the heights of the different floors, doors and windows on a per-floor basis. *SketSha-Achi*® also allows some more complex extrusion capabilities, useful to express non-flat roofs for instance. One of the sketching pens is dedicated to design draw and characterizes the roof edges. The roof generation tool analysis the drawn edges to propose a 3D interpretation. The figure below shows the roof edges drawing process and the generated result of a multiple sloped roof.

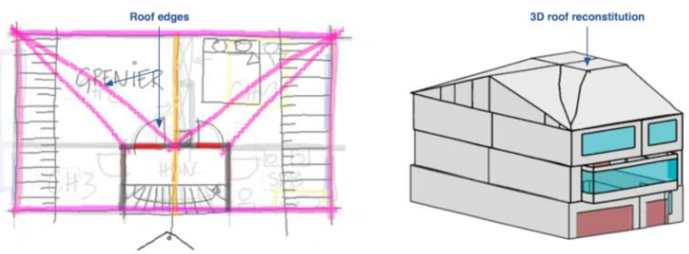

Fig. 5. An example of complex extrusions producing a roof

SketSha-Archi® allows many layers to be placed on top of each other and visualized through a controlled transparency. The designer can define which layers will be part of the 3D model, and which layers are just pure 2D annotations. This mixing of interpreted and non-interpreted layers enables a two-step process for a design iteration. The user can freely explore his design ideas with non-interpreted sketches. Then, when the project reaches the required level of maturity, the user can create the interpreted layers, and overlay his previous sketches with the interpreted pens. The user can decide whether the 2D sketches are displayed in the 3D view or not. The generated model must be integrated in the design process to develop and enhance the performance and features of the proposed solutions. It must be used as a base line model to operate exploration and optimization activities.

The generated models are unique with fixed characteristics. The modification process of the generated models needs a major intervention of the designer (the use of modeling tools to modify the model features). This cognitive load reduces the possibilities to integrate the generated models in an iterative optimization and evaluation process.

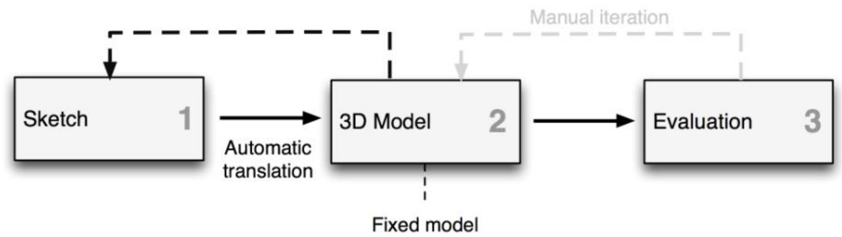

Fig. 6. Skeching, 3D model generation and evaluation process

3 Association of sketch-based and parametric modeling

3.1 Association process

We propose a design aid strategy to help the designer to externalize his ideas and to explore potential solutions during early stages. The method aims to keep design freedom characterizing sketching steps and to propose a solution to associate complex activities (evaluation, modification and optimization) to these steps. This strategy associates the interactivity of sketch modeling methods and the exploration ability offered by the parametric ones. We consider them as two externalization devices able to support design activities during the early steps of design process operating at different levels of accuracy. Sketch-based modeling methods will be used to materialize ideas (free hand sketching) and to translate them to 3D dynamic models (translate sketches to parametric models) able to operate exploration and evaluation activities. The association of the sketch-based and the parametric modeling methods creates an iterative process of “propose, evaluate and modify” activities. The designer uses this process to operate an optimized process of architectural and technical solutions generation verifying a given targets.

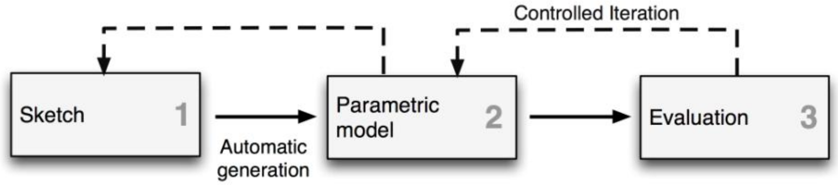

Fig. 7. Association process of sketch-based and parametric modeling methods for evaluation and optimization purposes

3.2 Advanced sketch based modeling process

Evaluation and generation activities need detailed design information. These information concern the project features participating the optimization process. For daylight behavior optimization process we need detailed information about project as wall reflection factor or aperture transmission one. We propose to associate these semantic information to the drawn sketches. Designer can characterizes the designed project by a drawing colored strokes on the drawn object. These strokes will be interpreted as extra-information to be transferred to the parametric tool. The exact semantic of this information is not embedded in *SketSha Archi*®, but is left to the user and to the parametric tool itself. Designer can change the signification of the different tags to associate them to new features or new king of materials depending on design context.

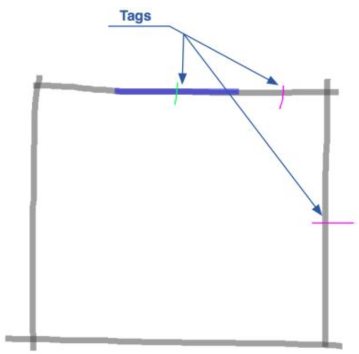

Fig. 8. Illustration of some added information to the building description

The figure below illustrates the possibility to add extra information to the building. The window in blue is tagged with a green stroke, when the wall itself is tagged by a

A Parametric Process for Shelters and Refugees’ Camps Design

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Many situations related to natural environment and human activities increase the risk related to housing and create a demand for rapid post-disaster solutions. The solutions implemented by both the non-governmental organizations (NGOs) and the local and national organizations should fulfill the requirements of the temporarily displaced populations. However post-disaster design faces many challenges in its process making the response always more complex. At the same time, computer-based design is a growing approach in both architectural practice and research. The research described in this paper aims to help in finding solutions to design issues by addressing the potential of computer-based architectural design support. It is applied to shelter and camp development and takes into account physical, contextual and climatic parameters. The outcome is a design process for shelter and camp, which has been validated by a parametric prototype experiment in a case study. This should support humanitarian teams and contribute to enhancing the quality of design as well as to reducing the time required for the design and construction processes.

Keywords: *Parametric architecture, Generative design, Humanitarian design, Computer aided architectural design*

1. INTRODUCTION

Currently, factors related to natural environment and human activities increase the risk relating to housing. These factors create a demand for a rapid, sustainable and effective post-disaster response. This response is a collection of interventions during and after crisis based on previous experiences (Santos et al. 2013), either to answer the direct need of the displaced population or to focus on a long-term process of development. Still, the solutions implemented by NGOs, the local and national organizations most often target to meet the emergency needs of the displaced population. Criteria such as time reduction, resources conservation, safety and cost should also be taken into consideration. The unpredictability and diversity of cases in addition to the different locations as well as the culture and tradition of each region make the response more complex (Balcik et al. 2010).

However, the need of sheltering is increasing. In addition to that, the average lifespan of camps is 10 years while families can remain up to 17 years. Poorly organized camps are often transformed into slums with harsh living conditions, thus the interests of anticipating camp planning at the urban scale. Moreover, the refugees' camps planning should be performed as soon as possible during the intervention process rather than to wait for calm or stable periods (Corsellis and Vitale 2005).

2. PARAMETRIC GENERATIVE DESIGN

The application of computational design is increasing in the Architecture, Engineering and Construction industry. "Parametric Modeling" reflects recent trends in computing design in academic research and market innovation. It allows the designers to control the generation of visualized 3D objects from an overall logical computing script or scenario (Davis et al. 2011). They embed mathematical formulas, constraints and control functions to derive a geometric model from series of input data through a generative process. The characteristic of this approach is that it produces more than static geometry, i.e. a model with a collection of primitive shapes (Fernando et al. 2012).

Parametric design and humanitarian field

In disaster and crisis, the need for shelter is increasingly significant and the design must meet multiple constraints (technical, sociological). Therefore, the design should not only take into account physical parameters (such as gross area, height or structure), but also the contextual and climatic parameters (e.g. site conditions, culture of inhabitants, tradition, climate etc). Generation tools can be the optimum solution for meeting this increasing need by implementing different types of parameters.

Only few applications related to design computing have appeared in the humanitarian design field. One of the studies focused on the application of the digital architecture in low-tech reconstruction of the Solomon Islands (Yeung and Harkins 2011). This study targeted a set of tools needed to start with the latrine by identifying appropriate parameters. Another example was the application of digital architecture to humanitarian design in the case study of a post-earthquake case study in Haiti (Benros and Granadeiro 2011), when automated systems were developed to create houses. This example focused on a set of construction drawings as the resulting documentation. Jinuntuya focused in his research on the use of digital tools and a game 3D virtual environment engine for decision-making support system (Jinuntuya and Theppipt 2007) for humanitarian needs. Another way to integrate the community in the design process for low cost housing design was the development of an application user interface (Wutthikornthanawt and Jinuntuya 2011). This interface was created for non-CAD users and has the advantage of being able to import information from different concerned fields with integrated real-time cost estimation. Sener has also proposed a parametric system to randomly arrange container shelters within a given site (Sener and Torus 2009) for an immediate answer to post-disaster relief. Recently, the research of Gonçalves (Gonçalves 2014) was based on grammars and configuration modules starting from an initial shape, and allowing the development of the original form to generate shelter housing. The generation process followed by this previous example is interesting in terms of mass production as was also shown in the research of Deborah for the reconstruction of post-earthquake Haiti (Deborah et al. 2011).

On the other hand, the infiltration of a parametric approach into an urban context was carried out within different projects and researches. Steino shows in his research (Steino and Veirum 2005) the capabilities of a parametric design approach in urban design through a case study. According to him, urban components share a similarity that can be defined parametrically. Aspects such as density, functions, forms, and spaces, can be translated into parameters. This approach can help to evaluate different scenarios and to reach the optimum solution. Thus, the infiltration of a parametric approach in urban design can lead to a sustainable result (Saleh and Al-Hagla 2012). In his research, Saleh examines the

use of a parametric approach in sustainable urban development. The case study developed in this research was the generation of an Arabian city by taking into account constraints such as wind and solar envelopes. Saleh identifies different components such as traffic, density and zoning that can be linked to urban design.

This brief state-of-the-art shows that:

- The contextual, climatic and ethnographic conditions that have an impact on the design process were not taken into consideration as structured sets of constraints, both regarding shelter and camp design.
- The humanitarian "urban design" (i.e. refugee camp scale) was not fully addressed in previous research efforts.
- A parametric system has the potential to be used as decision-making support in humanitarian design.

3. RESEARCH METHODOLOGY

This work is based on the previous recovery of post-disaster process by humanitarian groups. It was validated through an experimental phase with humanitarian partners. In particular the Shelter Research Unit (SRU) of The International Federation of the Red Cross (IFRC) was involved in the design process and in the identification of pertinent problems, as well as in the determination of essential parameters affecting the shelter and camp design. These parameters are translated into algorithms in a 3D modeling software allowing by this the experimentation of the prototype.

Identification of parameters. Problem solving requires the analysis of similar projects in similar crisis situations to extract the list of specific variables, as well as the identification of shelters and camps parameters (physical and contextual) and relations between them.

Among the list of identified variables, parameters are chosen for the design and modeling demonstrator. The chosen parameters are specified according to their importance in the shelter and camp design. Pertinent components are specified with external partners with an experience in the design of humanitarian housing.

Generative algorithm and their implementation. The generation of solutions that fit design requirements involves the identification of an accurate algorithmic resolution and formulas. Basic algorithms are implemented in a 3D modeling parametric software in order to create the physical model with a list of criteria and constraints to be taken into account.

Experimentation. The utility has been assessed with the IFRC expertise and in particular the SRU. This validation helps to reconsider the parameters used and to verify the methodology implemented in the process of humanitarian design for shelter and camps.

4. PARAMETRIC DESIGN PROCESS

This work assumes that the constraints and requirements in the design of the shelters and emergency camps can be connected to parametric digital design approaches. Variables and parameters proposed in the paper reflect the constraints defined at the level of both shelters and camps.

Figure 2
Shelter model provided by the Red Cross, Haiti 2010

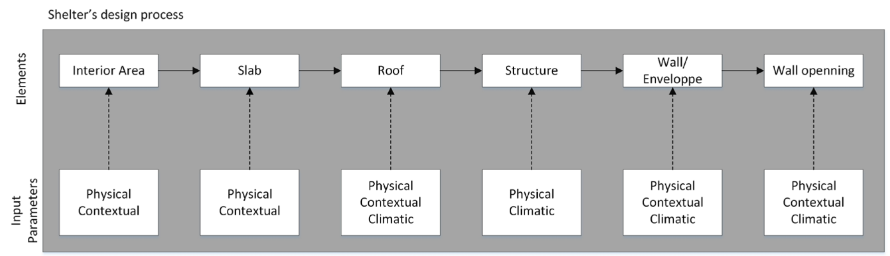

Figure 1
Shelter's design process

Shelter design process

The shelter design process is a linear process. It was essential to identify this process (Figure 1) to understand the logical order in which information concerning these various elements is defined and thus inserted in parametric modeling methods. For this paper, a "transitional shelter prototype" (Figure 2) was developed with parameters based on the Red Cross standards and prototypes for shelters (Saunders 2013). The degree of flexibility and the allowed elements to be controlled have been defined in the parametric model. Adjustment of the elements and parameters will give the ability to obtain the desired prototype according to the criteria set. A modelling process was developed by identifying possible relationships between different elements of the shelter, and by defining the specific phase for the implementation of the parameters in this process. The process begins with the number of people expected to live inside the shelter. This parameter enables to derive the requested surface shelter through the usual area per capita. According to RC standards, the minimum area by person should be >2.5 square meter: this will define the interior area of the shelter needed by each family. The process continues with all the further implemented construction parametric elements based on the interior surface. The slab and extensions as well as the roof and the structures are deducted thereafter through the contextual and climatic parameters. The structures and the envelope of accommodation are chosen by deducting the roof. The roof has a key role in customizing shelters indeed. The importance accorded to the roof as an essential element in the design stems from the fact that this form can also be the indicator of the typology of the region "Contextual parameter" and an answer to the local climatic conditions.

Camp design approach

Emergency camps design (Figure 3) is a more complex and non-linear process often addressed through the logistics issues raised. New concepts, requirements and ideas will constantly be introduced and planners should be prepared to adjust accordingly. The camp design should be linked to the types of solutions envisaged for sheltering which must be conform to standards. The authors propose a multi-criteria approach rather than a so-called "iterative design process" and identify the parameters and relationships between the pertinent elements in the camp. These relations were combined to define a conceptual model. The camp design process is then validated in a parametric experiment. The prototype was developed by defining the following elements: main camp configuration based on cultural and contextual criteria, mobility nodes, roads and distance between shelters, interior roads, height of shelters and distance between them, the location of different resources (gathering place, water and sanitary points, gathering area, school and religious buildings etc).

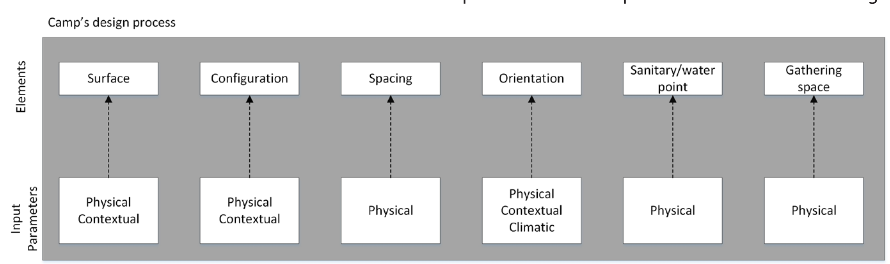

Figure 3
Camp's design elements and parameters

Parameters

The parameters identified are based on a list provided by the Red Cross (Sanders 2013). Parameters were classified according to their types in order to choose the pertinent parameters at the good step during the design process. We can identify three types of parameters: (1) contextual parameters related to living conditions and culture, (2) climatic parameters related to climatic conditions and weather, (3) physical parameters related to the forms, geometries and dimensions.

The identification of parameters shows that physical parameters can be easily expressed numerically, while contextual and climatic parameters are more complex to be be translated into qualitative or numerical values.

Note that the elements of the shelters and the camps can be affected by physical, contextual or climatic parameters at the same time, climatic and contextual parameters may have direct influence to a physical elements.

Parameters included in the shelter's design process. In order to define the design structure of the shelter, a decomposition with specific components is essential. These components represent the building elements, such as walls, columns, beams, roof, and wall opening. Relations between these components are defined and maintained along the design process. Components can have the same parameters, but they can also serve as entries to other components by transferring the data (geometrical or numerical) to them (table 1).

		Parameters category		
Elements	**Parameters**	**Physical**	**Contextual**	**Climatic**
Interior area	Nb of person	x	x	
	Area per person	x	x	
	Coefficient	x	x	
Slab	Offset Slab		x	x
	Extrusion of slab	x	x	
	Extension	x	x	
Roof	Type of the Roof	x	x	x
	General Height	x	x	x
	Extrusion of the roof	x	x	x
	Extension of the roof	x	x	x
Structure	Distance between columns	x		x
	Disposition of columns	x		x
Opening	Door	x		
	Window	x	x	

Table 1
Parameters of shelter

Parameters included in the camp's design process. A decomposition of camp's components is essential when extracting the elements of the camp, such as road, lots, sanitary, spaces, dimensions, green spaces, gathering spaces (table 2).

		Parameters category		
Elements	**Parameters**	**Physical**	**Contextual**	**Climatic**
Site	Form	x	x	
Roads	Width	x		
	Evacuation road	x		
Specific elements	Sanitary	x		
	Water Point	x		
	Green Space	x		
Shelter position	Specement between shelters	x	x	
	Rotation of lands		x	x
	Shelter additional PAD		x	
	Rotation of shelters	x	x	x

Table 2
Parameters of camp

5. VALIDATION

Implementation

Shelters and camps parameters used for assessing our research propositions are implemented in a 3D modeling software allowing the generation of the prototype taking into account parameters and constraints. Grasshopper and Rhino 3D are used in our study. The choice of Grasshopper and Rhino 3D is justified by the ability of these software systems to easily design and manipulate algorithms based on visual objects and defining the constraints and parameters. The prototype developed deals with parameters and constraints that can be expressed numerically or geometrically. However while physical parameters were easily expressed, other parameters for the climatic and contextual variables could not be defined by numbers. For handling this kind of parameters, we defined scenarios, the objective was to create scenarios taking into account these parameters and translate them into numerical algorithmic formulas. In this project, the acceptable values of parameters are defined and are manually introduced into Grasshopper. These parameters are linked to Rhino 3D allowing the visualization of the physical model. This model can be controlled by the parameters included in Grasshopper giving the ability to choose the final desired model.

The figure 4 shows the overall generation of the shelter design process. The parameters used for the shelter are implemented in Grasshopper, where we can manually modify the values. For each element of the shelter, a sub-process were created allowing the generation of a 3D geometry which can be used as an entry for other element. Each element of the shelter is developped by a sub-process and related to other elements. The figure 5 is an example of the implementation of the roof parameters.

At the camp level, the scenario experimented in this case considers a flat land. For that, a module is proposed which divides each parcel into four different surface plots where the surfaces of plots are proportional to the shelter surface. The four surfaces can vary proportionally, respecting defined limits. Each surface is hosting one shelter. The plots can change according to the shelter's surface. In addition, formulas were developed to give each shelter a different height, allowing by this a dynamic non standard camp. Similarly, the second part of the work focuses on the camp development of previously cited elements (figure 6).

Assessment

The proposed system presents an opportunity for future development with NGOs interested in the humanitarian design taking into account selected physical and contextual parameters. Even though limits and constraints were fixed in the model, this does not prevent a certain level of flexibility; parameters can be modified according to the given scenarios. These limits were necessary in the definition of margins, thus reducing any unacceptable form they may be having.

To test and evaluate the effectiveness of this system, the prototype was confronted with experts from both the humanitarian field and architectural and urban design. The review is done thru different experiments describing different scenarios created instantly by modifying the parameters to test the ability of the design process to answering scenarios similar to real cases.

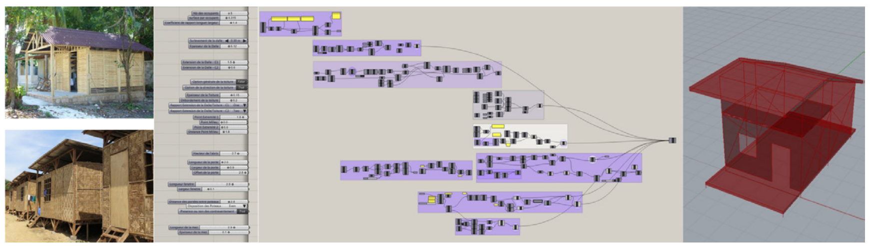

Figure 4
Overall process for the generation of the shelter prototype

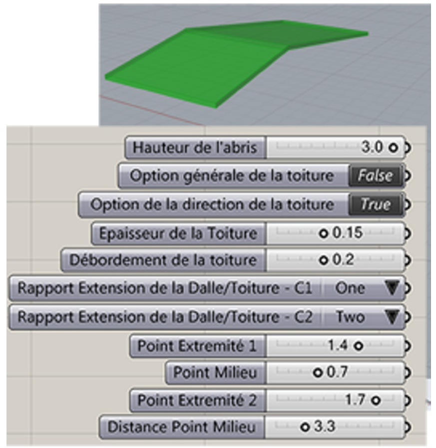

Figure 5
Roof generation process and parameters

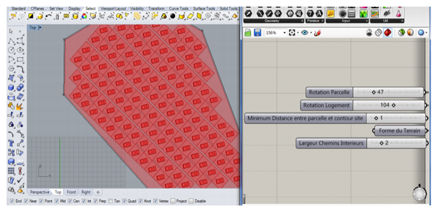

Figure 6
Camp experiment model

6. DISCUSSION

The shelter process can be criticized in real cases, where the mass production and rapid prototyping are considered the best answer for post-disaster reconstruction. Personalizing the shelters according to some parameters (including the area of interior surface) will help accelerating the mental recovery of beneficiaries (Lawther 2009). The validation shows that the design process developed for shelters and the planning of the camps can be adapted to possible real cases. The practitioners in the validation found that the prototype process is adaptable to real case assessments, and that such approach will help potential users in emergency design in term of flexibility, collaboration and time economy.

7. CONCLUSION AND PERSPECTIVE

This paper describes the research carried out to investigate the potential application of computational design to assist humanitarian design. It attempts to explore the capacity offered by the parametric modeling in the design of emergency shelters and camps in order to help architects and humanitarian in decision-making, and it attempts as well to explore the limits of this technology. It starts with developing a design process for the shelter and camp. This process is based on the idea to personalize each shelter according to the size of the family, taking into account some cultural and contextual parameters. The main result of this paper is a prototype of parametric shelter and a model of a camp based on the Red Cross standards. The prototype is linked to a set of parameters and constraints with contextual and climatic impact. Another part of this work was to define a list of recurring parameters, to be used to model a shelter and an emergency camp. Three types have been identified: physical parameters, contextual parameters and climatic parameters. It thus was necessary to identify, with the external partners, the relationships between parameters and variation margins of values as well as the elements to be controlled.

The research field is delimited by the identification of parameters for modeling a prototype shelter and a layout of a camp. This prototype is inspired by the shelters designed by the IFRC following disasters in several regions. In addition, the design at the scale of a camp is proposed using some relations identified between the designed camps and shelters. Aspects related to construction materials cost and bills of quantity are not taken into account in this part of the research even if they are important in the humanitarian field. Future research should focus on these points. This paper is part of a future project attempting to answer humanitarians' needs by providing a decision-making support system in the design of shelter and emergency camps, taking into consideration multi-contextual conditions.

ACKNOWLEDGEMENT

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THÈME 3

Approches collaboratives et maquette numérique

THÈME 3

Approches collaboratives et maquette numérique

La simulation 4D, qui consiste à utiliser un modèle 3D associé à un planning pour simuler des phases de chantier d'un bâtiment, s'est largement développée ces dernières années, notamment par la publication de nombreux travaux présentant des expériences. Ici, la 4D est considérée comme un usage BIM dans le but d'identifier les niveaux de développement (LOD) des modèles utilisés. Les auteurs mettent en avant la diversité d'utilisation des modèles 4D ainsi que la compréhension des niveaux de développements impliqués par la présentation de deux expériences.

Cet article aborde la question de la quantité d'informations générée par les pratiques BIM dans l'industrie de la construction. Les systèmes de gestion de données classiques se montrent de plus en plus limités au regard de la quantité et du type d'informations à traiter pour cette industrie particulière. Le « nuage informatique » et les technologies émergentes issues du BIG DATA sont de plus en plus présentes et utilisées dans d'autres domaines. Cet article propose d'interroger ces technologies et leur usage pour une exploitation dédiée à l'industrie de la construction.

Pendant les phases de conception d'un bâtiment, les architectes conçoivent des espaces en décrivant des éléments physiques comme des dalles et des murs. La représentation dans une modélisation 3D (BIM) des exigences sur les espaces, souvent sensibles et impalpables, ne peut être exprimée que par des aspects techniques et mesurés. Cet article examine quelques propositions récentes permettant de caractériser les espaces et leur dimension sensible dans des modèles adaptés. Il présente également une première analyse des pratiques coopératives BIM orientées « espace ».

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4D/BIM simulation for pre-construction and construction scheduling. Multiple levels of development within a single case study.

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Abstract

4D modeling has been an applied research area for around two decades since the first seminal works. In the last years, a number of case studies have been published both for demonstrating the various applications of 4D and for assessing technological propositions. However, in most papers only little place is given to the particular content of 4D models. In parallel, following the growing implementation of Building Information Modelling, 4D is usually recognized as a "BIM use". In BIM protocols, the Level Of Development of datasets is a fundamental issue. This paper describes two distinct 4D uses conducted on a single pilot project. They aim to assess the levels of graphical and temporal details required for the implemented uses. The authors finally discuss the diversity of 4D uses with 4D models, both planned or ad-hoc, as well as the logical understanding related to 4D LOD.

Keywords: 4D simulation, Construction scheduling, BIM, LOD, Case study research

1. Introduction

4D simulation consists in linking construction activities in a planning to 3D objects in a building model in order to simulate the construction process over time. 4D simulations can be used at different stages of a construction project to analyze the design and its constructability, as well as for construction planning and monitoring [1, 2]. The "4D simulation" concept was introduced before the advent of Building Information Modeling (BIM) [3] but gained from the development of BIM's three-dimensional models. BIM is a recent approach to object-oriented modeling and integration of multi-dimensional construction data. In the last years it is also more and more related to efficiency and quality of digital information exchanges fostering collaboration between construction practitioners.

It could be mentioned that the adoption rate of 4D simulation by construction practitioners remains low [4–6]. Although it is increasingly used in wide-scale or very specific building/engineering projects, there are quite a few feedbacks from experiments on regular projects. One must say that it is a young technology that still has to be adapted to the real business needs [7]. In particular, if 4D modeling fits with traditional Anglo-Saxon approaches to project management, it is not exactly the case in the French nor Luxembourgish construction management culture. One of the main issues is related to the level of detail of the information comprised in Building Information Models, which should fit to the expected 4D usage performed practitioners. This is a particularly complex issue because 4D simulations incorporate both 3D models' objects and construction activities schedules. It must therefore manage both the graphical

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level of details and the temporal level of detail [8]. In addition, levels of detail must match to business needs corresponding to the usage of the model at different stages of the construction project. In the BIM approach, the term "level of development" (LOD) is widely used to show that detailing is not only about geometry but also deals with non-graphical information.

This paper presents a multi-phases and multi-LOD 4D case study on a construction project in Luxembourg. The theoretical background, the context, the study and its main results are presented. A discussion is finally provided about the findings.

2. Related works

Case studies using 4D simulation have been reported in literature. In 2002, Dawood et al. used two real life case studies in order to introduce a new approach of extensible 4D simulations development. Their aim was to assess the Man-Hours input necessary to run the model prototype. The two cases studied are a school of health project (a complex project) and a primary school project considered as a simpler project [9]. They concluded that "man-hours increase according to availability of design information".

In 2011, Hartman reported an ethnographic-action research experiment on safe planning of hospital renovations based on 4D models and proposed a method to develop hospital construction process based on 4D simulation [10]. Olde Scholtenhuis and Hartmann presented a second experimentation in 2014 [11]. Using the same ethnographic-action research approach, the researchers explored the influence of scheduling purpose changes on the 4D-model setup. Thus, they studied how practitioners iteratively implemented and used a real-life 4D model. As result, they observed that identifying tasks, allocating resources and communicating among stakeholders are the main purposes at planning stage. Planning logistics, studying dependencies between tasks and mitigating delay are the main focuses of jobsite scheduling. Other recent experiments have been reported including those related to the use of 4D simulation to support workspace conflict analysis [12], path analysis [13], construction quality inspection [14] and fall hazard identification [15].

All these experiments are of course very informative but do not focus on the particular issue related to "LOD". But the question of the level of development was only quickly addressed in the 4D research works. In 2000, Koo and Fischer noted that 4D models convey a unique perspective of the project, i.e. related to scheduling, with a dedicated LOD. According to them, it does not enable the various practitioners involved in the project to use the 4D model for other needs. These authors studied the feasibility of 4D simulation in commercial buildings and concluded that users should be able to generate models with different LOD, in order to rapidly explore different alternatives [16].

The principle of LOD is to specify the information that the model must contain according to its use at the different stages of a project lifecycle. Numerous definitions were proposed in the context of BIM implementation or BIM guidelines [17–19]. The American Institute of Architects (AIA)'s project BIM protocol is one of the most cited. It defines five levels of development: LOD 100 to LOD 500 [18]. An intermediary level (LOD 350) has been proposed between LOD 300 and LOD 400, to support coordination between different trades [17].

To address the question of the LOD required for particular phases in construction lifecycle, Kriphal and Grilo [20] made a state about the compatibility between design and construction building information models. According to them, the LOD "grows during the design phase, and reaches its peak during construction". They then stated that level of detail for "design BIM" focuses on geometric complexities, while in construction BIM it specifically focuses on the construction resources including equipment, materials, labour and productivity.

In the following parts, the authors characterize development levels on the basis of these LOD definitions. The research approach is quite similar to the ethnographic-action research approach used in previous research works [21].

3. A multi-LOD case study: The NeoBuild Innovation Center

The NeoBuild Innovation Center (NIC) is a building project planned to host the team of NeoBuild, an innovation cluster for sustainable construction in Luxembourg. The NIC project is highly experimental and the building is designed to support different forms of activities related to construction research, experimental and educational purposes. The construction started in April 2013. BIM has been implemented in the project for multiple purposes: 1) to experimentally model the building, 2) to provide accurate information for the construction site monitoring as well as 3) to include technical assets data required for further facility management. This article focuses on the aspects related to 4D simulation. The 4D experiment presented here was conducted in two parts during the project development: the first part at pre-construction phase and the second part during the construction phase.

3.1. Part 1: 4D simulation at pre-construction phase

The first part of the experiment aimed to study the constructability of technical design choices and to anticipate the sequencing issues in early design stage of the project development. The design work was not entirely over at the time of developing the 4D simulation. In particular many technical details were still to be defined but it did not really impact the results of this part of the experiment which was conducted at a "low" LOD. The main actors involved in the simulation were the architect, the structural and energy engineers, the project manager (technically skilled in this project) and the 4D modeller.

Among the 4D simulation goals identified by Kriphal and Grilo [20], three goals appear more or less clearly in this part of the experimentation: planning (pre-construction planning), visualization and analysis. It consisted in realizing a first sequencing of the construction activities over time on the basis of a rough schedule produced by the architect, in order to spatially visualize the construction sequences, and to analyse the technical constructability, the possible clashes and the other issues in collaborative team meeting sessions. A particular analysis studied the front wall construction steps and the interface between the sealing and the glazed wall.

The 3D model was created using *SketchUp* at LOD 200 on the basis of architectural design drawings imported from *ArchiCAD*. The volume and the orientation of the building were precisely modelled but many other 3D elements were approximated. The activities sequencing was done directly within the *4D Virtual Builder©* plugin for *SketchUp*. Results and details are directly exported as slides in *MS Powerpoint* format. The front wall and the glazed wall were modeled at LOD 300. This made it possible to analyze the wall construction (Figure 1a) and to study with more details the interface between glazed wall and the sealing (Figure 1b). The 4D simulation at this stage made it possible to note that the stairwell and the atrium were planned to be built at the same time, after the construction of the main building and removal of scaffolding. This obviously highlighted an issue for allowing workers to access to the upper floors of the building, as well as to the roof (Figure 1c).

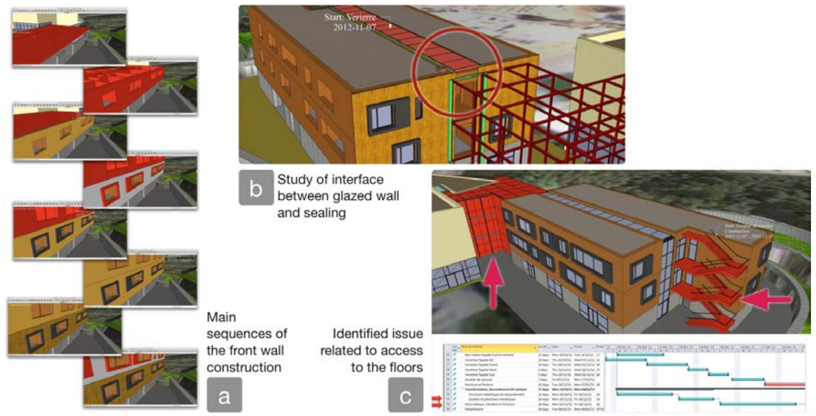

Figure 1: Illustrations from the pre-construction model

3.2. Part 2: 4D simulation at construction phase

The main purpose of the second part, which was developed in parallel with the evolution of the construction, was to control and coordinate the project, to simulate logistics and manage construction site areas, but also to study more finely some construction details. Apart from the architect, the project manager and 4D modeler, others actors participated in the realization of this part. These actors are the BIM manager, the MEP specialist and the site manager. Many of the goals identified by Kriphal and Grilo [20] appeared in this part of the case study: visualization, analysis, documentation, coordination, planning and control. The aim was to plan, control and coordinate the construction by the various trades, to visualize and analyze conflicts and clashes in models before construction, to analyze and document logistics management (cranes, scaffolding, restricted areas, etc.). In particular the team aimed also to study in a more detailed way the components of the front wall.

Four models were developed. First the architectural model was created with *Revit™*. The level of development of the architectural model was LOD 350, but the front wall was modelled at LOD 400. At the same time, a HVAC model (LOD 200) was created using *Plancal Nova™* and improved to level 300 (through addition of parameters) with *Revit MEP™*. Moreover, the architectural model was the basis for the creation of a fourth model with *Revit™*: the logistic model (LOD 100) with generic logistics elements. The macro schedule proposed by the architect has been detailed in *MS Project™*. All these files have been imported into *Navisworks™* to create the 4D model.

Some clashes were identified. For example, some HVAC elements were not at the right height level and generated overlaps with the ceiling (Figure 2a). For logistics management purpose, restricted areas, worksite huts and garbage collection areas were indicated (Figure 2b). The cranes and scaffolding movements were also studied and optimized. The construction of the front wall was studied with accurate details (Figure 2c). The aim here was about the construction sequence of wooden wall, which is built through many steps involving multiple subcontractors (i.e. woodwork, insulation, and cladding). Moreover windows had to be installed in two separate processes, during and after the assembly of the wall itself. A smooth coordination among actors was then necessary to drill accurate reservations within walls and to ensure that the openings on the wall fit the windows dimensions. This kind of situation often causes issues because of a lack of coordination. In our case, the woodwork subcontractor has been obliged to come back many times to adjust the chambers. The 4D simulation was useful to model the components of the wall, to find the optimal construction sequencing and to provide visual support for contractors.

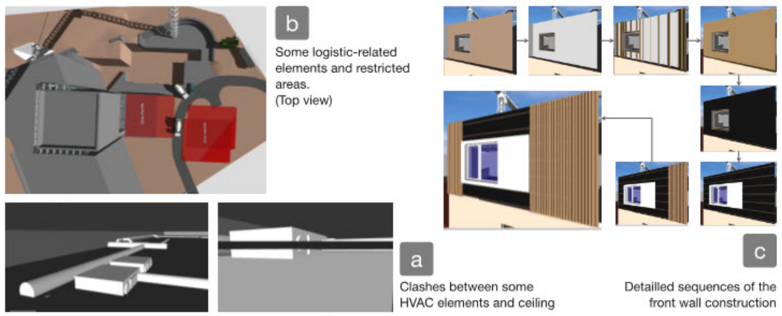

Figure 2: Illustrations from the construction phase model

4. Discussions

4.1. About the work time investment for the case study

In the pre-construction case study, the modelling of architecture components was the most time-consuming effort because data imported from architect's BIM authoring software was not correctly retrieved in SketchUp mainly because of errors in the way the software was used. Numerous adjustments was required for correctly linking 3D objects to schedule tasks. The modelling of logistics elements took very less time because logistic model consisted in a few generic logistic elements at LOD 100, mainly retrieved from the *Sketchup 3D Warehouse*.

In the construction phase case study, only the logistics model was created by the 4D modeler. The others models were already created for other purposes in the framework of the BIM approach. It took more time to create the 4D model than in the first part of the case study mainly because the number of elements and details was higher. Although this part aimed to manage more elements and was much more accurate, we noted that it was less time-consuming than the first part. This is because 4D simulation was fully integrated in a wider BIM development workflow where the coordinated architecture, MEP and structure models used had been prepared in previous BIM processes and were reusable by the 4D modeler.

4.2. About the graphical LOD

Overall, the level of development was between LOD 200 and LOD 300 at pre-construction phase and between LOD 100 and LOD 400 during the construction phase. Compared to the Kriphal and Grilo work [20], it is confirmed that the level of development required for the construction phase is higher than the level used at pre-construction stage. But the assumption that a single LOD is sufficient is not justified, particularly during the construction phase. Indeed, if the analysis and planning have used a unique level of development for the two phases, it was not the same for visualization, coordination and documentation for which different levels of development were necessary depending on the 4D model purpose and the particular construction issues that arised during the construction and modeling processes. What determines the choice of levels of development seems to be the usages and the simulation needs which are not uniform throughout the building development phases and also specific to the project and constructive system.

In addition, the models developed by different stakeholders often present different levels of development. Specific issues discovered during the construction process can also require 4D details to be modeled on very limited areas of the project model, either with more or less details (from LOD 100 to LOD 400). Of course, the owner may prescribe a uniform LOD for coordination goal (i.e. LOD 350 according to the BIM Forum working group). But, as observed in our cases some simulation needs may require to model with more or less details a few elements without this given level of development being necessary for the entire model.

4.3. About the temporal LOD

Managing the correspondence between the graphical LOD and the temporal LOD is not a trivial issue in 4D simulation. In the first part of the experiment (pre-construction phase) only a rough schedule was available, as shown on Figure 2. Approximated sequences of construction process were proposed by the 4D modeler mainly based on the major changes from one step to another and not on dates nor milestones or work breakdown structure. The temporal LOD was therefore derived from the 3D model LOD. But a detailed planning was made available from the beginning of the second part of the case study (construction phase). It was a macro planning with a very low LOD, showing the major stages of the construction process. The Project Breakdown Structure elements were not at the same LOD as the 3D models elements. In addition, the site manager had a more detailed schedule but it did not cover the whole construction process. It was therefore necessary to the 4D modeler to define an additional work sequence representing detailed activities in order to make them correspond to 3D models elements.

The creation of this detailed planning has led to a considerable workload. To the extent of our knowledge, this is mainly due to the lack of guidelines for managing temporal LOD requirements. Indeed, it was necessary to export a selection sets nomenclature from 3D model, to sequence the activities corresponding to these selection sets, and to validate the sequences with the site and project managers. It was then also necessary to import the new schedule in order to link construction activities to 3D building elements. This suggests that it might be interesting to define standardized temporal LODs which correspond to the graphical LODs of BIM approach. The ultimate goal can be the creation of standardized 4D LOD, as combinations of graphical LOD and temporal LOD. The seminal research performed by Aalami et al. [22] can be a very interesting starting point.

4.4. About the bidirectional exchange between the construction site and the model

The second part of the experiment took place during the construction phase. It was a situation of interesting bidirectional communication and exchange between the 4D model and the construction site. It was then possible to study on the model a number of problems and to anticipate them before they appear on the construction site. But the model also benefited from feedbacks from the site. Indeed, some problems appeared on the construction site before being studied on the model. In such cases, the feedbacks from the site made it possible to run simulations on the 4D model in order to analyse alternatives, to choose the best solutions to apply on site, and to update the model. For example, it was the case of the front wall construction (see Fig. 2).

Some problems on the site could not be solved with the 4D simulation because of the limitations of the software features. For example, the site manager wanted to automatically generate cable-trays according to the position of cranes and space constraints of the site. The aim was to ensure that electric power supplying was still possible especially when mobile cranes were at some particular locations. This feature was not covered by the software used. A solution of non-automatic cable-trays has been used.

5. Conclusion

This paper reported a 4D simulation case study conducted on the NeoBuild Innovation Center project in Luxembourg. The first part of the experiment was conducted at the pre-construction phase and aimed at studying the constructability of technical choices and at anticipating sequencing issues in collaborative team meetings. The second part was conducted during the construction phase and the aim was to coordinate the site work, to simulate the logistics and site areas but also to analysis more precisely some construction details.

It was shown that it is required to manage multiple graphical LOD corresponding to the different usages of the model either expected (i.e. required) or unexpected (ad-hoc analysis with the model). Moreover different parts of the model came from different actors with different LOD. The graphical LOD necessary for construction phase is higher than the graphical LOD at pre-construction phase. Uniformed temporal LOD should be proposed and validated in order to define LOD for 4D/BIM purposes, a first step towards models sharing among 4D tools. The bidirectional exchange between the construction site and the 4D model in the second part of the experiment was another very interesting finding.

In future works, authors will work on the issue of 4D LOD specifications, including temporal LOD description and correspondence between temporal LOD and existing graphical LOD in BIM approaches.

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Challenges of Big Data in the age of Building Information Modeling: A high-level conceptual pipeline

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Abstract. N-dimensional BIM models integrates many aspects of construction projects information. Construction project managers are facing an important challenge related to making meaningful deduction from this data. Because it is interesting to associate BIM with other information sources and because of the increasing growth of cloud computing, the current data mining tools are showing their limitations. Big data is then gradually getting a reality in the construction industry. This paper tries to define what it means and proposes a high-level conceptual pipeline in order to bridge the gap between BIM-based related visualization works and information visualization domain.

Keywords: BIM, Big Data, Information Visualization, Information pipeline, Architecture, Engineering and Construction.

1 Introduction

With the advent of Building Information Modeling (BIM) in the construction industry, the perspective of information management is changing. Reddy compared the transformative aspect of BIM to the Internet and stated that it is becoming necessary to manage building data on projects of any size [1]. According to him, “the most interesting aspect of BIM in the long term is the application of data mining and analyzing” [1]. Moreover, building information models are increasingly associated with other sources, including urban cartographies, Geographic Information Systems (GIS) [2, 3], Building Automation Systems (BAS) , Facility Management (FM) [4, 5], Electronic Document Management Systems (EDMS) [6] and Computerized Maintenance Management Systems (CMMS) [7]. Combining such different sources in order to extend the BIM-based decision-support can quickly become very complex for current data mining tools due to the variety and the amount of the information.

Thus, Big Data has the potential to become a common reality in the industry. In 2011, the McKinsley Global Institute proposed a map showing how it is easy to capture the value potential of Big Data cross sectors. On a scale of five, construction sector is positioned on the third quintile for IT intensity, for data-driven mind-set, and for data availability, and for the overall ease of capture index [8].

Because of the peculiarity of the industry, data integration and management is a challenging issue in the development of Architecture, Engineering and Construction (AEC) projects. It is worth to remind that fragmentation, non-standardized collaboration and heterogeneity of actors and skills characterize collaborative processes in AEC projects management. Moreover it is not trivial to give a precise definition of what Big Data currently means in construction projects. Moreover, with the growing implementation of Building Information Modeling approach in the AEC industry, one can state that no conceptual formalization has been provided so far to identify construction projects' related information challenges. This paper proposes to explore the literature in order to define what Big Data really means in construction industry. It then proposes a conceptual model of Big Data based on previous seminal frameworks and information visualization theories.

2 Big Data in construction management in an era of BIM: what does it mean?

Provost and Fawcett defined Big Data as "datasets that are too large for traditional data-processing systems and that therefore require new technologies" [9]. According to the McKinsley Global Institute, it "refers to datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyze" [8]. McAfee and Brynjolfsson (2012) identified three key differences between Big Data and analytics used before. These differences are related to the variety, the volume, and the velocity of the data [10].

2.1 As regards the variety

A large variety of information is managed and used in construction projects. It generally encompasses functional brief requirements, feasibility studies, architectural drawings, engineering drawings, technical specifications, tender documents, bills of quantities, cost estimations, invoices, reports, lifecycle information, technical data sheets, as-built records. This list is far to be exhaustive and we can add design know-how, building regulations, construction know-now, client brief, schematic drawings, observations, measurements, etc. [11].

Jiao et al. (2013) distinguishes project engineering data (PED) from project management data (PMD). According to them, PED refers to "geometric presentation, parametric descriptions and legal regulations associated with the construction of a building" [12]. PMD are "control and communication information that are generated in and closely related to management activities throughout the construction lifecycle". Björk showed that information is required to control the material activities, to specify the building requirements (design information) and the activities to be performed (management information) [11]. The construction projects information is presented in

Table 36 of the OmniClass[1] classification. Its three broad categories (general references, office resources, project information) and their content well illustrate the variety of information in construction project.

With the development of the BIM approach, both PMD and PED are integrated and coordinated with the aim of managing nD models. nD modeling can be defined as the addition of supplementary information to tridimensional model(s) for analyses and simulation purposes. Thus, it is commonly agreed that a 4D model links scheduling information to 3D model's objects in order to simulate construction process over time. The fifth dimension is related to costs information. It is more and more accepted that the sixth dimension is represented by facility management information but it is important to note that beyond the fifth dimension (cost), there is no consensus about what each dimension represents. Lee et al. identify eight possible dimensions which notably show how nD modelling can increase the variety of information to be managed in BIM models. The dimensions are: maintenance needs, acoustics, process, cost, energy requirements, crime deterrent features, sustainability, people's accessibility [13].

This variety of model-related dimensions of information is highly structured and relies on object-based conceptual modeling techniques, such as BuildingSmart's IFC. However, design and construction processes also rely on huge raw datasets, such as the 3D point clouds delivered in the surveying tasks using laser scanning techniques. Moreover, as mentioned in the introduction many research works have reported other information sources which can be integrated with BIM. Such integration approaches of course dramatically increase the variety of information to be managed, but also the volume.

2.2 As regards the volume

As regards the volume, it is hard to say beyond which size data can be called Big data because it depends on the sector, the advances of the technology over time and the complexity of data [8]. In the AEC industry, "construction projects are associated with voluminous and often unstructured data sets" [15]. According to Jiao et al., "individual file sizes currently range from Megabytes to Gigabytes, however there is an apparent trend of increasing file size" [12]. These authors mention a huge volume of data representing "tens of thousands of files" at a project level. The McKinsey Global Institute (2011) estimated the data storage for the USA construction industry in 2009 at 51 petabytes, with 231 terabytes for each of the 222 firms with more than 1000 employees [8].

Traditionally, the stored data is in the form of images and text/numbers but with BIM and nD modeling, other forms of data are now stored. For example, 4D models are commonly exported and stored as video animations. In the frame of nD modeling, the size of the handled data can grow very rapidly due to the multiple dimensions conveyed, their size, their variety and their complexity. Joyce recently published in a professional journal a very interesting case related to 4D modelling. He stated that when managers associate costs information to "the three-day schedule of a crane, the five-day schedule of its crew, the seven-day schedule of the materials and the cost of

[1] http://omniclass.org

the crew's labor” the size of the data to manage can rapidly get out of control [16]. According to him, with the growth of 4D BIM in the construction sector, “big data arrives each day with an ever-louder thud”[16].

2.3 As regards the velocity

Thanks to new delivery methods including Integrated Project Delivery (IPD), BIM level 3 has already been adopted in a few construction projects. A survey conducted in 2010 by Kent and Becerik-Gerber showed that the adoption of IPD by construction professionals in the United States was still not very significant, but noted a huge interest in the principle and some good perspectives [17]. Both experienced professionals (66.7%) and informed ones (58.3%) see the IPD becoming one day a widely adopted method for project delivery. BIM level 3 is defined as network-based integration, a collaborative use of an integrated object-oriented model, shared over a network in which users can connect to feed and use the model, within their respective areas of responsibility [18, 19]. Beyond “building-related” data, recent policies plan to integrate “infrastructure-related” to the models required for public tendering in UK.

Two main methods are currently used for models integration in the BIM approach. The first method use object-oriented database named “BIM servers” to manage IFC objects with their versions, their variants, their business views and the associated notifications. The interface with the BIM server is enabled via BIM authoring software systems or intermediary viewers coupled to the server with APIs. The second method consists in the use of Project Lifecycle Management (PLM) collaborative platforms to establish and maintain the link between IFC objects collections corresponding to the responsibility and the production of the different stakeholders within the same construction phase or among different phases of the project. This requires the use of new technologies such as “cloud computing” [20].

Whether for PLM or BIM server, the velocity of data will be an important challenge in the next years. Indeed, the speed needed for data input/output is getting increasingly higher because data must be processed quickly despite its big volume. In fact, the volume of data and the diversity of transactions coming from multiple sources considerably increase the flow of information. Moreover, Jiao et al. (2013) have notably well stated the current data velocity challenges in construction.

3 A Big Data conceptual pipeline for Construction Industry

3.1 Background

The following proposition relies on important previous works dedicated to both 1) the information technology and flow in construction and 2) the (Big) data flow proposed by Information Visualization scientific fields.

In 1999, Bjork defined the definition and the main research issues associated with the emerging domain of Information Technology in construction. The work proposed a global model of construction process relying on two interacting sub-processes: the material process and the information process [11]. It then used the IDEF0

methodology to model the interactions of the four generic information process activities: person-to-person communication, creation of new information, information search and retrieval, making information available. Due to the complexity of processes in construction and their interrelations, Turk proposed to distinguish the glue processes (or integration processes) from the base processes [21]. According to Turk, while base processes are the core processes (including information creation processes and information utilization processes), glue processes “make sure that material items or information flow from creation process to utilization process and that the utilization process can use them” [21]. Information creation includes four steps: create, edit, record, and distribute [21]. The glue process includes five steps: find, retrieve, store, convert, and store (the converted version). According to Turk, information processes have five main features: input, output, performer, customer, method, and time frame.

As developed in previous sections, BIM can generate voluminous and various data set to support the management functions in construction projects. According to Russell et al. (2009), making meaningful deduction from this data is one important challenge construction project managers are facing. He also remarked that information processing and visualization can be very helpful. Mazza defined visualization as a “cognitive activity, facilitated by external visual representations from which people build an internal mental representation of the world” [22]. Geovisualization (about geospatial data), Scientific Visualization (about physical “things”) and Information Visualization (about abstract data) are the three main research fields that provide scientific body of knowledge on information processing and visualization. With the advances of IT, many tools exist to assist users in creating visual representations of abstract data. Although these tools are very different from each other, they all follow the same steps and process of generating visual representations. Mazza (2009) presented a conceptual model inspired from the pipeline proposed by Haber and McNabb [23]. Three main steps have been identified: pre-processing, visual mapping, and view creation. One of the reference models in collaborative visualization is also based on this pipeline [24].

In construction industry, Russell et al. identified four main steps necessary for an efficient information processing activity: identifying the purpose, selecting the data representations and transformations, choosing the visual representation and the interaction technology, and presenting and disseminating [15]. More recently, assuming that 4D/nD simulation works are largely collaborative, Boton et al. proposed a method to design adapted visualization in collaborative 4D applications [25]. The method includes four main steps: characterizing collaborative situation, identifying visualization needs, selecting adapted business views, composing coordinated multiple views.

The amount of data in every sectors and function of the global economy has been exploding and the current models and applications seem inappropriate to manage the volume, the variety and the velocity of data. New conceptual models are then appearing. In 2012, Fisher et al. proposed a conceptual big data pipeline, based on interviews with experienced practitioners [26]. Five main steps appeared in the proposed pipeline: acquiring data, choosing architecture, shaping data into architecture, coding/debugging, and reflecting.

3.2 A new (big) data pipeline dedicated to construction industry

In this section, and based on the previous approaches, we propose a conceptual data pipeline for construction industry. The IDEF0 formalism is used, which is well used by the Information Technology in Construction scientific community. IDEF0 is known to be used for the enterprise activities and information flows modeling [27]. In IDEF0 simple syntax, activities are placed in a box and described by verb-based labels. Arrows entering the left side of the box represent inputs. Arrows exiting from the right side of the box show outputs of the activities. The top entering arrows represents the control concepts while the bottom entering arrows show the mechanisms or involved actors.

The proposed pipeline relies both on the pipeline proposed by Fisher et al. (2012) and the existing work in the construction industry, including the 4 main steps identified by Russell et al. (2009) and the method proposed by Boton et al. (2013). It identifies four main steps: acquiring data, choosing architecture, Shaping and coding data, reflecting and interacting.

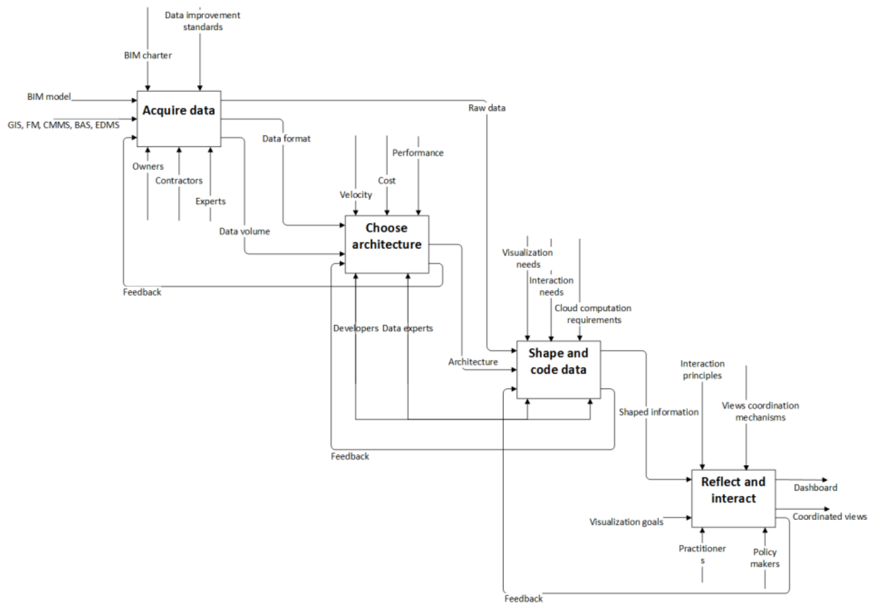

Figure 1: A high-level conceptual pipeline

The first challenge in the Big Data pipeline is related to acquiring data. Data can come from BIM models but also from other sources including GIS, FM systems, CMMS, BAS and EDMS. The structured data from BIM have to be deconstructed in order to be processed, restructured and analyzed. Data come from owners, contractors

and other experts. BIM charters and data improvement standards are used to control the way data are acquired.

The second challenge in the Big Data pipeline is related to choosing architecture. This activity is mainly devoted to developers and data mining experts. The formats and the volume of the data from the previous step will highly determine the choice. The cost, the velocity and other performance criterion are used for architectures comparison in order to choose the most appropriate one.

The third challenge in the Big Data pipeline is related to shaping and coding data. Raw data acquired at the first step are shaped and coded in the frame of the chosen architecture. It is important here to understand users' visualization and interaction needs. It is also interesting to take into account the cloud computing requirements. This activity is also devoted to data mining experts.

The fourth challenge in the Big Data pipeline is related to reflecting information and interacting with it. The aim is to provide users, policy makers and other practitioners with decision support dashboards which present meaningful information and coordinated multiple views. Users' visualization goals are some important input in the achievement of this step. Interactions principles related to visualization tasks and views coordination mechanism are also to be considered.

4 Conclusion

This paper explored the literature in order to define what Big Data can mean for the construction industry at the age of Building Information Modeling. It also proposed a high-level conceptual model dedicated to the industry based on previous seminal frameworks and information visualization theories.

This is a first step of an important work which aim at bridging the gap between BIM-based related visualization works and information visualization domain, usually applied to unstructured data. Future works will apply the proposed pipeline to real construction organization in order to evaluate it.

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Toward Space Oriented BIM Practices

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When performing design tasks, architects think in terms of space, and act on physical elements. They often use various representation means to shape and to communicate the complex aspects of space. Architectural representation is often driven by visual perception whilst current BIM practices seem to be based on semantics associated with scheduling building items (element, position, quantity, etc.). The reduction of architectural sensitive approaches to merely technical ones, reveals only quantitative and restrictive information that does not reflect the architect's multi-sensorial experience. This paper examines some recent model proposals which include descriptions of architectural space concept, and tries to suggest a possible synthesis of this work. It focuses on cooperative practices necessary to unveil the sensitive dimension of the architectural design, and presents a state of existing BIM tools based on relevant tasks used in these practices in order to acquire more knowledge about the concepts which ensure a cooperative work taking into account the sensitive spatial aspects.

Keywords: *Cooperative design, Architectural space, BIM, Qualitative property, Topology*

INTRODUCTION

The overall sensation of a space cannot be understood by an analysis of its measurable properties. The overall ambiance of a space is given by all the interconnected computational factors of which it is composed (Drozd 2009). Shadow, light, transparency, depth, sound, smell, heat, airflow, materials, textures, etc., are all elements that simultaneously participate in discovering and perceiving a space (Bonnaud 2012). Referring to physical experience, it is observed that architecture engages and assembles a large number of sensory dimensions: lighting and thermal ambiance, openness and sunshine of a space, etc. Topology is also an important aspect to qualitatively describe a space. It plays a leading role in evoking feelings in space (ex. communicating spaces, space with exterior relation, etc.). The perception of ambiance induces a questioning about the representation of sensitive spatial aspects. According to Mark Crunelle, it is complex to translate through visual features all perceptions provided by our various senses (Crunelle 1996). That is why, architects always used representations evoking the observers' sensations to reveal the intended ambiance of designed spaces.

BIM models are defined as a consolidated base of parametric objects organized into multiple layers of information describing the physical and functional characteristics of a building (BIM handbook 2014). BIM modelling introduces a technical approach into digital cooperative practices. Such an approach is based on the use of measured standards and codifications, transforming all building information into quantitative data. Only constructive information is taking into account during the design phases. However, a sensitive space approach is not yet integrated. Visual representations used in BIM tools do not allow the user to recognize all elements properties existing in BIM models. BIM models provide information about spaces that not include the relationship between them (Brodeschi 2015). Current BIM practices cover limited points of view that cannot apprehend all the architectural knowledge (form and function) expressed in the philosophical discourse (Bhatt and Kutz 2012).

In this study, we discuss the sensitive space approach during architectural design phases. The first chapter focuses on recent research having addressed data modelling of architectural space concept. The second chapter looks at relevant tasks enabling collaborating on spaces, taking into account their sensitive aspect. Then, the third chapter explores the capability of current BIM tools to realize such tasks. Finally, we try in the last chapter to formalize in a first data model all core concepts allowing taking into account qualitative and topological information about spaces. Our long-term objective is to propose an alternative approach based on these types of sensitive information to assist cooperative work during the design phases.

BACKGROUND

Architectural space is often considered as a construction result. An empty element bounded physically or virtually, in which we can experience a feeling of enclosedness. The generally accepted perception of space within science today is as a relation between things (Ekholm 2000). A building is constructed to provide a set of interior and exterior spaces. It is designed on the basis of a specific program designating the properties of those spaces (shape, location, ambiance, openness, sunshine, relation and communication between, etc.). Most of existing space models treat only the intrinsic properties of a space (ex. geometric data, location, quantity, etc.) and abstract properties related to human experience. The IFC model supports, in part, this type of information. It contains data describing the quality of space including:

- Thermal requirements (required temperature, minimum and maximum values depending on the season, etc.).
- Lighting requirements (lighting values, whether the space requires artificial lighting (true or false), etc.).
- Occupancy requirements (activity type, headroom required for the activity assigned, number of users, areas rate by users, daily duration of the activity, whether an external view is desirable, etc.)
- Safety requirements (fire risk factor, whether the space is intended to serve as a storage of inflammable material, or as an exit, etc.)
- Space covering requirements (nature and thickness of floors, walls, ceilings, etc.).

However, this model does not take into account the rest of qualitative spatial requirements, like the openness of a space, its sunshine, its acoustic ambiance, etc.

Proposing a method for automatic updating of spatial requirements during the design phases, Kim specifies two types of space requirements: activity-based requirements and space-based requirements (Kim 2015). These requirements cover only spatial information supported by the IFC model and do not include requirements related to the topology of spaces. Topological requirements are usually requested by the future user of the building, focusing mainly on information about the boundary and the neighbourhood of spaces. E.g. The openness of a space to the outside, its sunshine, its orientation and its relationship with the rest of surrounding spaces (proximity, communication, container / content, etc.).

Based on an analysis of the conceptual model of spaces, space boundaries and enclosing structures advanced by Bjork (Bjork 1992), Ekholm and Fridqvist present a modelling for spaces including descriptions of their topology in a building (Ekholm and Fridqvist 2000). Using a spatial view, they introduce the concept of user organization to conceptually separate between the intrinsic properties of the built environment and the properties of human activities that are to be housed within. But there is no reflection in the two previous models that addresses the design requirements for the topology of spaces or for their qualitative properties related to the user activity. Among existing recent models, it is only the work of Bhatt who takes into account, implicitly, topological requirements (Bhatt 2011). It proposes a spatial modelling based on modular ontology, including both qualitative and topological requirements, to verify compliance of the spatial properties proposed during the design phases with regulatory requirements. E.g. the range space of a sensory device, the distance between emergency exits in public spaces, etc.

We have just shown that spaces are taken into account, in existing data models, particularly in the IFC model as a set of quantitative and topological properties. Quantitative properties can be guided by qualitative requirements. Currently addressed qualitative requirements cited above are related to designers' field of intervention. E.g. MEP engineer determines the thermal requirements, electrical engineer determines the lighting requirements, etc. However, the user requirements are given in terms of further qualitative properties (e.g. an open and sunny living room communicating with a large kitchen). Hence, information about qualitative and topological spatial requirements must be present in a useful model for design, checking and validation of spaces during the teamwork evolution. In our work, we specifically focus on qualitative and topological requirements expressed by the future user of the building (the owner). In continuity with the work of KIM, this study aims to integrate these types of requirements in current BIM practices and to suggest a decision support method allowing designers to control them.

RELEVANCE OF SPACE CONCEPT IN COOPERATIVE PRACTICES

According to Ireland, spatial problems are complex (Ireland 2015). He argues that to organize spaces, architectural practices tend to flatten spatial problems into something quantifiable so that they can be managed and planned. He states that *"Approaching the configuration of space in the standard way raises the question whether any richness is lost? There is often a qualitative disconnect between the articulation of spatiality in the built environment and the spatiality of being"*. To overcome this issue, we propose to integrate spatial logic in BIM practices. Indeed, the architectural space concept is a shared knowledge between all AEC actors, unlike physical structural or MEP elements, which define it in BIM models. This integration will enhance designers' cooperative work, and enables them to act on the container (building elements) taking into account the quality of the content (spaces) through sensitive dimension expression.

The architectural space; a design entity loaded with sense

Evoking the sensitive dimension of space raises the issue of its representation as a negative empty and immaterial entity: did the designer need BIM tools to translate the feeling of space and communicate it? How to represent what cannot be seen, but can be felt? How can we represent both physical and abstract information necessary to describe sensitive knowledge about a space? All this information seems very useful, especially during the design phases, when user requirements are given in terms of spatial qualities (e.g. the first intentions required by a house owner might be: a large kitchen, an open and sunny living room, etc.) and spatial topology (living room near the kitchen, bedroom upstairs, etc.). Current BIM practices must therefore translate this diversity of properties by moving towards new representative and cooperative methods (associating representation, description, relations, etc.). In addition to **adding** and **visualizing** spaces, BIM tools functionalities must allow designers to **enrich**, to **navigate** on and to **check** sensitive spatial data to express all owners' requirements. They must also allow them to **receive**, instantly, all information about changed spaces, responsible actors and resulting required tasks, according to each actor needs.

To provide a useful conceptual framework in order to lead a collaborative situation functional analysis, Ellis and Wainer established a functional clover, which defines three cooperative areas: co-production, coordination, and communication (Ellis and Wainer 1994). Based on this functional clover, we highlight in the next sections the relevance of space concept in cooperative activity.

Space as a co-production aid

Spatial logic in BIM practices facilitates co-production of spaces. Actors manipulate space as a generic entity including a set of building elements (walls, ceilings, floors, doors, windows, etc.). This practice is helpful, especially, when the project program is governed by regulatory requirements on space (quantitative, qualitative and topological requirements). Some specific public projects (museums, hospitals, courthouses, airports, etc.) or projects having graphical charters (banks, stores, etc.) have this kind of requirements. For example, French hospital operating theater design is governed by regulatory spatial requirements, e.g. 1. *"A relaxation room can be internal or external to the operating room. It must have a natural lighting."*; 2. *"The pre-anesthetic room must be next the operating theater. It is desirable to provide mood lighting and / or specialized lighting."*; 3. *"A doctors' cloakroom is compulsory, it ensures changing theater dress... It should connect common circulation areas to the operating theater."*; 4. *"The recovery room is a part of an operating theater. It is considered a buffer zone between the theater and the common area of the hospital."* (Translated by the authors from: French circular DH / FH / 2000/264 on 19 May 2000 on the establishment of operating theater boards in public health institutions).

Such spatial requirements are only known implicitly by architects and designers, who are continually trying to satisfy during the advancement of the design. Thus, a checking process is indispensable. BIM practices should enable designers to **enrich qualitative and topological properties of space** in order to take into account requirements during the design process (Siala et al. 2016). These qualitative and topological aspects of a space should be generalizable to all spaces of the same type. For example, in requirement 1) above: *"natural lighting"* must be generalized on all *"relaxation rooms"* of the hospital. Also, in requirement 3) each *"operating theatre"* in the hospital must be separated from the common circulation by a *"cloakroom"*.

During the conceptual design phases, traditional communication means, like minutes of meetings, show certain limits, especially when coordination involves certain particular structural or MEP elements (a dropout beam, a pipe reservation in a slab, etc.). Indeed, the localization of observations in the designed building is difficult, particularly when actor has not attended the coordination meeting. That is why, often the architect must annotate the observations on building plans in order to localize and then communicate them to the interested actors. Thus, allow actors **enriching spaces with meeting observations** facilitates the reuse of information by all actors and the identification of actors' actions. To structure all the information about spaces, it will also be of interest to enable designers to **enrich spatial data associating notes** (to report an issue, point out a remark, etc.), **documents and links** (mood lighting data sheet, specific lighting website, etc.).

At the operation and maintenance phase, the integration of the building user in BIM practices will provide the possibility to take into account the changes he brought to his private spaces. Indeed, the decomposition of BIM models into individual "space-objects" (a detached and shared part of the whole model) allows the building user to **enrich spatial information adding his changes** and thus give asset managers a clear vision of the real state of the entire building at a time t.

Space as a coordination aid

During architectural design process, coordination activities cover, in most cases, changing the state of some building elements (add a wall, enlarge a window, move a column, etc.). Existing BIM practices enable the structuring of information concerning various building elements, classifying them by type. Thus, to coordinate on a specific element implies consulting all lists of elements (walls, columns, beams, etc.). In this context, a **spatial logic navigation** will provide not only a space-oriented coordination (by zone, floor, space type, etc.), but also the identification of the actors who are concerned by a specific activity. For example, to coordinate about a 'kitchen design' needs all element layers forming this space: enclosing walls, ceilings, openings, equipment, etc. Based on selected layers, it could be easy to determine the necessary actors to coordinate this activity (e.g. in this case: architect, designer, electrical engineer, MEP engineer, kitchen designer, etc.). To ensure a spatial logic navigation through the project, a definition of relating enclosing elements, openings and even eventual sub-spaces, is necessary. So that selecting a space involves the selection of all building objects belonging to it. With this feature spatial logic navigation becomes a reality. The integration of qualitative and topological spatial information in current BIM practices would make it possible **to check whether designed models satisfy required constraints**, during updating models. This will aid the co-production of spaces by orienting designer's vision towards the desired spatial quality. This checking will highlight problematic changes which do not respect the requirements previously enriched by the architect. For example, in requirement 3) of the previous section: *"A doctors' cloak-*

	Tasks	Data	Support
Co-production	**Add/ modify/ delate**	Space	BIM model
	Visualize/ navigate	Space	BIM model
	Enrich	Qualitative requirements	Space
		Topological requirements	Space
		Design notes*	Space
		Operation notes**	Space
Coordination	**Navigate**	Spaces	BIM model
	Check	Requirements	Space
		Updating changes	Space
	Detect	Actor's actions	Spaces
Communication	**Receive /emit**	Changes***	Spaces
		Required tasks	Spaces

* Notes enriched by designers (notes that report issues, meetings observations, remarks, etc.).
** Notes enriched by the building user (describing changes he brought or needs to bring to his private space)
*** Includes updating changes and changes added by the building user

Table 1
Relevant tasks for collaborating taking into account sensitive spatial dimensions.

room is compulsory, it ensures changing theatre dress... It should connect common circulation areas to the operating theatre." A method must enable BIM tools to verify if proposed design solutions satisfy this topological requirements (for example by focusing on the location of those three spaces: operating theatre, cloakroom, common circulation areas).

During the evolution of design, models are exchanged between actors, so that each one introduces adjustments according to his related competence and field of intervention. In this context, current BIM practices should allow **checking automatically changes that have been carried out on spaces during updating models**. This will help to determine the impact of changes on the quality of spaces, and then to communicate relevant updating changes to interested actors. For example, once an architect has expanded a space, the MEP engineer should have the notification allowing him to revise heating and cooling requirements. Checking updating changes also enables BIM tools to associate changes with the responsible actor. This will facilitate **the detection of all actors' actions** and ensure a more detailed tracking of the design progress.

Space as a communication aid

Respectively to the previously intended two **checking process**, current BIM practices must ensure the distribution of the resulting information flow, according to each actor's needs. So that **each actor receives only relevant information relating to his filed of intervention**, and then acts quickly. E.g. 1. An architect has changed the function of a space from "staff office" to "conference room". The acoustic engineer should have the notification to act on the acoustic treatments of enclosing walls, according to the new function; 2. During the operation of a residential building, a user has changed the spatial arrangement of a bathroom. The plumbing enterprise should have the notification to verify the piping connection. Likewise, the asset manager should have the notification allowing him to actualize the BIM model taking into account the latest changes. Based on the conveyed information, the BIM manager can **emit various suggested tasks** on spaces for each concerned actor, in order to structure the coordination activity.

In this chapter we explained how BIM practices can offer new opportunities to collaborate on sensitive spatial information. Table 1 summarizes required tasks of this approach. In the following chapter we will highlight limitations of current BIM tools to provide such tasks.

STATE OF CURRENT BIM PRACTICES

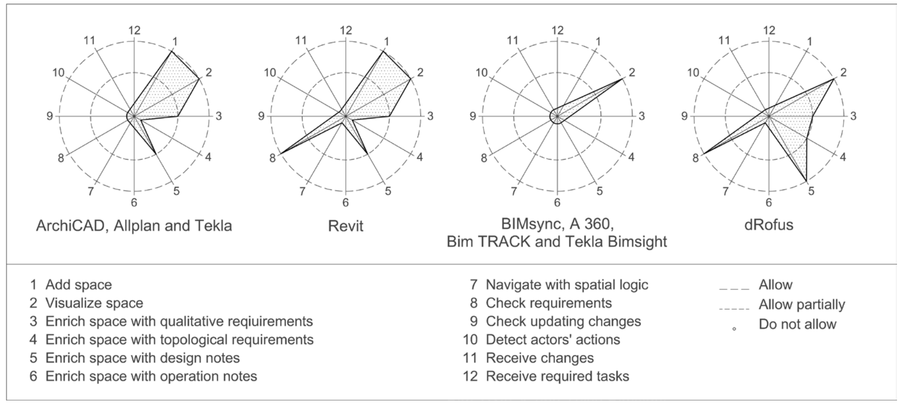
In order to establish the need for a new vision of spaces in current BIM practices, existing BIM tools are first investigated.

Methodology

According to Table 1, we have first defined a set of simple modelling tasks. These tasks have been established to highlight fundamental limits of the various BIM tools with regard to tasks described in the previous chapter (allowing the cooperation on sensitive spatial data). Then, sets of qualitative and topological information were associated with a set of spaces modelled by a CAD tool, then registered under IFC instance to be tested. Regarding topological information, several kinds of link relations have been used in this model, in order to make connection between spaces (e.g. adjacency, intersection, content of subspaces, etc.).Qualitative data concern spatial requirements supported by the IFC model.

Finally, handling these types of data by different BIM tools enabled the detection of the limits of each tested tool to represent and manage initially enriched semantics, to continue enriching them and finally to cooperate throughout. The observation work was carried out on a set of CAD tools (ArchiCAD, Revit, Allplan, and Tekla) and groupware (BIMsync , A360 , BimTRACK , Tekla BIMsight and dRofus). The results of this study are illustrated in Figure 1.

Figure 1
Ability of tested BIM tools to support defined tasks.



CAD tools

Creating space involves the automatic setting of its quantitative properties. Tested tools are limited to spatial requirements supported by the IFC model and do not consider the rest of the qualitative spatial requirements such as those concerning the openness of a space, its sunshine, etc. Likewise, they do not offer the opportunity to add the topological constraints explained in the previous chapter. In most of the investigated tools, a control approach allowing verifying the compliance of design solutions with related specified requirements is missing. CAD tools serve, among others, to organize spaces during the architectural design. However, they do not understand the connection between spaces and even the relation linking them to the enclosing elements. Tested CAD tools allow designers adding notes to a space (name, function, area, headroom, etc.), but do not permit further enriching it with associated documents, links and other personalized remarks like notes that report issues, meetings' observations, etc. Reporting issues is made possible by several integrated modules into CAD tools like A360 and Bim Track. Such modules provide the possibility to illustrate and share screen shots or recoverable views of a design situation, but they do not link remarks to corresponding spaces. With tested tools, it was possible to navigate on designed spaces within 2D or 3D visualization. However, given that all of these tools do not understand the topology of architectural objects, they do not provide navigation with a spatial logic.

Most of tested tools allow team-working on the same model. They enable designers to select and borrow desired building objects from the BIM model, working on and then synchronizing data. Using the same approach, we can imagine integration of the building user in the collaborative environment, in order to facilitate communication during asset management phase. Feature which is not provided at present by existing BIM tools and which requires that "space-objects" should be defined and loaned by asset managers to the building users. Although CAD tools offer advanced collaboration features, they show some limits when it comes to architectural space and specifically to spatial quality of the designed building. To facilitate collaboration, most of these tools can detect changes made to the building objects whilst updating models. A simple comparison between two versions serves to identify all building elements that have changed. Information about changes brought to spaces remains, however, unaddressed by all tested tools.

THÈME 4

Modélisation et fabrication numérique multi-échelle

THÈME 4

Modélisation et fabrication numérique multi-échelle

Cet article présente une recherche dans le domaine des structures architecturales plissées conçues dans un environnement numérique. Les outils numériques utilisés permettent de traduire la forme architecturale proposée par le concepteur en structure plissée pour laquelle la stabilité et la résistance technique sont testées numériquement. Les outils proposés et utilisés au cours de ce travail sécurisent les propositions structurelles et génèrent les fichiers exploitables pour une fabrication robotisée des panneaux bois d'une structure plissée.

L'approche non-standard a progressivement fait son apparition en architecture. Elle correspond à l'utilisation de parois et structures courbes ou déstructurées, et fait appel à des géométries plus complexes qu'auparavant. Pour réaliser cette architecture appelée « non standard », nous faisons de plus en plus appel à des outils de Conception Assistée par Ordinateur (CAO). Cet article propose une méthode pour créer des parois et enveloppes non standards, constituées de cellules en panneaux bois. Nous présentons les résultats obtenus à partir d'une modélisation informatique et d'un prototype construit grandeur réelle.

L'objectif de ce travail est de développer un système innovant pour créer une construction durable de type structure plissée en bois. Dans un premier temps, cet article décrit la chaîne numérique (appelée continuum numérique) qui est associée au développement des structures plissées non standards constituées de panneaux en bois. Nous proposons ensuite un processus de conception de ce type de structure, de la modélisation paramétrique à la construction d'un pavillon grandeur réelle, en passant par la fabrication qui est effectuée grâce à des machines à commande numérique (CNC).

Le pli, une figure d'interface entre architecture et ingénierie

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RÉSUMÉ. Cet article présente une recherche dans le domaine des structures architecturales plissées. Nous abordons plus spécifiquement la technique des composants en panneaux de bois massif contrecollés. L'environnement numérique proposé permet, d'une part, l'ajustement de la structure en plis à la forme architecturale dessinée par le concepteur et, d'autre part, la vérification de sa stabilité et de sa résistance. Il est composé d'un modeleur géométrique paramétrique couplé à un logiciel de calcul de structure. L'interaction de ces deux outils numériques guide le concepteur architecte dans la recherche de formes fondées sur des plis, sécurise les propositions structurelles et fournit les fichiers numériques pour une fabrication robotisée des panneaux.

MOTS-CLÉS : Dimension architecturale, Dimension structurelle, Structure plissée, CLT (Cross Laminated Timber), Modélisation paramétrique.

ABSTRACT. This paper deals with a research in the field of folded architectural structures. We specifically discuss the technical components of CLT (Cross Laminated Timber) panels. We suggest a digital environment which allows a pleated structure to be adjusted to an architectural form drawn by the designer, while corroborating stability and joining. Consisting of a geometric parametric modeler coupled with structural analysis software. The interaction of these two digital tools guides the architect designer in the research of folded forms, improves the reliability of structural proposals and provides digital files for automated manufactured panels.

KEYWORDS: Architectural dimension, Structural dimension, Pleated structure, CLT (Cross Laminated Timber), Parametric modeling.

1 Introduction

L'utilisation du terme de « pli » voire « d'origami » dans de nombreux projets architecturaux, manifeste aujourd'hui un déplacement dans le vocabulaire des formes contemporaines en quête d'une nouvelle écriture architecturale.

Cette notion de pli, figure à la fois géométrique et structurale, n'est pas nouvelle et parcourt même l'histoire de l'architecture. L'architecture du XXème siècle nous offre des exemples intéressants de réalisations architecturales qui empruntent un vocabulaire à la géométrie de leur structure et en particulier à la géométrie du pli. On évoquera en particulier les travaux de Walter Netsch pour la United States Air Force Academy Cadet Chapel (1954) ou encore ceux de Jorn Utzon, avec le projet du stade à Djeddah, en Arabie Saoudite (1999).

Plus récemment, avec le développement de nouvelles technicités liées à la robotique, l'emploi de nouveaux matériaux et l'essor des outils numériques, le vocabulaire des formes s'est à nouveau emparé des géométries structurales et finit même par donner consistance à un courant architectural nommé « New structuralism » par R. Oxman (Oxman, 2010).

Dans le domaine de l'architecture et de la construction bois, le développement de nouveaux composants comme le Lamibois et le Contrecollé ouvre la porte à des réalisations qui renouent avec les vocabulaires de la morphologie structurale et en particulier celui du pli et du plissage (Weinand, 2010). Outre sa dimension plastique qui enrichit le vocabulaire des espaces et des formes construites, le plissage apporte par inertie de forme, une qualité structurale économe en matière.

C'est l'objet de cet article que d'aborder et de caractériser le concept de pli structural en architecture et de présenter un modèle et un environnement numérique interdisciplinaire permettant de concevoir et réaliser des structures non standards plissées en bois.

2 Le pli en bois dans l'architecture

Bien qu'exceptionnelles, plusieurs réalisations au caractère fortement expérimental ont montré les potentialités du bois pour réaliser des architectures particulièrement inventives. Parmi celles–ci, deux réalisations récentes viennent attester de l'intérêt du principe du pli en architecture. Le pavillon temporaire à Osaka de l'agence RAA, Ryuichi Ashizawa

Architects (Ashizawa, 2010) et la chapelle St Loup à Pompaples du groupement d'architectes Localarchitecture / Mondada (Mondada, 2008).

Par leurs qualités structurales associées aux qualités architecturales, ces deux projets manifestent les vertus des structures plissées en bois. En effet, une série de plis, orientée de manière mono-directionnelle, permet de rigidifier considérablement une surface de faible épaisseur. La portée en est ainsi augmentée et la matière économisée.

Le caractère architectural issu de ce plissage est tout aussi intéressant. On reprendra ici les variables émotionnelles définies par J.M Delarue (Delarue, 1997):

– la « fascination de l'animé », par le rythme.
– l'« euphonie », arrêtes supérieures et inférieures, sommets et vallées, positif et négatif.
– les « nuances » issues de la lumière révélée.
– l'« emprise du trait » guidant le regard.

Divers travaux de recherche comme ceux réalisés par l'IBOIS, laboratoire de l'EPFL dirigé par Y. Weinand (Buri, 2010) viennent conforter cette interrelation entre les qualités physiques et environnementales du matériau bois avec les potentialités géométriques du pli, tant structurales que plastiques.

3 Modèle théorique

Nous proposons un modèle permettant de décrire et de créer une forme structurale et architecturale plissée. Les données du modèle doivent permettre de concevoir cette forme, tant d'un point de vue géométrique que mécanique. Modèle commun, il peut être utilisé comme une passerelle entre deux disciplines : l'architecture et l'ingénierie. Ce modèle est implémenté dans un modeleur numérique permettant une géométrie paramétrique du pli, de manière à rendre compatible la forme architecturale recherchée à un comportement structural satisfaisant.

3.1 Caractérisation du pli

D'une manière générale, un pli est une altération d'une surface matérielle (couche géologique du sol, tissus, feuille de papier…) généralement de faible épaisseur et possédant un rayon de courbure de petite dimension au regard de l'épaisseur de la matière. Il peut être originaire d'actions de déformation d'une surface initiale comme plier, plisser, froisser ou encore de tout autre procédé aboutissant à relier deux ou plusieurs plans formant un angle.

Cette différenciation est importante dans notre démarche visant à générer géométriquement un pli tant structural qu'architectural. En effet, notre définition ne limite pas le pli à une surface originelle à l'exemple de l'origami, mais accepte le pli comme l'union de différentes surfaces.

La définition d'un pli peut être interprétée de différentes manières (Figure 1). On distingue deux cas de pli. Le premier se caractérise par la courbure. On estime que les tangentes en un point de la surface (relative à la dérivée première) sont continues dans toutes les directions. Dans ce cas, le rayon de courbure minimum (relative à la dérivée seconde) est défini par un rayon acceptable avant rupture de la matière. Un pli peut donc être définit selon un rapport entre l'épaisseur du matériau et le rayon de courbure. A ce stade, un facteur d'échelle, définit par le rapport entre le rayon de courbure et la dimension globale du matériau courbé, doit être considéré. Nous faisons référence aux plaques de tôle ondulée.

Un deuxième cas de pli se défini mathématiquement par discontinuité des tangentes en un point d'une surface et dans une direction donnée. Ce changement ponctuel de direction se traduit physiquement par une interruption de la matière, entrainant de ce fait, une notion d'assemblage. C'est dans cette hypothèse que nous avons établi notre recherche de pli en panneaux de bois massif. Le travail avec des panneaux de bois influe sur notre caractérisation du pli. Même si le bois peut être courbé, il nous parait plus judicieux, d'un point de vue industriel, de travailler par assemblage de pièces de bois planes.

Figure 1. Tangente continue (rayon de courbure minimum).
Tangente discontinue (assemblage du matériau).

D'un point de vue géométrique, le pli se définit comme l'intersection de deux surfaces planes dans l'espace selon une valeur angulaire. Cet angle sera déterminé en fonction du nombre de plis choisi sur une distance définie, soit la fréquence du plissage et la hauteur du pli. Cette intersection se caractérise comme la ligne de sommet ou de vallée selon

que le pli est sortant ou rentrant. Ces deux caractéristiques sont déterminées en fonction de la vision extérieure de l'enveloppe plissée. On parlera également du signe d'un pli par rapport à un autre. Sachant que le retournement de la structure implique l'inversion du signe des plis. L'arête ou axe désigne la direction du pli.

D'un point de vue structural, le pli s'associe principalement à l'idée d'inertie. On parle ici de hauteur du pli ou amplitude du pli, distance de projection entre la ligne de pli et le plan moyen formé par les arêtes opposées constituant les faces connexes.

3.2 Dimension morphologique

Cette dimension se base sur des constats issus des pratiques architecturales. En effet, on admet que l'architecte travaille par ajustement successif de sa forme avant d'arriver à une ou plusieurs solutions acceptables (Wetzel, 2009). Le concepteur conçoit la volumétrie de son projet en fonction de l'usage qui lui est affecté et des effets spatiaux et sensibles qu'il recherche. L'objectif de notre application consiste donc à offrir au concepteur, un maximum de liberté créative tant sur la forme que sur les caractéristiques spatiales du pli. Pour cela, un opérateur morphologique supervise une série de paramètres permettant d'agir à tout moment sur le travail de modélisation géométrique : d'une part sur le dimensionnement global de la surface travaillée, d'autre part, plus en détails sur les caractéristiques du pli : la fréquence (le rythme) et l'amplitude (la hauteur du pli).

Si le pli peut être appliqué en principe à toutes surfaces ou formes, nous avons limité, dans l'état actuel de notre travail, la forme initiale ou enveloppe support à une surface semi-cylindrique dont l'axe et le profil sont variables. L'utilité considérée de la structure plissée réside en effet dans ses capacités techniques et formelles à recouvrir un espace de grandes dimensions avec une faible épaisseur. Parmi toutes les potentialités morphologiques en architecture, la forme de la voute a été retenue pour ses qualités à couvrir de grands espaces. Cette forme sert de support au plissage.

Le plissage est construit par une succession de plis dont la direction est voisine de la normale à l'axe directeur. L'archétype du pli retenu présente plusieurs qualités. Tout d'abord, il est l'une des techniques du pli les plus intuitives pour la construction d'une forme stable. Ensuite, la simplicité et l'homogénéité du rythme du pli lui confèrent une dynamique esthétique. Le découpage de « l'enveloppe support » par des plans de pli a permis la représentation d'arcs, trajectoire des nœuds reliant les lignes de pli. Cette méthode s'avère particulièrement robuste à la modélisation dynamique. La correction de la forme primaire entraine un ajustage automatique du plissage. Enfin et surtout, cette technique s'adapte relativement bien aux nombreuses variations de formes du support.

3.3 Dimension structurale

La dimension structurale du plissage passe par l'utilisation d'un logiciel de calcul d'éléments finis utilisant des éléments coques afin de déterminer la stabilité structurelle (sous le poids propre par exemple) et matérielle (flambement). Cet évaluateur structural permet également de valider le dimensionnement (sous chargement externe) de la structure plissée. La notion d'assemblage entraine une caractérisation des liaisons entre les différents éléments constituants la coque. Par défaut, on considère les liaisons comme des encastrements (continuité matérielle). Cependant, tous les types de lois de comportement des assemblages peuvent être définis grâce à l'introduction d'une matrice dans le logiciel de calcul. Pour des raisons constructives (discontinuité matérielle), une recherche vers des assemblages du type « pivot linéique », assimilable à des charnières, semble souhaitable. Dans ce cas, la nature des assemblages étant insuffisante pour assurer la stabilité de la structure, une disposition des panneaux selon une géométrie du plissage est nécessaire. Enfin, une caractérisation des appuis, correspondant aux nœuds définis par la surface de référence, est essentielle pour la validation de la structure.

3.4 Interaction / Rétroactions

Une part importante de notre travail se situe à l'interaction des deux dimensions que nous venons d'évoquer. La géométrie constructive du pli apparaît alors comme l'interface entre ces deux domaines. D'une part, elle induit les caractéristiques morphologiques de la structure plissée et, d'autre part, elle renseigne le logiciel de calcul sur les données nécessaires à la caractérisation de la structure. Elle permet un dialogue entre l'expression architecturale et l'expression structurale au travers d'un processus itératif. Ce processus est basé sur trois activités:

– la proposition : la morphologie architecturale est définie selon les paramètres appliqués à la géométrie constructive du pli et les besoins déterminés par le concepteur.

– l'évaluation : cette géométrie formelle ainsi fixée est analysée structurellement selon les caractéristiques nécessaires à la stabilité et au dimensionnement de la structure.

– l'adaptation : le rapport d'expertise informe sur les modifications utiles via les paramètres géométriques du pli.

Lors des différents cycles du processus de conception, les allers et retours dans la recherche de la forme conduisent à une modification par ajustement de celle-ci. Ces modifications peuvent être engendrées soit par le logiciel de calcul dans le cas de caractéristiques du pli inadaptées à la structure, soit par la géométrie de plissage lors d'une modification de la forme initiale ou encore par des opérateurs internes comme celui appliqué à la gestion de planéité des surfaces.

La relation entre l'opérateur morphologique et l'évaluateur structural est gérée par un contrôleur conditionnel. Ce dernier indique le nombre d'itération nécessaire afin de correspondre au mieux à la forme souhaitée. L'ensemble des opérateurs (géométriques, structurels et conditionnels) permet au concepteur de maîtriser le passage entre de la morphologie initialement souhaitée et la forme optimisée.

Aux travers des données introduites dans le contrôleur, les besoins peuvent être affinés au fur et à mesure de la conception. On obtient ainsi une vision concrète de la progression du projet.

4 Implémentation du modèle

Dans notre travail le processus de modélisation de la structure plissée passe par plusieurs étapes morphologiques successives: la mise en forme de l'enveloppe support et la mise en forme du pli selon sa géométrie constructive (paramètre du profil, de la fréquence et de l'amplitude).

La modélisation géométrique s'effectue dans l'environnement du modeleur Rhinocéros couplé à Grasshopper, éditeur d'algorithme graphique de gestion de données géométriques paramétriques.

L'enveloppe support est définie par une surface gauche. Elle est délimitée par quatre splines, elles-mêmes contrôlées par trois points chacune. Cette série de points possède des coordonnées paramétrables en X;Y;Z, permettant une première mise en forme de l'enveloppe support. Les coordonnées des points, caractérisant la surface initiale, restent modifiable à tous moments. Une fois déterminé, ce volume primaire peut accueillir l'algorithme de plissage (Figure 2).

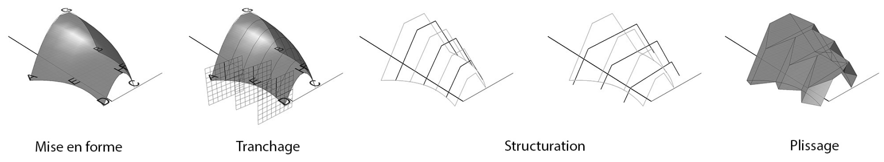

Figure 2. Représentation de la procédure de plissage.

Il existe différentes géométries du pli. Dans le cadre de ce travail, nous avons privilégié une géométrie qui vient s'ajuster sur la surface de référence de manière à correspondre au mieux à la volumétrie de départ. En effet, une série de lignes polygonales est construite à partir du découpage de l'enveloppe support par une série de plans verticaux et normaux à son axe directeur. Chaque polyligne, renommée 'profil', est composée de segments, auxquels on affecte alternativement, dans un plan vertical, un décalage d'une valeur paramétrable marquant les sommets et les vallées du plissage. Le profil, défini par rapport à une surface initiale, donne la direction du plissage. Chaque sommet du profil constitue un nœud pouvant avoir jusqu'à quatre faces communes. Le nombre de segments détermine le nombre de pans, soit n-1 brisis, ligne de cassure du plissage. Les segments constituant un pan n'étant pas forcément parallèles, les facettes ne sont donc pas nécessairement planes.

En effet, les formes aléatoires engendrées par le modelage de l'enveloppe initiale, peuvent entrainer, lors de la construction géométrique du plissage, des facettes gauches. Un paramètre de gestion de surface des facettes a donc été introduit. Un script de programmation en VBnet, permet de déterminer une surface plane, avec un degré de précision variable. Cette précision dépend du rayon de courbure acceptable par le matériau. Ainsi la structure s'ajuste à la capacité de déformation du matériau. Cependant, lorsqu'on se rapporte à une surface quasi plane (matériau à faible rayon de courbure), un écart morphologique important peut être observé. Pour l'instant, seule une correction manuelle permet de se rapprocher de la forme initiale spécifiée par le concepteur. Le composant programmé possède deux entrées : les surfaces définies par leurs sommets et le degré de précision que l'on souhaite obtenir. En sortie de composant, nous avons un récapitulatif des actions menées, les coordonnées des nouveaux sommets constituant les facettes, ainsi que le résidu de l'action avec le nombre d'opération nécessaire de bouclage pour arriver au résultat final. Accepter un rayon de courbure sur une facette entraine une précontrainte dans le matériau, qui nécessitera une vérification structurelle supplémentaire.

Afin de tester la stabilité et le dimensionnement des panneaux en bois, une passerelle informatique est créée entre le modeleur de la structure plissée et un logiciel de calcul d'éléments finis (Castem). Ces données sont définies par la géométrie constructive du pli. Elles correspondent aux coordonnées des sommets de chaque face constituant le plissage généré dans Grasshopper. Les sommets réitérés sont regroupés sous la forme de nœuds, constituants le maillage de la structure reconstruit dans l'environnement de Castem.

Dans un premier temps, cette approche se contente de vérifier la stabilité et le dimensionnement de la structure plissée en fonction du chargement. Un paramètre de subdivision des éléments formant la coque permet d'augmenter la précision de calcul. Pour les premiers tests de stabilité étudiée sous le poids propre de la structure (affectation d'un matériau et d'une épaisseur), les nœuds structuraux sont considérés comme des encastrements. Actuellement, les résultats de contraintes et de déformées nous font part d'un état qualitatif de la structure. Les résultats nous dirigent vers deux paramètres pouvant agir comme correcteurs morphologiques du plissage (Figure 3). Le premier concerne la raideur du matériau en variant l'épaisseur ou la dimension des plaques. Le second se rapporte à la raideur des assemblages. À terme, ces informations agiront comme correcteurs morphologiques du plissage se référant à des instructeurs, évitant ainsi un écart formel trop important avec le plissage initial.

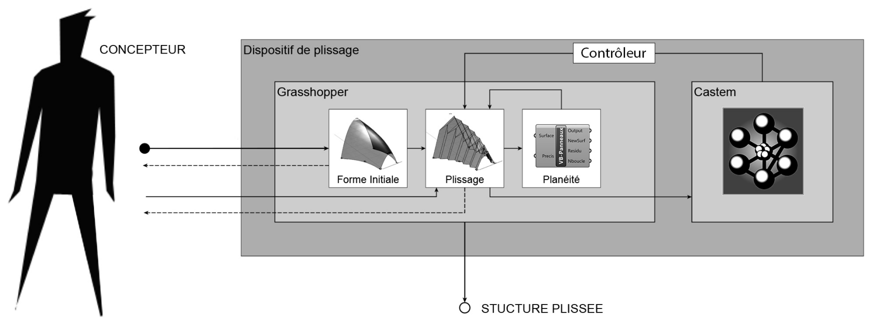

Figure 3. Implémentation du processus d'optimisation géométrique et structurale.

5 Expérimentations

Pour valider notre travail, deux expérimentations ont été menées. La première testant l'aptitude du modèle de l'enveloppe support ainsi que le modèle du plissage à produire une structure plissée conforme à une structure existante. La deuxième vérifiant l'utilisabilité de l'outil prototype en situation de conception.

5.1 Reconstitution de la chapelle St Loup de Pompaples

Dans cette première expérimentation, nous prenons comme référence la chapelle St Loup. Notre recherche de modélisation repose sur l'enveloppe structurelle composée de panneaux de bois contrecollés (6 cm pour la toiture et 4 cm pour les porteurs verticaux).

Le modèle donne une approximation morphologique satisfaisante avec une faiblesse d'ajustement dans la troisième direction (Figure 4). D'une part, l'approximation linéaire de l'enveloppe support nécessiterait un niveau supérieur du type quadratique (au niveau de la courbure de la partie couvrante). D'autre part, un défaut d'informations paramétriques sur le rythme du pli entraine un écart morphologique important. Cependant, le rythme de plissage de la chapelle St Loup est plutôt lié à un aspect matériel et de mise en œuvre (taille des panneaux industriels) qu'au caractère géométrique du plissage.

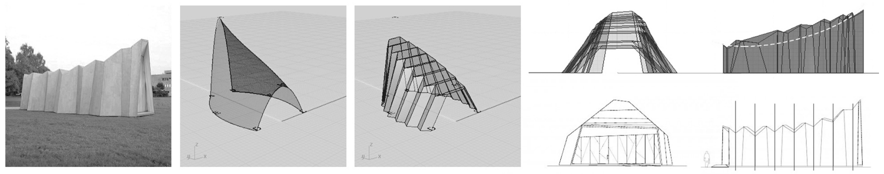

Figure 4. Test de représentation de la chapelle St Loup.

5.2 Réhabilitation de l'église Saint François d'Assise de Vandœuvre

La seconde expérimentation a pour objectif de valider la démarche de conception assistée par notre application. Le projet prend place dans la nef d'une église en reconversion. L'expérimentation débute par la validation de son utilité : la démarche adoptée permet de définir une morphologie capable de faire face aux contraintes architecturales du projet: estimation de la forme support, choix du nombre de brisis et de leurs positionnements, réglage de la fréquence et de l'amplitude du pli, définition du degré de courbure des panneaux et enfin, l'évaluation morphologique et structurale (Figure 5).

Le moteur d'évaluation permet de définir une série de critères d'ajustements sur lesquelles le concepteur peut agir: épaisseur du matériau (définie par le dimensionnement), type d'assemblage des panneaux (défini par la stabilité), taille des panneaux, angle du pli (domaine défini par la technique de fabrication), rayon de courbure (accepté par le matériau) et le nombre d'appuis.

Les premières applications de la méthode montrent un fonctionnement correct où les rétroactions reste cependant à commande manuelle. Les perspectives visent à développer l'assistance du moteur d'évaluation. Par la suite, ce dernier pourra être enrichi par divers critères architecturaux et techniques.

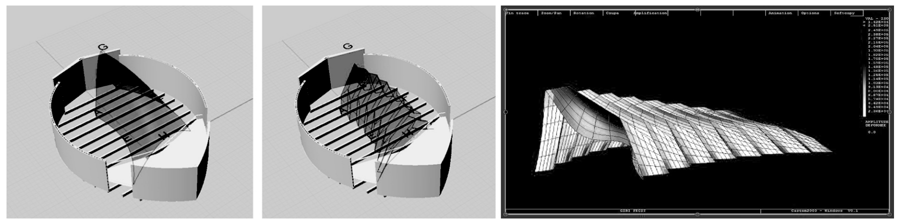

Figure 5. Validation de la démarche de conception.

6 Conclusion

Le pli fait partie aujourd'hui des nouveaux langages de conception en architecture. La recherche morphologique adaptée tant aux capacités structurales que formelles du pliage est source d'inspiration pour de nombreux concepteurs.

Dans notre travail, nous avons tenté d'esquisser un premier modèle du pli qui favorise l'interaction entre la conception architecturale et la conception structurale tout en procédant à son implémentation dans un outil numérique. Des recherches dans le domaine de la géométrie et des mathématiques nous ont permis de déterminer que la conception de la forme est fortement contrainte par la logique du processus de pliage.

Les expérimentations menées dans ce travail ont défini les qualités et les faiblesses de notre modeleur. Les limites de notre opérateur morphologique se situent dans la manière de construire sa géométrie. Bien que le modèle soit fonctionnel et dans certain cas acceptable, la morphogenèse se caractérise par une technique particulière de plissage, entrainant un champ trop restrictif des possibilités du pli.

L'esthétique et les partis structuraux adoptés, dans les projets exposés dans cette recherche ont soulevé une grande variété de questions, dont beaucoup restent encore à approfondir. La réalité constructive engendre des contraintes physiques. Une meilleure association de cet outil morphologique avec l'outil de calcul, Castem, permettra un ajustement formel adapté aux contraintes structurelles.

Les perspectives proposées se scindent en plusieurs parties. D'une part, une correction des techniques géométriques utilisées pour le pli est indispensable. D'autre part, la prise en compte de données constructives liées à l'épaisseur et aux assemblages devra être poursuivie. Enfin, la réalisation de structures prototypes semble une étape cruciale dans la détermination d'éléments favorable à une réalité constructive. L'objectif de cette recherche restant l'étude des structures plissée en panneaux bois, de la conception à la réalisation.

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ASSISTED CONSTRUCTION OF NON-STANDARD WOODEN WALLS AND ENVELOPE STRUCTURES BY PARAMETRIC MODELING

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Abstract. The non-standard approach, widely discussed in the past years as Architecture progressively uses alternative design methods different from the Euclidean paradigm, has allowed architects to transform the way architecture is conceived and materialized. Such evolution uses computer-aided design along with automation in production to originate the environment for the aided architectural conception field in which we present a method, in its early development stage, intended to create non-standard walls and envelopes based on cellular patterns using wood as base material. We present the results obtained from modeling and building two full-scale prototypes of non-standard wooden walls.

Keywords. Non-standard walls; parametric modeling; CNC fabrication; cellular structures; wood construction.

1. Introduction.

This paper shows the results obtained through a parametric modeling method whose aim is to create non-standard wooden walls composed by cellular structures as part of the development of a computer-aided architectural design tool. Based on principle of subdividing Nurbs surfaces by cell patterns as an approach to create non-standard facade walls and envelopes, the method applies the concept of mass customization (Anzalone, Vidich and when conceived and produced, are dissimilar.

In such context, the non-standard concept applied to wooden-cellular walls characterizes the architectural entity which physical components have different shapes, dimensions and/or materials; escaping from the Fordian paradigm of serial production.

To test the capabilities of our method at its initial development stage two wall prototypes were built as part of the wood challenges, a student contest organized by the School of Architecture of Nancy, France (ENSAN) and the Superior National School of Technologies and Wood Industries (ENSTIB) in the town of Epinal, France from May 13th to 20th, 2014.

The experiment dealt with two cell morphologies which meant a different approach for modeling, joint management, fabrication and mounting. An interface between the conception and the production environment created a feedback loop that allowed to adapt the parametric model to the production circumstances (delays, machinery type and human capital).

Precedent works in the field of modeling and fabrication of complex wood structures use a 2D fabrication approach for their production. Our method privileges the three-dimensional cutting approach to model and build such structures, so instead of cutting joints perpendicularly to the cutting bed, the machining equipment (CNC milling machines, robots....) have the necessary multi-axis displacement functions and should be able to perform angle-cut joints.

The format exchange from CAD to CAM proved to be complex as it relies on software capabilities to produce fabrication commands without losing information. More specifically, the lack of compatibility between a CAD program and the CAM interface led the parametric model to a series of adjustments that diminished the quality of the produced elements in order to make them feasible by the available production means.

2. The Non-Standard Concept.

The non-standard approach, widely treated in academic and professional environments, has emerged as an alternative concept to the Euclidean paradigm and the Fordian serial model. It rests on the principles of shape freedom and assisted production to create non-repetitive structures and architectural objects based on mass-customization (Anzalone, Vidich and Draper, 2008) production systems.

manifold shaped objects that make part of an architectural or structural object by using contemporary robotic tools.

Precedent referred works analyse design production and integrated digital fabrication (Sass, 2007) and discuss how the CAD and CAM environments are used to achieve the production of architectural objects conceived through digital modeling.

Another approach on Digital Morphogenesis (Kolarevic, 2005) and algorithmic-generated patterns used as a design resource (Artopulos, Roudavski and Penz, n.d.), treat the relationship between cellular biological structures and architecture. They study how modern digital tools allow creating structures that respond to specific architectural needs by employing random biological patterns as a design conceptual basis. Since patterns can take manifold morphologic approaches (Figure 1), they emerge as a mechanism to explore cells as structural components through parametric modeling. We treat these structural cells as "boxes" derived from paneling a Nurbs surface by a cellular pattern (Figure 2).

The cited works refer to CNC fabrication methods, applied to architectural entities, as a part of the conception process. In order to match those techniques a deep knowledge in computing and programming is needed (Scheurer, 2010) for architects, engineers and designers to materialize their work. In that manner, the non-standard approach not only refers to the shape of an architectural entity but to the way it is conceived in function of the means to materialize it.

3. Method description.

We present the early development stage of a method used to produce non-standard facade walls and envelopes, composed by wood-cells (boxes), via parametric modeling and 3D digital fabrication.

Parametric modeling of non-standard walls. A non-standard wall is defined by a Nurbs surface obtained from a specific context which can be a facade outline or a free shape defined by the designer.

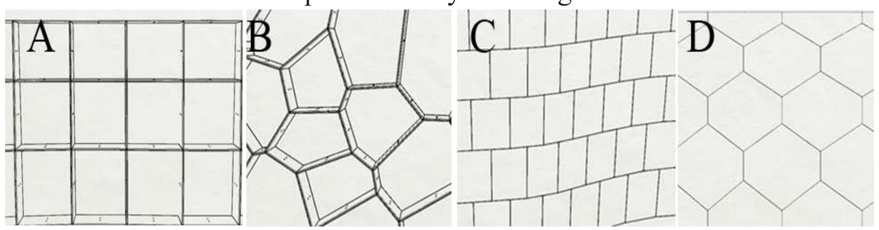

Figure 1. Exploration patterns. A-Quad pattern. B- Voronoi. C- Running bond. D-Hexagonal

and treated with the aid of grasshopper following these steps: a) Pattern choice; b) surface subdivision by a pattern; c) creation of cells (boxes) from the panelling process; d) box characterization (cover and cell-wall thickness, joinery) (Figure 2).

The various pattern options, possible to obtain out of parametric tools, offer the possibility to choose between different valid alternatives (Figure 1). Prior to a pattern choice for exploration, an analysis to evaluate the complexity of patterns was performed considering the following aspects:

Pattern density: Since a pattern is derived from a collection of center points placed in a container and the size of each pattern module (cell) is defined by the proximity between these points; the closer the points are, the smaller the cell gets; resulting in an increasing number of structural components and therefore of junction points. Subsequently, the number of elements to deal with, in function of their quantity, is harder to manage (more complex) from the computational point of view (modeling) and the production point of view.

Pattern typology: the complexity concept is bounded to the logical and computational processes needed to render the pattern into a wall structure. Honeycomb patterns and quad patterns are more like regular patterns in which the variables are easier to be controlled from the modeling point of view. But for other patterns like the Voronoi pattern, is different. The Voronoi pattern is more complex since the number of variables to treat cell vertices increases in function of the number of sides of every cell. As a result, the cutting paths are less regular and the cutting path programming is more demanding. Nesting is also different. With a regular pattern, there is more chance to get an optimal use of plywood sheets to avoid waste, however with irregular ones, the amount of waste increases resulting in a more demanding task of material optimization.

This analysis is useful to demonstrate, due to its computational backgrounds, that parametric modeling of cell structures refers its complexity to the concept of disorganized complexity (Weaver, 1948) in which the number of variables of a problem do not follow parallel paths but random paths.

In order to get feedback from pattern complexity and optimize the parametric model, we used which seemed to be the less and the most complex patterns to test: a regular quad-pattern and a Voronoi pattern (Figure 1A & B).

define the parameters to which the parametric model responds to. At the scale of the wall they define pattern morphology, curvature (on X, Y and Z axes), cell creation by paneling (Issa, 2013), cell density, cell size and wall thickness (constant or variable). In the following paragraphs we will refer to cells as boxes.

At the scale of the box, inputs are: a) box-wall and box-cover thickness (inherited from the wood sheet in use); b) joinery (mitres and rabbets); c) cell-connector placement and drilling (bolts) (Figure 4D).

A box is derived from a paneling operation (Figure 2A), the panel boundary defines its creation perimeter, contour walls and covers whose thickness is inherited from the chosen wood sheet. The intersections between these items (box-walls and box-covers) are treated as joints too (Figure 2D).

Every box in a structure is composed by items and those, by more basic elements such as points, faces and edges represented as data in the parametric model (Figure 2B). As the complexity of the structure increases so does data. Through data filtering, the edges of every box are extracted to perform a series of intersections to obtain the points that generate joints like rabbets and mitres (Figure 2D).

Junction points are ordered to create joint profiles and then applied to all of the items in every box (Figure 2C). Some difficulties appeared when doing so, since the point extraction technique does not tolerate excessive wall curvature resulting in erroneous or null joint profiles. For the prototypes presented herein, a positive result was achieved by diminishing curvature on a curved wall; nevertheless, the idea is to obtain curved walls without joint creation being a hard constraint.

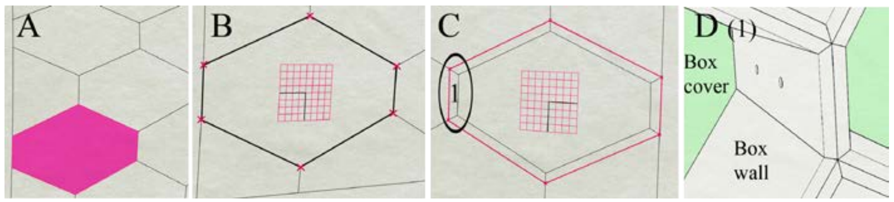

Figure 2. Box generation. A-Surface paneling by a pattern. B-Loop (box) creation by a closed polyline and work plane extraction. C- Box-wall thickness defined by patch subdivision with profile lines. D-Box-wall creation by profile extrusion along a plane normal. Mitre joints

The parametric model allows the numbering, flattening and nesting of structural items previous to the CNC cutting process (Figure 3); however, a manual nesting optimization was made to save material and time during cutting. Prior to the production stage, the following machinery constraints are integrated into the parametric model: a) A CNC Güdel industrial 5-axis robot with an ABB controller; b) Robot tools: a 25mm coarse tooth mill and a 15” saw.

These constraints induced changes to the parametric model that match the capabilities of the equipment. For instance, rabbets were forced to a 90º angle because angle cuts in rabbet operations are not possible to do because of the mill-end diameter. Also, the gap between items after nesting was adjusted to a minimum of 50 mm so that the mill-end gets room enough to displace without damaging any items when cutting (Figure 3B).

As a result of the interaction of parametric modeling with digital production, a workflow that sets the process to follow when conceiving and fabricating a structure by parametric and robotic means, was defined (A plywood sheet is processed in about 18 minutes by CNC cutting including fastening to the cutting bed, cutting, numbering, clearing and sorting of items. The cutting interface of the robot, simulates the fabrication routine before launching it (Figure 6C), providing information about invalid cutting paths which can be directly adjusted in the CAM interface without repeating the file exchange process (Figure 6B).).

4. Full-scale prototype production.

The production stage takes into account two more variables: transportation and mounting. Structural components are prefabricated and their size should be adequate for them to be handled, transported and mounted; such final optimization can be made by increasing cell density (which diminishes box size).

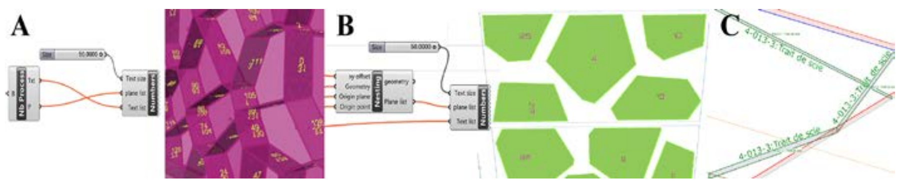

Figure 3. A-On-model tagging. B-Nesting. C-Cadwork BTL instructions.

structures though a schedule optimization was critical. A projection established that the production stage would take more time than available, so a balance between handling and production efficiency had to be found.

The optimization of box density in the structures improved the production schedule in 48 working hours by reducing the grid structure from 60 to 24 boxes and the Voronoi structure from 38 to 18 boxes (Figure 4).

A file exchange is also necessary to obtain the CAM commands that lead to CNC cutting. To do so, a “Step” file exported from Rhinoceros is imported into Cadwork to produce the BTL files (Cadwork and SEMA, 2014) that the CAM interface (LignoCAM) uses to communicate with the robot controller (Figure 3C & Figure 6A-B). Some difficulties emerged since the Cadwork interface did not read some milling operations like acute angles and angled mitres from the imported geometry. This led to manual programming of several BTL instructions.

A plywood sheet is processed in about 18 minutes by CNC cutting including fastening to the cutting bed, cutting, numbering, clearing and sorting of items. The cutting interface of the robot, simulates the fabrication routine before launching it (Figure 6C), providing information about invalid cutting paths which can be directly adjusted in the CAM interface without repeating the file exchange process (Figure 6B).

Despite the fact of using parametric modeling as main tool, the method is not fail-safe yet. For the Voronoi structure, a complication with the mill-end occurred when some items of the Voronoi structure could not be fabricated due to high acute angles in mitres so that manual production or finishing was necessary (Figure 7B&C). After cutting and classifying the items, the boxes were assembled and a mounting test was executed before sending the structural components to the construction site. It took two days to mount the finished prototypes (Figure 8).

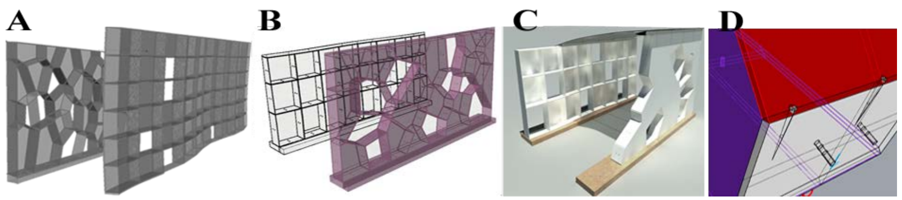

Figure 4. Box density optimization (quad/voronoi). A, 60/38. B, 24/30. C, 24/18.D, Assembly detail on mitre joints. Items are put together by using fasteners and bolts.

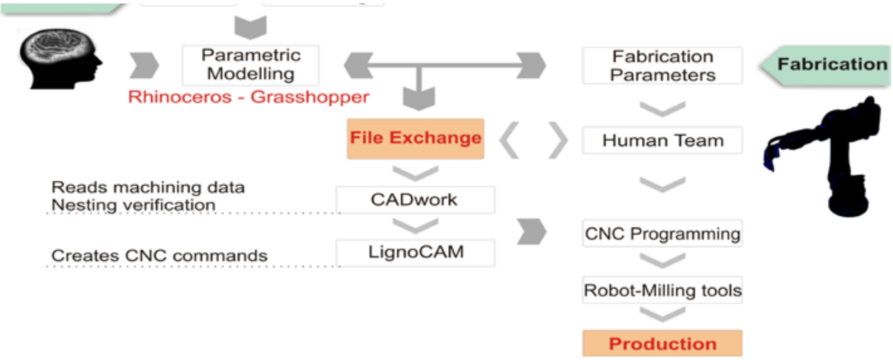

Figure 5. Conception to production workflow

5. Discussion.

We presented a method that deals with the conception by parametric modeling of non-standard wooden walls, suitable for being used in facade rehabilitation projects or as a design tool for new buildings whereby they can get to perform as energetically passive architectural envelopes.

By building two full-scale prototypes we found a series of problems that need to be avoided for this method (and others similar to it) to succeed since parametric modeling manages the necessary data to model and fabricate joints such as mitres and rabbets repeating them over different shaped structural elements regardless of the pattern variations and geometric deformations of the structure of which they make part.

A first improvement should be stop using third-party software to create de CAM routines exported from Rhinoceros to LignoCAM, the loss of information generated with the file exchange proved to be significant and led to several mistakes when reprogramming the prototypes' cutting routine.

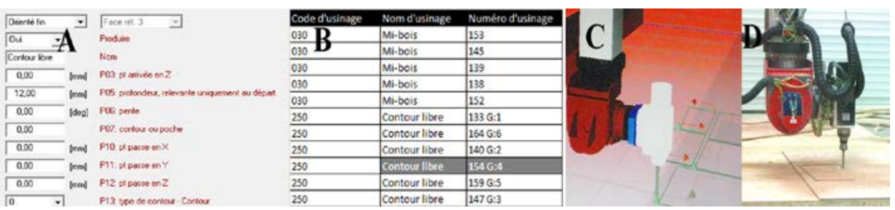

Figure 6. A, CAM commands. B, ISO cutting path table. C, Cutting path simulation. D, CNC cutting.

Figure 7. A, 3d scanned image of an unsuccessful rabbet. B, Mitre joint. Angles not coupling well after cutting. C, Manual correction of mitres and rabbets. D, An item containing both a successful mitre and rabbet. E, Correct coupling with rabbet joints.

In no way the production of these walls should be limited by the capabilities of a machine, so the right set of tools should be available to produce accurate wood-detail operations. In such case, a mill-end of about 8 mm diameter should be used; it would allow performing acute and straight cuts without major restrictions. As time is important too, the human team in charge of automated machinery should be familiar with such operations in order to avoid unnecessary tests and mistakes.

6. Conclusion.

Having tested two joint types, it becomes clear that joinery treatment is a complex task to be performed from the modeling and production point of view. The success of any cellular structure intended for non-standard walls, as it is the case, depends heavily on the joinery conception method, a process that must take into account the production means available for such task.

The results showed herein, regarding the modeling and construction of two cell-patterned wall prototypes as an early research stage on this matter, proved the feasibility of such structures by using basic joint types which leads to think that a more complex approach is possible in order to improve the method, take it to a more practical level and apply it on actual buildings as a facade rehabilitation alternative, which is the next stage of research.

Acknowledgements.

Special thanks for the technologic and human support from the ENSTIB, the Laboratory for Studies and Research in Wood (LERMAB) in Epinal – France and the School of Architecture of Nancy.

Figure 8. Finished wall prototypes. A, Grid-pattern wall view through a voronoi cell. B, Voronoi-patterned wall. C, Grid-pattern finished wall. D, Finished prototypes.

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Analysis and validation of the digital chain relating to architectural design process

Achievement of a folded structure composed of wood panels

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Abstract. The research presented in this paper revolves around the experimental development of the morpho-structural potential of folded architectural structures made of wood. The aims are to develop an innovative system for timber used in sustainable construction and to increase the inventory of wood architectural tectonics. First, this article provides a characterization of the digital chain associated to the development of non-standard folded structures consisting of wood panels. The purpose is to study the architectural design process from parametric modeling (through CNC machining) and assembly operations to production by way of a full-scale experimental pavilion. Secondly, a number of analytical experiments have been performed towards the completion of the pavilion, in order to validate the design process.

Keywords: Architecture, folded structure, robotic fabrication, computational design, parametric modeling, wood panels.

1 Introduction

The term “fold” as used in the field of architecture shows a shift in the designs and vocabularies of contemporary forms. For example, Peter Eisenman has used, for the Rebstockpark project, the fold as a concept of changing forms continuously through time [1] or even Rem Koolhaas for his work on the "trajectory" where folds generate more singularities [2]. The fold is partly based on the theoretical foundations of the philosopher Gilles Deleuze, in which the traditional form and its material relation as a spatial mold, has given way to “a continuous variation of matter as a continuous development of form” [3]. The designed architectural object, takes place in an evolutionary continuum where the parameter variation replaces the constant laws. The “event object” with vast potentials and modulation possibilities is replacing the traditional “fixed monument object”. The fold as a process means an adaptive formalization mechanism. Henceforth, the fold is becoming a conceptual tool to address the realm of contexts and perspectives in architecture.

The practices of digital technology as developed today in the field of architectural design and manufacture have instrumented the idea of a continuous development of the shape. This practice has spread the idea of fold to the production process. The chronological chain, from design to manufacturing, is no longer linear but becomes a series of simultaneous developments and possible variations. As the philosophical concept can operate as an architectural one, the fold becomes a productive concept that can be explored. The emergence of new materials or new components and their relating technicalities makes possible this continuum of shape (de)formation and virtualization on a basis of potential variations of the production tools. It aims, although to a limited extent, is to focus on the fold with respect to its morpho-geometrical dimension and its ability to respond to a fluctuation of contexts and uses. The fold brings a fresh look on the integration of the structural dimension as a modulation factor and allows adaptive modeling within the design-manufacturing continuum. Finally, we report on an experiment leading to the production of a folded structural envelope made of laminated wood panels.

2 The fold

2.1 The fold : a Morpho-structural system

In nature the fold can adapt to local stresses and external forces which will lead to a deformation of the material. The fold can suffer a deformation as in the case of geological folds characterized by orogenesis. It may also be a shaping genetically adapted like palm leaves which fold is formed during the growth cycle to provide it with wind resistance. Generally, the fold provides rigidity while minimizing the material used. For example, we find that this logic of resistance in the field of stamped metal sheet technology is used in the automotive, aerospace and general engineering industrial sectors. In architecture the fold provides many morphological but also structural possibilities. It brings rigidity and inertia as required for the structural stability of the architectural works adopting it. Moreover, by principle, the fold highlights an efficient relationship between the projected area and the material quantity required for the construction. The saving made on the material gives a real environmental dimension to the fold. In addition to the conceptual dimension mentioned in the introduction, the fold provides a genuine tectonics in architecture. This leads to a visual evidence superposing both the clarity of a plastic form, and veracity of a construction design [4] benchmarked against the material and structural dimension of the designed shape. The characteristics of the fold define a language; a source of architectural and structural motion [5].

2.2 The folded material

From a physical point of view, every material can theoretically be folded. But from the viscous to the rigid substance, the folding can result in stress efforts specific to each matter. We can classify a fold by continuity or discontinuity of material.

The continuous material. The fold is commonly associated with the deformation of a thin material surface with a small bend radius regarding the thickness of the material (metal foil, paper, fabrics ...) but it can also be obtained by means of molding technologies. A bending action, which consist to roll back the material according to a determined angle, introduces internal stresses of traction / compression and causes a reduction of material thickness. Mathematically, it is estimated that the tangents at a point of the surface are continuous in all directions. In that case, we can define a minimum acceptable bend radius before the material breaks. Materials with plastic dimension have a maximum degree of deformation. This plastic deformation gives limits to bending radius. However, the disadvantage of this technique lies in its inability to produce big structures.

The discontinuous material. A fold can be accepted as a union of different surfaces. Mathematically it can be defined by the discontinuity of tangents to a point of a surface and in a given direction. The one-time change of direction in physics means an interruption of matter and thus the notion of assembly. A classification of assembly types must be appropriate to the material in use, to ensure continuity of internal its forces. This third method interests us regarding its use on industrial wood panels.

Fig. 1. Continuous tangent (minimum radius of curvature) - Discontinuous tangent (assembly)

3 Fold and Folding models

Our research turns to the use of flat industrial panels for the developing folded wood structures. Currently, an insufficient mastership of the physical wood behavior laws to make panels deformable has not yet allowed an easy use of the material. Hence, we orientate our work towards a technology of assembled folds.

3.1 Study corpus

Applied initially to walls or roofs, folded structures quickly evolve towards arch, portal frame or folded shell. The first two projects present folding structures with continuous material. The UNESCO concrete building in Paris by P.L. Nervi reconnects the dialogue between form and structure [6]. The architectural realization "Corogami Folding Hut" by David Penner reveals folds generated by mechanical bending action in order to obtain a sufficient rigidity [7]. In the environment of wood material several experimental achievements have demonstrated the high potentials of wood assemblies to create particularly inventive architectural design. The pavilion designed by Hybrid Space Lab office in Berlin, consists of triangular plywood sheets sewn together with cable ties [8]. The Thannhausen Music Hall in Germany designed by architect Regina Schineis, shows a regular folding ensuring a portal frame system fixed to a concrete slab [9]. The temporary pavilion in Osaka realized by Ryuichi Ashizawa Architects [10] and the Chapel of St Loup in Pompaples [11] attest wooden folded structures virtues by their structural and architectural qualities. Oriented mono-directionally folds increase the stiffness of thin surfaces. Structurally, these constructions work as a series of portal frames. The Japanese pavilion is equipped with a primary skeleton creating ridge and valley edges and covered of panels in a wind bracing way. Quite the contrary, the chapel wood panels ensure both the architectural envelope and the structural system. Laminated timber panels associated with a "digital production line" approach have opened up new perspectives for the building industry in creating prefabricated wooden structures. Timber panels like cross-laminated timber (CLT), or laminated veneer lumber (LVL) introduce specific features like their availability on large sizes or their high strength even for thin panels. While traditional timber-frame structures use timber panels only for cladding and cross-bracing of beams, new typologies such as Timber Folded Plates use plate-assemblies as load-bearing structures (i.e. Interlocking Folded Plate Structure) [12].

Fig. 2. Interlocking Folded Plate Structure (left) and The Temporary Pavilion (right)

3.2 The fold model

The fold is the unit element of the folding. It consists of two entities called "faces". As part of our work on folded architectural structures made of wood panels, we consider only planar faces. The combination of two faces at a common edge and to the appropriate non-zero angular value, creates geometrically a fold. It is characterized by the notion of amplitude (height of the fold defining its inertia) and the concept of frequency (base of the fold). Folding is the combination of several folds.

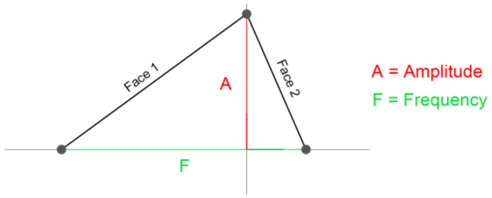

Fig. 3. Model of fold

3.3 The folding model

Architectural typologies concern continuous covering envelopes (vaults) or revolving forms which interest lies in their inherent stability (dome). The shape of the envelope, as defined by architectural criteria, represents the basis of fold modeling. The use of flat panels leads to the creation of break lines during the generation of the folded envelope. These break lines discretize the support skin in planar surfaces matching with the curvilinear morphology of the initial envelope. The fold is then oriented in relation to the normal of the envelope surfaces; it is controlled by parameters of frequency and amplitude of the fold. The folding method defines the disposition rules of peaks and valleys edges according to the normal of the face. Pilot criteria based on the material, structural behavior and manufacturing techniques are associated to these parameters. The choice of material interacts with the rigidity (Young's modulus), thickness of the panels (changing the assembly by nature, reacting to the weight), and the dimensioning of raw panels (modifying the pattern layout and size of the panels). The structural validity is generated by an analysis software that impacts stiffness, folding inertia (controlling amplitude and frequency), and stability (modifying the break lines, assembly stiffness). The manufacturing imposes geometric constraints derived from a Numerical-Control tool parameter settings, such as angular cuts and maximum panel size (weight and size management). Finally, it makes sense to set up a management system monitoring the kinematic impact to verify the feasibility and accuracy of the assembly parameters. The architectural validation will be established by the designer.

4 Digital fold

The current state of the digital chain as proposed in our work consists of a parametric design phase of morpho-structural envelopes associated to a robotics manufacturing phase. The digital design environment is composed by the modeler Rhinoceros coupled to Grasshopper (editor of graphic algorithm for parametric geometric data management) and the finite elements analysis software Cast3M for structural verification. The digital production environment is organized according to the Computer Numerical Control (CNC) machine used.

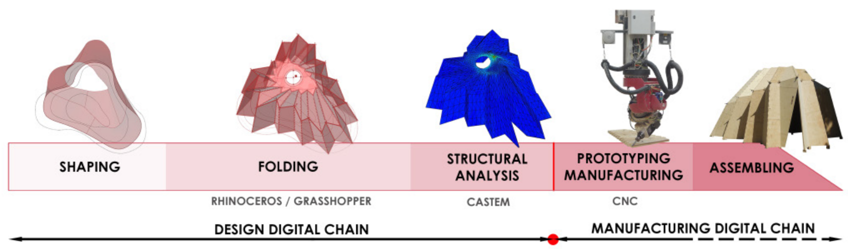

Fig. 4. Progress of digital chain

4.1 Parametric design

The digital continuum is ensured by the creation of clusters so as to generate different command codes. This digital model does not define an optimal solution but is sufficient. Those parameters allow the architectural folded shapes to match as much as possible the satisfactory structural features without deviating from the morphology of the initial envelope.

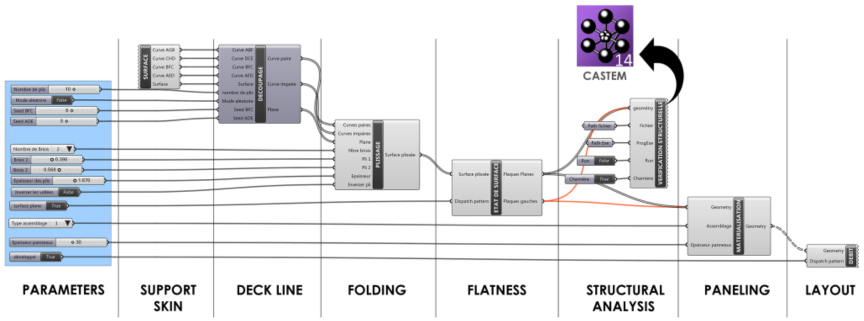

Fig. 5. Digital device of design

Shape Parameters . The "envelope support" is defined by a Nurbs typed curvilinear surface.. These envelopes are characterized by two directions. The first enables a discretization of the initial envelope into a number of configurable break lines, and the second corresponds to the folding orientation. The folding algorithm determines a regular or an irregular grid. It can manage the fold's amplitude by using the normal vector of the faces alternated positively or negatively. The frequency and amplitude parameters are managed through a table of values. The creation of the fold generates two panels of 4 non-coplanar edges; a VBnet script allows the determination of surface flatness with a variable degree of precision. The structure thus adapts to the deformation capacity of the material which requires pre-stressed panels for mounting.

Assembly parameters. When applied to wood structures, each panel has to be assembled. The assembly is defined by the number of degrees of freedom (lineal pivot), as well as by a specific joint method (dovetail joints). The choice of the number of degrees of freedom for stability verification is imposed on us. The modeling of timber structures requires to take joint slips in consideration (refer to paragraph 5.2). The technological part of the assembly leads to a specific production level and assembly kinetics. Currently, kinetics of assembly in the digital continuum is not taken into account. Setting the thickness of the surface model reveals a geometric complication which leads to, in most cases, a duplication of nodes. This problem can be tackled by a local construction feature (obviously by connectors…). Nevertheless, this kind of intervention remains manual thus calling for further reflection on the design.

Structural analysis parameters. The introduction of a structural evaluator using the method of shell type finite elements (Cast3M) enables the validation of stability of the structure and its dimensioning. The meshing (discretized geometry), the materials and the limited kinematic (supports) and static (loads) conditions are commanded by specific clusters (Grasshopper). The structural fold gives inertia to the envelope, brings stiffness to big surfaces with a minimum of material, and stabilizes the structure through three-dimensional combinations. These three mechanic principles of the fold are considered to be the evaluation criteria for structural envelopes. Although the structural analysis has not yet led to automatic modifications effected on the envelope morphology thus data has to be treated manually as a means to interact with the different parameters set out in the morphological modeler.

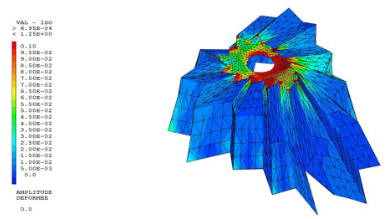

Fig. 6. Deformation structural analysis

4.2 Digital manufacturing

The machining methodology depends directly on the characteristics of the tools used (admissible size of raw wood panels, characteristics of cutting tools, methodology of clamping system, …) and of the material (nature of the material, …). These characteristics make it possible to define the pattern layout of different elements comprising the folded structures. This layout takes into consideration the management of woodgrain and off-cuts to achieve structural optimization. The model integrates an algorithm that numbers the pieces and examines the different elements from all angles by a grid pattern defined on a two-dimensional plan. At this stage, the numeric command necessitates the writing of command lines to enable the generation of tool paths in order to cut pieces according to the pattern layout made beforehand.

5 Experimental fold

The purpose of this experiment is to validate the accuracy of the parameters implemented in the design phase as well as the correctness of the implementation. The experiment takes place against the backdrop of an exhibition known as the “Wood Challenges” [13], where the inventive capacities of wood to deal with architectural, technical, economic and environmental issues of today and tomorrow are demonstrated. This " welcome pavilion” (L=8m; l=5m; h=4m) has been created to test the digital chain of computer design to digital manufacturing.

The envelope support was folded according to the morphological criteria as required by the designer and coupled to the parameters of the material (laminated wood panels 10500mm x1800mm x 40mm) and those of the CNC machine tool (5 axes CNC Güdel machine, figure 4a) put at our disposal as well as the parameters set out from the structural analysis. A dovetail connection system was chosen to process the folding edges and a tongue-and-groove system was adopted to join the panels along the break lines. In order to distribute the structural forces more evenly, a compression ring was added. This type of piece requires manual intervention in the computer model. The digital manufacturing requires several data transfer formats. A STEP standard was used in order to achieve the data transfer from Grasshoper to Lignocam; a BTL standard, provided by Lignocam, is particularly interesting since it takes into account the specifics of wood process; for example, a half lap on a piece extremity cannot be machined in the same way as a longitudinal process. Finally the trajectories generated by Lignocam are transferred to Woodlex gantry thanks to L1E and ABB Robo-studio. The different data exchange formats (STEP, BTL, ISO and RAPID) evidence a risk of breakdown in the continuity of the digital chain.

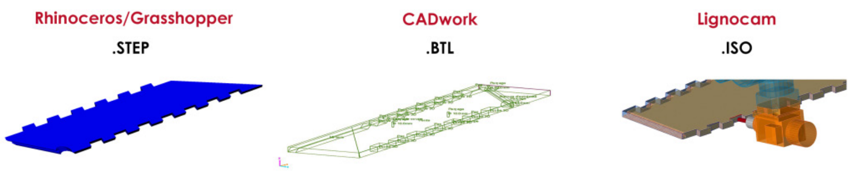

Fig. 7. Data transfer formats

The production process included the cutting and machining of 57 wood pieces. The problematic of raw panel constrains a specific clamping method needing a double positioning of wood pieces. So clamping system has been divided into two steps. First, a nesting procedure is necessary before placing drillings over the raw timber panel in order to locate the pre-machined items at their correct position. After doing so, each pre-milled panel is finished and a mounting test is performed at the workshop in order to check the installation kinematics and joint gaps.

Fig. 8. Digital device of manufacturing and Assembled structure.

5.1 Characteristics of assemblies

Technological choice of connections. A twisted dovetail joint might be sufficient for assembling the structure [14]. However, the assembling kinematics selected, linked to the difficulty of handling such heavy panels, required the use of two different joints; the dovetail defined in the project does not allow a complete panel blockage, so a tongue and groove system was used to lock each panel.

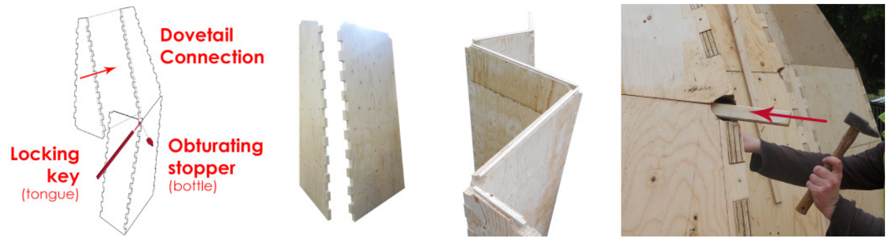

Fig. 9. Woodworking joints

Structural characterization of connections. Each assembly is defined by a junction family (dovetail, tongue and groove, ...). A parametric and geometrical definition of assemblies in Grasshopper software allows the manufacturing of these assemblies. The assembly is modeled by its connection type (linear pivot) in a finite elements shell type software (CAST3M). Each assembly is represented by a coupling of different degrees of freedom (3 translations and 3 rotations) and is defined by the stiffness corresponding to the joint slip (1 joint slip per degree of freedom). This coupling is implemented in the finite element analysis software by a stiffness behavior associated to its technological landmark.

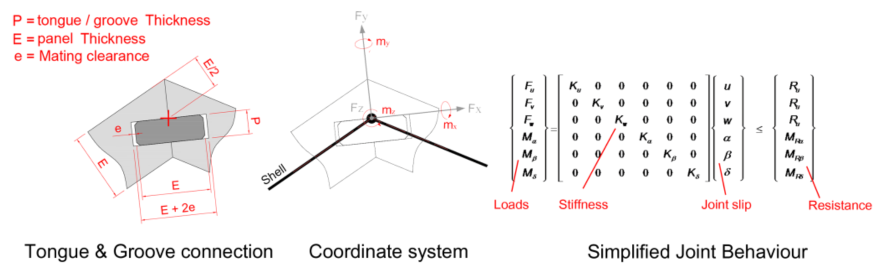

Fig. 10. Structural characterization of tongue and groove assemblies

5.2 Morphological and structural validation

The morphological analysis is done in two steps. Firstly, the morphological analysis helps validating the lassergrammetry work performed on the piece after milling it, giving us information about the dimensional error in percentage between the numerically modeled piece, and the processing panel piece (5%). This error is due to a lack of precision in the robot's movements and also the positioning of the tool holder. Secondly, the analysis is to validate the assembling methodology with the complete use of lasergrammetry for structure assembly, so as to analyze the morpho-structural impact of dimensional deviations on each assembled element (average precision 1/1000). These errors are the result of an incomplete imaging linked to the scanner, manual cleaning of specks and spots, scanner precision and hygrometrical behavior of the material used. By examining the tolerances in traditional wood construction, we find this to be an exceptionally low value. This precision fulfills the necessary and sufficient conditions for the machining precision process to be validated and the assembly protocol confirmed.

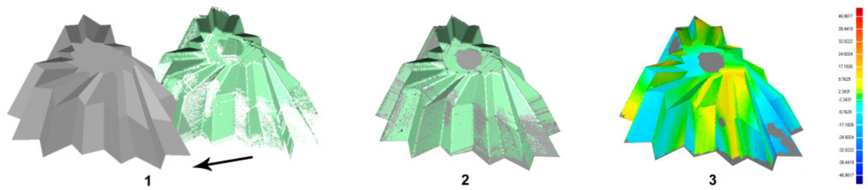

Fig. 11. Morphological analysis by scanning

The experiment is to replicates the effects of a specific vertical load and the effect of wind on the structure by lateral traction. To identify the structure's experimental stiffness (Ks), the displacement ratio of structural nodes was measured by using mechanical sensors and lasergrammetry devices.

The structural validation is performed through backward reasoning. In order to adjust the joint slip variable in the numerical model the conditions of the experiment were simulated in the finite shell elements calculation software (CASTEM). Parameters concern elastic properties of the material (Young's modulus for dry wood) and the stiffness of assemblies. These, define a relaxation of the degrees of freedom, as well as the internal joint slip of the assemblies (relative movements between two assembled pieces). To confirm the correctness of the parameters, we compared the overall digital behavior of the structure with the results of the experiment. The elastic behavior obtained during the loading phase corresponds to a structural accommodation cycle. Analysis and experimentation thus rest on the stiffness obtained during unloading, which becomes purely elastic. At the same time, this experimental loading was simulated on finite elements calculation software to define a digital elastic stiffness of the structure (Ks) depending on joint slip according to an assembly stiffness (Ka) with an enterprise value of zero to (+) infinity. Against the data obtained from the calculation software, the digital model of a perfect assembly is ten times superior to the experimental value found. It is therefore necessary to take assembly shifting into account. It can be stated that the assemblies correspond to a lineal pivot coupled to stiffness [15]. Experimental structural stiffness obtained by unloading is plotted on the curve (Ks as function of Ka) to define the assembly stiffness of the folded structure. The value of the stiffness obtained is relatively low.

This is due to high humidity present in the wood panels. Important work on assemblies still needs to be done. By playing with different assembly typologies and technologies (connectors, gluing, etc.), the stability of structures can be increased.

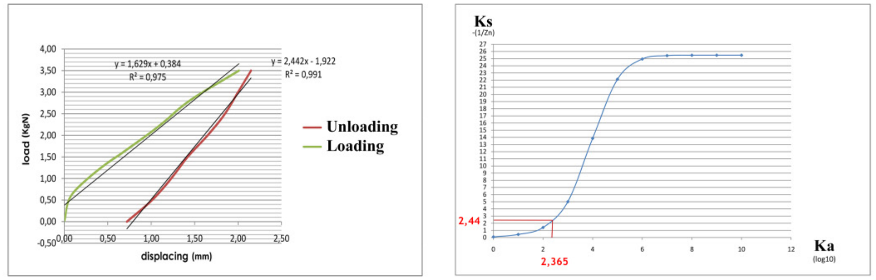

Fig. 12. Experimental stiffness (left) - Ks as function of Ka (right)

6 Conclusion

The fold is part of the new architectural design languages. The digital dimension participates actively in this morphological quest and is today a basic of architectural research. In our work, we tried to outline a first numeric controlled design tool whereby the folded structures under study are considered to be architectural "objectiles" [16]. Technical variables (structural analysis, manufacturing, erecting and materiological) integrate the architectural design genesis. In the context of the fold as a formalization process, these variables lead to a geometrical fold (re)configuration in order to find an acceptable form.

Nevertheless, the numeric continuum is incomplete. Several actions require a manual intervention, notably in the return of results of the structural analysis, data management of the tooling and the installation phase. The experiment, as conducted, allows us to validate our digital design tool and digital manufacture of folded structures made of solid wood panels. This pushes us to further pursue our work in the automatization of geometric correctors and optimization of the digital chain.

One possible perspective of our work consists of developing the assembly by robots. Its usefulness lies in the development of alternative construction techniques ensuring transposition of industrial manufacturing technologies by combining prefabrication and production advantages [17]. Our morphological study on the theme of fold, and its derivative towards folding, is presented as a possible solution to an architectural production assisted by digital technology, as Lynn [18] or even Cache has conceived. The interest of the dynamic flow of morphological genesis with literally complex structures does not lie in the shape obtained, but in the technological process itself. This digital approach, leading to new practices, requires special training in order not to lose the scope of skills acquired previously.

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THÈME 5

Approches pédagogiques et professionnelles

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Cet article constitue un retour sur six années d'expérimentations pédagogiques menées en France et en Belgique au sujet de l'enseignement de la modélisation et conception paramétriques. Ces résultats ont abouti à un processus pédagogique avancé, adapté à l'enseignement de la pratique architecturale.

La plupart des agences d'architecture en France sont assez petites (2-3 personnes) et réalisent des projets de petite et moyenne taille. Elles ont également souvent une utilisation assez limitée des outils numériques et de la modélisation des bâtiments (BIM). La question de la transition numérique pour les projets d'architecture est de plus en plus abordée, mais les exemples et expérimentations réalisés avec des petites agences et des petits projets restent assez rares. Dans cet article, nous présentons une expérimentation concernant des échanges de maquettes numériques réalisés entre une petite agence d'architecture et une entreprise de charpente.

Les pratiques de projet autour du BIM nécessitent une bonne compréhension des différents modèles du bâtiment impliqués (maquette numérique, BIM). Cet article présente une expérience pédagogique, mêlant la modélisation paramétrique et la modélisation conceptuelle, dans le but d'analyser et de décrire les différentes notions caractérisant ces modèles avec les étudiants. L'objectif de cette sensibilisation est de leur offrir une meilleure compréhension des enjeux des différentes pratiques (modélisation, coopération, etc.) autour d'un outil BIM.

Parametric Modeling: An Advanced Design Process for Architectural Education

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The first part of this paper is giving an overview, experimentation results and feedback of a six years experience of parametric design education in schools of architecture from France and Belgium. The second part addresses a structure of an advanced educational process of parametric modeling able to support architectural design praxis.

Keywords: *Parametric design, Digital design, Form generation, Digital fabrication*

INTRODUCTION

Parametric geometry modeling is a field studying algorithms that compute geometry (Kelly 2013). A major barrier concerns the level of effort necessary to implement the algorithms: "the task is foremost, the tool need only be adequate to it" (Woodbury 2010). Since 2003 and the release of a new parametric software like GenerativeComponents [1] or Grasshopper [2], the conceptual representation containing the algorithms can be achieved through visual dataflow programming language (VDPL) dedicated to 3D modeling. The amount of abstraction between VDPL and machine language is high enough to allow non-programmers to implement complex parametric 3D models. Users with basic knowledge of geometry 3D modeling can specify a sequence of relationships and operations to automate the construction of geometry in the form of links and nodes. They do not require any textual programming skills whereas they can achieve the creation of complex 3D parametric scenes in short time span and "efficiently explore alternative forms without having to manually build each different version of the design model for each scenario" [3].

OVERVIEW OF PARAMETRIC MODELING EDUCATION

The first part of this paper is giving an overview, an experimentation results and feedback of a six years experience of parametric design education in schools of architecture from France and Belgium. The second part addresses a structure of an advanced educational process of integration of parametric modeling and digital continuum able to support architectural design praxis.

Cognitive operations and design thinking

After the first digital age defined by productions such as *blob*, developed by the use of animate form (Lynn 98), we attend an evolution of production, tools and methods in digital architectural design. Among the different tendencies on digital architectural design, the parametric way has a specific place. Parametric modeling led to the development of a model that is not a single object, but the potentiality of a family of objects called instances. As teachers, we often attend to the same situation: at the end of the parametric design studio, some students cannot identify how they arrive to the solution. The main reason seems to be a gap between the knowledge application and the skills trained during the lessons. In fact, the most important problem is the lack of knowledge and skills about digital design in general and specifically about the digital design in architecture. The theoretical aspect of architectural design is still on a traditional way.

Education context and technological mutation

As we know, the last fifteen years are witnesses of a mutation of the architectural production through the improvement of digital design and fabrication tools. It is now more and more possible to overtake a situation noted by A. Picon (2010) about the rupture between free-form seduction and tectonics . This evolution is mainly due to a methodological threshold, which enables the integration of computational processes like parametric in the core of the architectural design process. We also attend an evolution of the structures closely linked to the matter and the continuity namely digital data transmission in the "design to fabrication continuum" of building elements, indeed the whole building process. To meet this transformation, teachings, should integrate a computational approach both theoretical and practical allowing the student to acquire a culture in contemporary architectural practices, knowledge and parametric modeling capabilities and reach an experience in the "design to manufacture continuum". At the practical teaching of the parametric, the crux lies in the transition from paper sketch to the parametric structure (Couwenbergh 2015).

Design pedagogy and digital design concepts

More precisely about the architectural design thinking, we have to point an essential notion: there are significant differences between traditional architectural design and the digital mediated design. We can say the digital design constitutes a unique body of knowledge and architectural concepts (Oxman 2008). Many researchers have proposed as a foundation for design education and pedagogy that digital design has an influence on the development of theoretical, computational and cognitive approaches. Seven years ago, R. Oxman wrote that "any new framework for design pedagogy must be responsive to condition in which digital concepts are integrated as a unique body of knowledge consisting of the relationship between digital architectural design and digital design skills". Designing and modeling free-form surfaces and curves as building elements that are associated with different components and have multiple patterns are not an easy job to do with traditional methods. This is the power of algorithms and scripts that are further pushing the limits (Khabazi 2010). Custom CAD tools are examples of lowest algorithmic level in design, and the parametric modeling skills are not capable enough. High level of parametric modeling skill means using the computational power in a design process. It is obvious that even to think about a complex geometry, we need appropriate tools, especially software packages, which are capable of simulating these geometries and controlling their properties. Before training these skills and using such tools, there are a few elementary theoretical basements to teach. As a first step in the education of digital parametric design, the historical approach is paramount to provide context on the one hand and on the other to highlight the concept of parametric, which existed long before the arrival of the computer. It is necessary to first address to the origin of the terminology (parameter and parametric) questioning the history of science (Apollonius , Newton, Pascal, etc.), then take a look at its use in the arts (Dürer, etc.), architecture (Gaudi, Moretti, etc.) and structure (Frei Otto , Sergio Musmeci, etc.) (Couwenbergh 2015).

Parametric digital modeling

As we know, the defining feature of a parametric model is not the outputs but rather the need to construct and maintain relationships associated with the model. Some researchers develop this approach as the creation of process instead of formal product. In this design model, the visual representation is not a direct production from hand but appears as the result of a computational process in which the user has to manipulate geometrical concepts through a program (visual or textual). The student has also to be aware that the parametric model is defined by a set of heterogeneous elements (geometric or positional numerical constraints) put in relation to form a coherent whole (de Boissieu 2013) and the design logic of the model creates the complex relation sets as a network of associations (Oxman and Oxman 2013). Another topic, consequence of the latter subject is that the result of the computational modeling process is not simply a shape or an object but provides the possibility of a wide (or infinite) space of design solutions. The output variations can be achieved by the variations of the parameters included in the schematic structure of the model. In this way of thinking, we can say that the design method comes out of the linear and vertical design process only controlled by the architect. Every specialist steps in the first stages of the architectural project development. The last important prior information for the lessons is that the designer himself decides what parameters to use and what the range amplitude of the variations is the most relevant. In the next section of this paper, we will expose in our respective education how we explore different methods about construction of parametric design models and their outcomes, like the passage from sketch to logic model schema, the integration of material and structural constraints, or for example the capability in shape versatility.

AN INTEGRATED PARAMETRIC MODELING EDUCATION METHOD

The second part of this paper proposes a process of integration of parametric modeling and digital fabrication in architectural to support design praxis. The proposed process is a result of our experience in parametric modeling education and research in digital design praxis. The proposed process is structured in three steps: analyze, implementation and experimentation. This process associates digital design and fabrication tools to physical representation and modeling tools as freehand sketching and makeup realization (Sanguinetti and Kraus 2011). It combines also mathematics, non-Euclidian geometry, fractal design and design knowledge to create a design process by iteration. This educational approach gives the opportunity to students to apprehend the many application fields of parametric modeling that go beyond the expected framework of algorithmically generated forms.

ANALYSE STEP (MULTI-LEVELS)

A parametric model is based on both an explicit representation of an object and a conceptual representation containing the parameters and the operations (Agbodan et al. 1999). It is a dual structure, with on the one hand the geometric shape and on the other hand the algorithm. But to implement the algorithm that in turn will compute the geometry, it is first necessary to analyze the intended shape in order to identify its parameters and the generative operations. The analyze step starts by the definition of the geometric, physical and logical operators and the entities characterizing the different features of the intended model. This process is based on the formalization of the geometrical knowledge required to design the parametric model. At first, the concepts of the field under study have to be named, structured and prioritized to aid in the organization of the knowledge of the domain. It defines a model that is a synthetic and abstract representation of reality allowing a better understanding of it in the context of a determined purpose. This knowledge model identifies and defines every feature of a shape and its relationships with other features. Knowledge has to be modeled in order to make explicit the geometrical constraints (i.e. the relationships) that govern the spatial properties of the entities (i.e. the features) and linked them. Only then it is possible to develop the design rules that generated the final shape. Moreover, once the geometric knowledge of the studied object is modeled, it can be enhanced with semantic knowledge such as physical properties (acoustics, lightning, etc.) according to the purpose of the project (analysis, simulations and manufacturing). The analyze step is supported by sketching activities. Sketching as a free-hand drawing activity helps students to quickly represent the different step characterizing the modeling process (Schon 1984). They use it also to identify and characterize the major entities (geometrical, logical) used to materialize these steps. Using sketches, student can analyze the modeled object features and imagine different ways to create a parametric model of the aimed object (architectural or structural issue) (Gallas and Delfosse 2015).The drawing, the modification and the annotation of the sketching activity create an iterative process that supports the optimization of the parametric model (Sanguinetti and Abdelmohsen 2007).

IMPLEMENTATION STEP

Architecture students are not intended to be expert on programming. They may, however, be considered as end-user programmers who "write computer programs to satisfy a specific need, but programming is not their primary job function" (Lewis et al. 2009). Since 2003, visual programming languages have become popular among design communities as they allow students to focus on the problem solving activities rather than on the syntax of the programming language (Giordano and Maiorana 2015). Thus modern CAD tools are very similar to flowcharts. They share a visual program syntax that uses geometrical symbols to map the flow of relations from parameters through operations, decision, etc. (Marttila-Kontio 2011). In CAD, designers have to switch between the programming environment and the model view several times to make even the most simple modifications and evaluate their effects on the model, which results in a loss of focus and efficiency (Maleki and Woodbury 2010). The duration of the definition and the transformation of the parametric model depend on the designer knowledge level of parametric modeling method and tools. Experts users can reduce time spend on the parametric model generation and more focus on the design activities (supported by the generated parametric model). For novice uses, modeling activity is considered as an additive constraint that influences the design process. They spend the most part of their designing time to create the parametric model and not to operate it to support the design process. We propose a method (materialized by a physical device) to support the translation of the parametric model generation steps resulting from the analyzing step and materialized by sketches. We create a physical device called *parametric puzzle* integrating rectangular components (tabs) that describes the major geometric and logical entities used to describe the modeling process. Designers are asked to translate analyzed sketches representing the parametric modeling steps into a physical algorithm workflow very similar to flowcharts. This method allows a high level of modification and evaluation of the parametric workflow breaking away from the complexity generated by parametric modeling tools. Designer could generate different workflows and modify them to define the most optimized approach (using less number of entities and operations).

EXPERIMENTATION STEP

Parametric modeling is often used to design and explore new architectural and structural solutions characterized by a high level of complexity. To achieve this task, the designer needs to evaluate the generated instances behavior and their ability to support design constraints. The evaluation results helps designer to select the most pertinent solutions and by the way the most pertinent model parameters. The first experimentation level is a virtual evaluation realized using simulation tools and algorithms linked to the parametric model. The association of the parametric model and the simulation tools creates an iterative process structured on three activities: propose, evaluate and assess. Using the iterative process, the designer can integrate different design constraints (translated in logical, geometrical and physical operations) and propose a collection of optimized configurations. The second level of implementation aims to evaluate physically the behavior of the generated solutions. It is a confrontation step with the physical and material reality of the designed object. It help designer to determinate if the designed object could support the real constraints. The material experimentation is implemented by the realization of the project (or object) components and the evaluation of their behavior. The use of physical models and mock-ups is one of the most pertinent technics of material experimentation. Designers can visualize and physically evaluate if the designed object satisfies their intentions and verifies all the design constraints. They can modify and transform the physical model to ameliorate its performance or integrate new constraints. By this way, physical object is used as a design support device that influence and modify the parametric model to integrate the new features. The experimentation step is the lowest abstraction level of the parametric design process. At this step, the designer has all the information about the modeled object and its modeling process. These information are progressively defined through analyze and implementation steps. In the next part of this paper we will present some of the pedagogical experiences integrating (at different levels) this parametric modeling method.

METHOD IMPLEMENTATION

The presented method is integrated in different courses and workshops of digital modeling and fabrication from three European universities. We present the courses structures and purposes and how parametric modeling is integrated. The first institution is the faculty of Architecture of the University of Liège (Belgium) proposes for the fifth consecutive year an optional course in expression and communication, worth 2 credits within the framework of a two-year master program for Architecture. The course based on a previous experience developed from 2003 to 2005 (Bianchi and Defawes 2005), is intended to develop themes relating to formal and material research as part of the approach to architectural projects: it combines, digitally, the emergence of form, its control, and the media devoted to the materialization of designed objects (in their broadest sense). This relevant approach is reflected in the use of tools, which can aid design and lead to increased control over the project. In addition, the use of design assistance tools offers methodological opportunities.The analyzing step is supported by the integration of mathematical theories behind the research of architects concerned. The mathematical theories help students to define the morphological structure of the modeled object. The integration of mathematical concepts gives to students an analyzing context that simplifies the definition of the geometric operation and entities structuring the parametric model. The courses continues by introducing the students to the use of programming language used in the chosen modeling tool to generate complex 3D forms and to control them. Students learn to manipulate standard commands in architectural software packages, with a view to creating complex geometrical forms. The example integrated below (see figure 1) shows how parametric equations of wellknown curves are integrated to define the project concept and the parametric model features.

The second institution is the school of architecture of Nancy (France) that combines for the sixth consecutive year parametric design courses and a five-day workshop within the framework of a graduate program in digital culture for Architecture (Shadkhou and Bignon 2009). The course is indented to deepen the knowledge of students of methods and

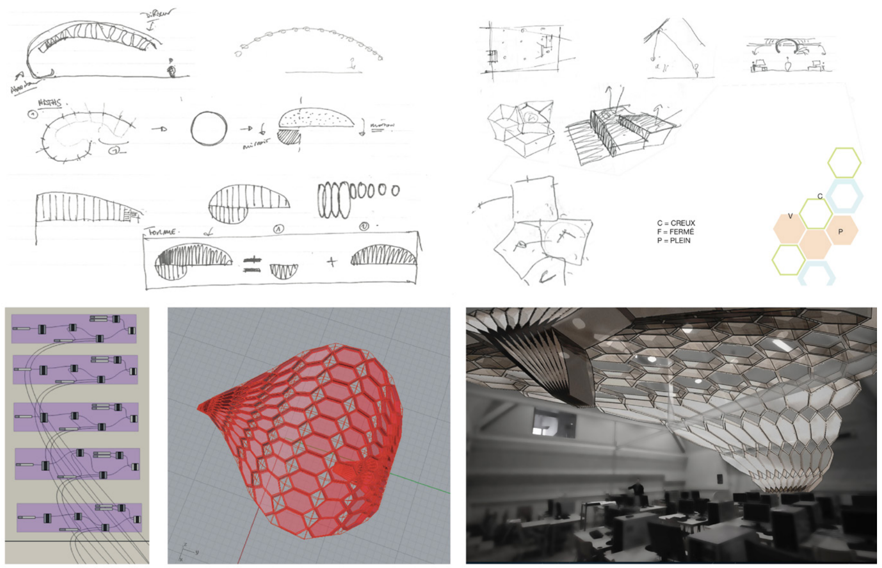

Figure 1
Example of student's work using mathematical functions to generate the project shape

digital tools in computer-aided design through the use of new generation parametric techniques based on visual programming (Grasshopper). The workshop of digital design and fabrication, flowing the courses, is the spearhead of parametric education in the program. It tries to experiment contemporary architectural practices (non-standard architecture design and complex shape generation) using parametric modeling, 3D printing machines and digital fabrication devices creating a digital continuum from digital file to physical object (Marin et al 2009). The workshop creates a design process to enhance architectural shape exploration and materiality by using parametric modeling and digital fabrication tools. The students use a reference object (from the nature) as a base model to design an exhibition space. They identify the formal structure of the reference object and represent using sketches. The students use the identified structure to propose an architectural solution and materialize it using parametric modeling tools. The designed response respects the functional and material constraints explained at the beginning of the workshop. The sketches (see figure 2) are used as a design tool to materialize the designed solution and define its different modeling steps.

In this way, the students participating on the workshop use simple paper model and more elaborated mockup to experiment the generated parametric model structure. They use the physical model to determinate how to join the project components. The result of this first experimentation was integrated in the parametric model by adding new geometric functions generating the assembling system. A second virtual experimentation based on 3D modeling help students to validate the assembling system and to start the fabrication process.

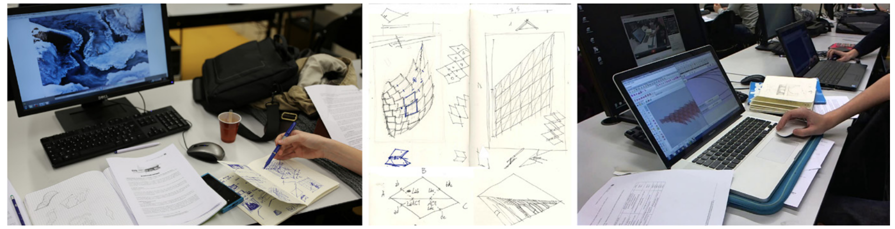

Figure 2
The use of sketches as design and implementation media

The Faculty of Applied Sciences of the University of Liège and its Engineer-Architect Department (Belgium) integrates parametric modeling as a part of Computer Aided Design courses. We propose a design exercise where students used parametric modeling tools to generate original forms integrating structural and construction constraints (create an interaction between structure and form). It combines, digital tools for modeling and fabrication tasks, and physical tools for the parametric analysis process. The analysis step comes before the modeling one to help students to focus on parametric model structure and features and not on the use of the modeling tool (Davis et al. 2011). We use the *parametric puzzle* (see figure 3) as a main device to analyze the designed object and define the main parametric modelling steps. We imagine the parametric modeling exercise as a reverse design process. The process starts by analyzing a physical model (mock up) representing a pavilion with a complex structure shape. They identify the structure components and tries to imagine how they could be designed. Sketching activity is used to

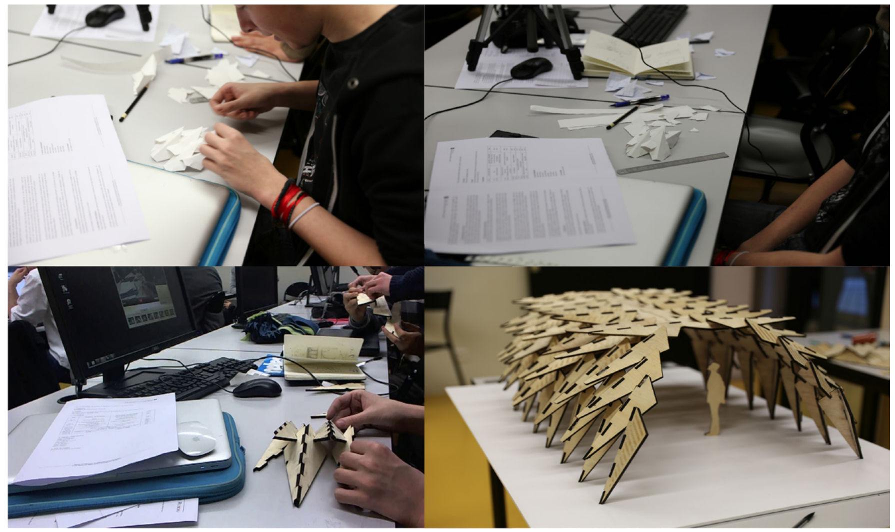

Figure 3
Physical model experimentation and mock-up realization

represent modeling process steps as a high-level abstraction activity.

The defined modeling steps are materialized using the *parametric puzzle* components. The students used it to translate the sketches in as graphical algorithms integrating geometrical and logical entities as a middle-level abstraction step. The device helps them to generate different ways of modeling and to select the most pertinent. The last step of the modeling process integrates the translation of the graphical algorithm using physical components to a graphical algorithm using Grasshopper components as a low-level abstraction activity. The use of the *parametric puzzle* as a parametric design device help students to create different levels of abstraction during the parametric modeling process.

CONCLUSION

This paper presents an advanced design method adapted to pedagogical architectural design context. The proposed method is structured in three major steps: analyze, implementation and experimentation. We integrate different pedagogical devices to support the proposed method activities. The method activities and devices were evaluated in different design contexts to determinate their efficiencies.The evaluation of the project realized with students from the Faculty of Architecture of the University of Liège (Belgium) shows that the integration of the mathematical theories during the analyze step helps them to define the structure of the designed models (not only the project form). The designed models are well optimized generating controlled forms and including reversibility functions.The use of the *parametric puzzle* device was experimented during the digital modeling courses of the Faculty of Applied Sciences of the University of Liège (Belgium). The group of students using this device understands quicker the parametric modeling method and how to use it in real design context (compared to students from precedent years). They use this process to analyze other complex design context and to define

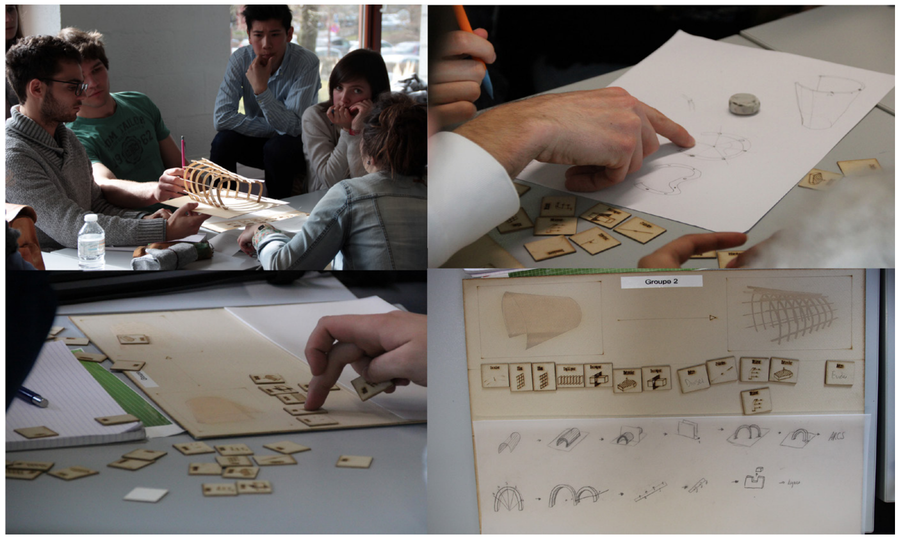

Figure 4
Students using the parametric puzzle device to define a parametric modeling process

(quickly) more efficient parametric models.The integration of the prototyping devices during the experimentation step helps students to integrate material constraints during the design process. This process was experimented during the digital design and fabrication workshop organized by the School of Architecture of Nancy (France). The evaluation of the designed projects and the design process shows that the integration of experimentation activities and devices create an exchange between design and material. This integration process generates new design solutions and a new materiality. This method is part of a global research work that aims to enhance the integration of digital design aid methods to create a digital continuum from concept to physical object. The next step is to define an optimized process for the integration of the digital continuum in design studios.

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BIM Implementation in SMEs: an Experience of Cooperation between an Architect Agency and a Carpentry Firm.

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Abstract:

Most of French architectural agencies are formed by less than 3 people. Architects are generally attached to both traditional knowledge and architectural processes. Thus, BIM is sometimes perceived in France as a disruptive technology that could negatively impact the architect's work. Usually, construction projects featured as BIM projects are often too large and out of touch of small architectural agencies. This situation does not allow them to assess BIM advantages for their daily work. This context and the current strained economic situation of the AEC sector make difficult the integration of new BIM practices in small architectural agencies.

The experience we made is a first step for the definition of a progressive appropriation method of BIM practices leading to a better comprehension of the contribution of these technologies in French architectural agencies.

We experienced a digital mock-up (DMU) exchange between a small architectural agency and a carpentry firm with an engineering consulting department. The architects from the agency have recently begun working with a BIM software program: ArchiCAD. They are very skilled users of Autocad and 2D drawing but have a good understanding of BIM modelling potentialities. According to the model of Succar, they are still in the transition between Pre-BIM and the first stage of BIM level maturity. The particularity here is the alignment between architects choices and engineers decisions who want to solve together errors generated by the traditional process. This context is favourable for implementing and experiencing BIM stage 2.

In this paper we present the context of the experience, the used methodology, the BIM implementation and finally the different encountered exchange problems and the brought solutions.

Keywords: BIM, construction, IFC sharing, carpentry, architecture, experiment, SME, digital mock-up, DMU, ArchiCAD, cadwork.

1. INTRODUCTION

Despite of all the examples of projects which show the advantages of a digital Mock-up (DMU) exploitation not only for clients but also for architects, some architectural agencies are still sceptical about BIM. French Architects are attached to both traditional knowledge and architectural processes. Therefore, BIM is sometimes perceived in by them as a disruptive technology that could negatively impact the architect's work. In France, we see more and more demands coming from public and private clients which want architects to deliver them a digital Mock-up (DMU) of their project. But if some architects (early adopters) are already able to produce it, they don't take all the benefits from this DMU production. Thus, this transition practices toward BIM in order to meet expectations of the clients is considered by architects as an obligation: the change is forced. Let us regard how the change factors can be considered by implicated actors.

1.1 The change factors : the unfreeze-moving-refreeze theory

Kurt Lewin demonstrated that the stability of human behaviour is based on the balance between several forces: status quo, psychological safety and survival anxiety (Burnes, 2004). When these forces are equilibrated, the situation is "frozen" and there is no need to change. According to him, change can't be initiated without destabilizing this balanced state: this is what he calls the «unfreeze» step.

It is exactly what's actually happening to architecture agencies: survival anxiety increases because architects feel that they will have to integrate BIM technologies to stay competitive. But "staying alive" must not be the only benefit of change, and even if some architects perceive the "state of emergency" they are not necessarily ready to take the plunge. The unfreeze step only creates motivation to learn: it's a path toward change.

Lewin also demonstrated that the change has to be followed by a «refreeze» state. During the change, everything is unstable, and if we want changes to last in time, we need to stabilize habits and find a new stable state.

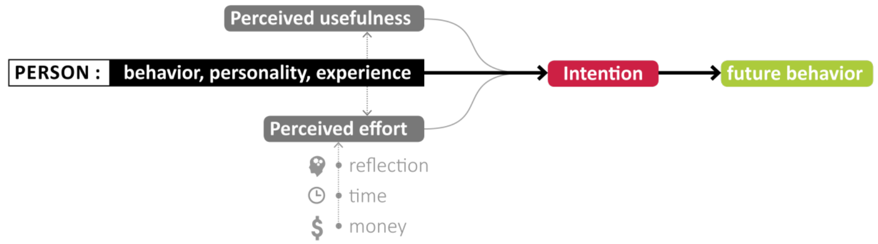

Figure 1. Personal factors that influence the intention to integrate a new technology; inspired from behaviourists models (Venkatesh et al., 2003), and the Lazy person Theory.

The "Lazy person Theory" (Tétard & Collan, 2008) is a theory that integrates the main behaviourists results as the Theory of Planned Behaviour or the Technology Adoption Model. According to these models, the acceptance of a new technology partly depends on the perceived usefulness of this technology and the effort that people think they have to make for the change (c.f. fig. 1). They also demonstrated that people always tend to try to make little effort: that makes change difficult.

The "unfreeze" step make people see the necessity of change, because they perceive the usefulness of it. But that is not enough to intend the change: they also have to find a balance between the perceived usefulness and the perceived effort for change.

1.2 EXPERIMENT change in small architectural agencies

A two architects agency wants to set up a DMU exchange process between their agency and a carpentry firm they often work with.

They solicited us spontaneously, it means that they already perceived the usefulness of using and sharing their DMU: unfreeze already occurred. Nevertheless, they considered that they need someone to work on this project because they have to give all their time to regular projects: the effort to make was considered too heavy.

We set up a first experience organized around two research Master student internships in order to absorb the three types of effort we previously identified (c.f. figure 1). One student worked at the agency, and shared his time between architect tasks and research tasks: his experience as an immersed architect was precious to collect information about the work practices of the architects. This student designed a first BIM model of the chosen project of the experimentation. This internship absorbed a part of architect extra-work and then reduced the reflection and time effort for the agency. The second student worked at the research laboratory to identify tools, methods and theories that could be useful for the operation. He also defined an usual method to guide the exchange practices on the 3D model designed by the agency student.

2. A METHOD FOR ADAPTED BIM INTEGRATION PRATICES

We first studied the needs, wants and demand of the agency to better understand our mission and to be able to situate their BIM maturity level. We also studied the BIM Project Execution Planning Guide (CIC, 2010), and adapted it in order to set up a method that matches our specific case.

2.1 Architecture agency and carpentry firm demand

Our approach takes into account the statement formulate by the two partner structures highlighting the boundaries of the actual data exchange model (c.f. fig. 2). Thus, as of today, architects were drawing their projects in 2D (Autocad) and were sending DWG files and paper plans to the carpenters. Then, carpenters use these documents as a basis for their own 3D modelling with their business software (cadwork). Two types of files result from this model: internal files, to produce the projects elements with CNC machines and the graphical files allowing architects to check the architectural and technical compliance of the projects. We can remark that this exchange scheme presents two data discontinuities in its global process (materialized by a cross in the figure) which cause interpretation and re-drawing errors. Furthermore, the graphical language used by one partner contains some specific points which are not directly understandable by other partner and then strengthens the previously identified types of errors.

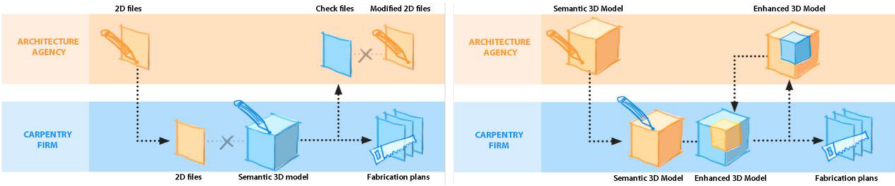

Figure 2. Actual data exchange process (left), and intended data exchange process (right)

The architects recently acquired a BIM software that allows them to draw in 3D and use semantical building objects enriched with construction information (ArchiCAD). Thus, they manipulate an enriched 3D model, from which all the 2D documents (plans, sections, elevations, etc.) are automatically generated. Now architects are able to create a 3D enriched model, so the process step where the carpenters realize this enrichment becomes redundant. This highlights the need to set up a new exchange process (c.f. fig. 2.). One of our main goals is to achieve an interoperable 3D enriched model that carpenters are able to manipulate and complete. After that, the model is sent back to the architects for validation. In this new exchange process, model discontinuities are no longer observed, avoiding the previously mentioned errors. This exchange process also allow a better handling of the changes during construction phase by a virtually overlaying in the 3D enriched model of geometrical objects of both companies.

The potential benefits obtained from this new exchange process are:

- time gain related to the suppression of the modelling step for the carpentry firm.
- reliability gain for the architects, with the automatic generation from one single 3D model of all other documents,
- legibility gain for both companies, with the use of an unique model that avoids wrong interpretations after data exchanging,
- errors risk minimization thanks to virtual checks.

2.2 BIM maturity of the experiment

According to the Bilal Succar BIM maturity levels model (Succar, 2012), the architects concerned in this experiment have achieved the BIM maturity stage 1: an object based modelling. With this experience, they want to reach the stage 2: a model-based collaboration. According to project phase concerned by this experiment, it is important for us to determine the Level of Detail (LOD) of the shared DMU to determine data we'll have to manage. In France, Le Moniteur worked on the description of the information that should be included or needed in a DMU for each project phase according to the French standards and laws (Le Moniteur, 2014). As the experience concerns a carpentry firm and an architecture agency, we will work with a DMU situated between the French level of detail ND3 (*Niveau de Développement*) and ND4, corresponding to LOD 300-Precise geometry, and LOD400-Fabrication.

2.3 BIM project implementation

The BIM Project Execution Planning Guide (PEPG) is a structured procedure for creating and implementing a BIM Execution Project plan. It includes four main steps (CICRP, 2010):

- STEP 1: Identifying BIM Goals and Uses: for example if one of the goals is "managing construction", the BIM use could be "make a 4D simulation".
- STEP 2: Design BIM Project Execution Process: with all the BIM uses identified at the first step, design and depict the process with BPMN to have an overview of the BIM process and information exchanges.
- STEP 3: Develop Information Exchanges: develop the information and DMU content and LOD. Identify responsible party for each exchange.
- STEP 4: Define Supporting Infrastructure for BIM implementation, according to the uses identified at the first step, and the information identified at the third one.

We identified a few problems with this procedure in our case. First of all, it is an extremely complete and complex procedure for BIM implementation. Moreover, the process designed at the second step contains only BIM uses, and doesn't integrate eventual regular practices of architects, engineers or other firms. Not taking into account the work context of people would be a failure factor for the operation. Furthermore, the fourth step of the procedure is to define the best supporting infrastructure for the ideal process designed at the third step. But it is difficult today for SMEs to buy new software programs, new equipment or take time of people.

These three observations make this procedure really difficult to put in practice in our case under this form.

2.4 An adapted method of BIM project implementation in SMEs

We developed an adapted method organised around a general process (cf. fig. 3) defined from the observations we realize on the PEPG. As unfreeze (A) is a lengthy and behaviour depending process, we only intervene after that it occurred. To minimize the impact on the usual process and to make the technology appropriable by the actors, we first study and model the usual practices (B). Then we organize the change by designing a new process that includes new BIM uses in usual practices (C). The exchange experiment (D) allow us to see what was possible to do in a first place with the current infrastructure. According to the observations realized during the previous experiment, we redefine the process (E) and finally we implement it (F).

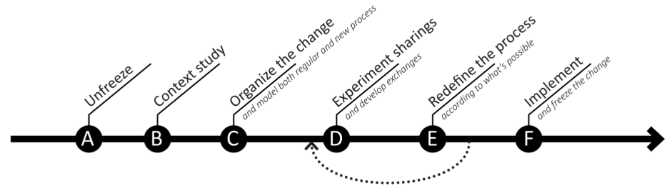

Figure 3. The general process of the proposed method

3. EXPERIMENT OF THE PROPOSED METHOD

3.1 Unfreeze (phase A)

As we said before, the unfreeze step occurred without our intervention in this experiment context. These architects feel particularly concerned about BIM and they want to experiment.

3.2 Context study (phase B)

To introduce our two partners goals, and the methods we set up, we need to describe the different contexts in which this experimentation takes place. The context notion comes from the usage-centred design approach (Constantine & Lockwood, 1999) and use in the model-centred description of collaborative practices and usages (Zignale et al., 2014). These contextual elements are classified and gathered in the Table 1 that summarizes the various identified contexts. Both partner companies will be described within the following table criteria.

Table 1. Contexts definition

Context type	Characteristics
User context	*Preferences, habits, competences*
Material context	*Equipment type, interacting device*
Temporal context	*Frequency, synchronization*
Location context	*Place, environment, co-presence*

3.2.1 Architecture agency context

User context – Two architects, currently working essentially on individual houses projects, manage the agency. They have a strong eco-conception approach and both equally developed CAO and construction monitoring competences. *Material context* – The agency is equipped with workstations that run 2D and 3D drawing software programs. They used Autocad for nearly a decade and recently decided to acquire a "BIM compatible" tool. They are now in the transition process between the endings of the last projects drawn in 2D and the starts of the first projects yards drawn in 3D. They are between a "defined maturity level" and a "managed maturity level" in BIM stage 1 (Succar, 2013). *Temporal context* – Agency's work is for a major part synchronized; they define together the architectural directions of every project. Then, work is divided and only one architect carry on a project. The drawing time is then asynchronous. *Location context* – Agency is located in northeast of France and the building is a mirror of the architects work, it is one of their projects.

3.2.2 Carpentry firm context

User context – The firm is specialized in framework, roof work and timber framed houses. It employs about 50 persons and works on a wide range of projects, individual houses as well as public equipment. An engineering office and a manufacture unit are integrated. *Material context* – The wood engineers work with the business software (cadwork) for a long time so they managed it well. However, architects and carpenters software programs cannot directly communicate. As a result, current exchanges are made with 2D DWG files and paper plans. *Temporal context* – There's no work synchronization. Thus, successive tasks allow switching from the initial 3D model to the final manufactured pieces. Each people within the company have a clearly defined role. *Location context* – Company is also located in northeast of France, about 40 km away from the architects.

3.3 Organize the change (phase C)

To organize the change, we modelled a process with the information we collected on each company, their habits of work and their needs of exploiting DMU. We used the same notation as used in the PEPG: the Business Process Model Notation (BPMN) (c.f. fig. 4.). It allows us to see at each exchange: where the file is coming from, and where it is going after. It's important to know which information it is possible to have in the IFC file as output, and which ones we will need as input. BPMN is not a well-known notation in architectural sector. In order to make the process representation accessible to project's actors we added a timeline representing the project milestones. The timeline shows the expected LOD of the model, which represent an essential information for architects and their partners. The figure bellow (fig. 3) illustrates this process of the collaboration between the two partners.

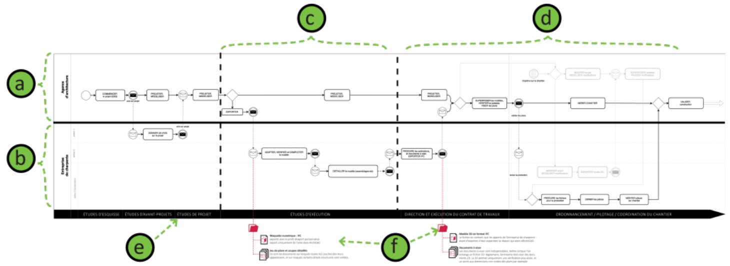

Figure 4. The file exchange process between the architects (a) and the carpentry firm (b). We drew the project milestones timeline (e), the ND3 DMU step (c), the ND4 DMU step (d), and the detail of the shared files (f).

3.4 Experiment and develop exchanges (Phase D)

We took as support for the experimentation a common project of the architects and the carpentry firm which has been already made with the usual process. The architects work with ArchiCAD and carpenters work with cadwork. The only file extension that can be exported and imported with these two software programs is the IFC format. Therefore, we chose to make all our exchanges tests with IFC files.

3.4.1 The reference project

The support of our experimentation is an individual house project, originally drawn in 2D (Autocad). The construction of this house is now completed (12.2015). The house is build with wood-frame walls and a masonry garage separated of the house by a small winter garden. To achieve our goals, the project was re-drawn in 3D (ArchiCAD). We chose this project for our experiment, because a particular mistake occurred during the construction process. The carpenters made confusion between the use of the '%' character and of '°' character in the frame design. The architects didn't noticed the mistake because of the lack of information on the carpenters' plans. One of our objectives is to determine if our method may allow to avoid such a mistake. The house has been re-modelled with ArchiCAD during the internship in the agency in order to have a DMU support for the experiment.

3.4.2 Architects to carpenters exchange

We made a first IFC export of this 3D semantic model with ArchiCAD with the default settings. When we imported the geometry in cadwork, some parts of the model were critically damaged, and we lost information during the exchange process: some walls and roofs are missing and walls are no longer connected to roofs (c.f. fig. 5).

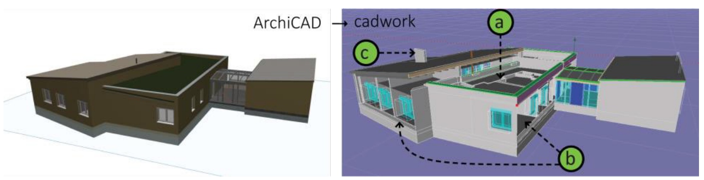

Figure 5. Result of our first IFC exchange test. Some roofs (a) and walls (b) are missing, and a wall lost its connection with the roof (c)

We made then three hypotheses concerning the reasons of this loss of information:
1 - The house was not modelled properly
2 - Cadwork doesn't read the file properly and deleted unreadable information
3 - ArchiCAD doesn't export the file properly.

1 – For the first hypothesis which concerns the modelling techniques, we made a set of tests to check the impact of some modelling practices as the manner in which the wall is modelled, its composition, the type of roof, etc. We noticed that the geometry is damaged when the walls are connected to roofs. The tests showed that the way we model a wall (clockwise or counter clockwise) and its composition (simple or composite) impacts the quality of the exported IFC file even when it is invisible and unnoticeable in ArchiCAD (c.f. fig. 6).

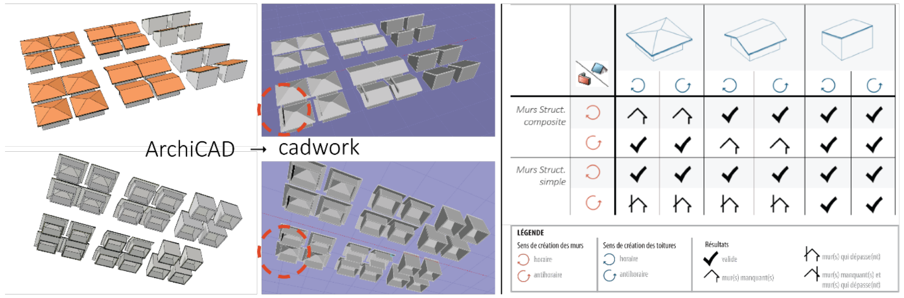

Figure 6. Results of the tests made for the hypothesis 1

2 – Then, after checking the quality of the file, we tried to identify if the problem comes from cadwork import functions. It's important to specify that cadwork is not certified yet by BuildingSMART for IFC2x3 import. We opened the same IFC file with different software programs: cadwork, Revit, Solibri Model Viewer (SMV), and Tekla Bimsight and compared the different obtained visualizations. None of these programs revealed the same damages on the same file. That means that cadwork, Revit and Tekla Bimsight aren't able to read this IFC file properly. The best importation of the IFC file was made by SMV: there is no difference between the visualisation of in SMV and that in ArchiCAD (c.f. fig. 7 and fig. 5).

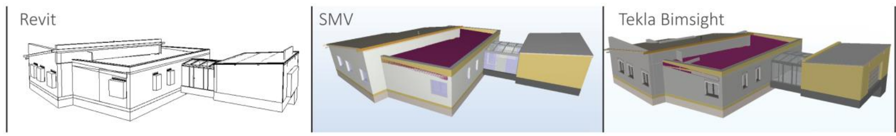

Figure 7. Visualization of the same IFC file in different software programs

3 – Finally, we checked the most essential factor: the IFC export profile settings in ArchiCAD. ArchiCAD is certified by BuildingSMART for IFC2x3 import and export. In this software, the IFC file export profile can be configured. Our tests showed that the IFC export profile has an important impact on the quality of the imported geometric information in cadwork.

Information handover– Cadwork and ArchiCAD work in a total different way. ArchiCAD allows architects to make an Object Oriented Model, whereas in cadwork carpenters work with panels and volumes. There is only five non-geometric data that can be recovered from an IFC file in cadwork: IFC class, global ID, name, building storey and layer of an object. These data are sufficient for carpenters to realize their work. In cadwork, the carpenters usually model only structural parts of a wall and use simple volumes as basis to define the whole structure of wooden framework of house.

3.4.3 Carpenters to architects: interoperability problems

A BIM exchange process is profitable only if the 3D model can go back and forth between the two companies. Now let us determine how the architects can exploit the carpenters' detailed model.

As previously explained, the actual exchange process contains a delicate step: the information exchange for the architects compliance check. Currently, this work is done using paper plans. Nonetheless, both companies don't need the same information. They don't use same graphical conventions for representation or measurement and thus the files become hardly readable by each other.

A way to decrease this issue is to translate the carpenters' model with IFC standard concept, and to overlay it with the architects' model either in their BIM software (ArchiCAD), or in an other software program, in order to detect possible errors or differences. This method immediately showed an error, and made it easier for architects to check technical compliance of the projects.

An IFC file was exported from cadwork, and then imported in ArchiCAD. Groups in cadwork are converted into building storeys in ArchiCAD and then disrupt the architect's work model.

4. RESULTS AND FINAL PROCESS (PHASE E)

4.1 Solutions found

4.1.1 Architects to carpenters: exporting settings recommendations

Export profile – We created a new IFC export profile in ArchiCAD that explodes and converts all the geometries into Breps. With this method, we lost a lot of information, but it made possible to keep geometric information we needed. We observed no more wall or roof removal, but a new visualization problem appeared. It seems that faces overtake edges boundary in convex edges (c.f. fig. 8).

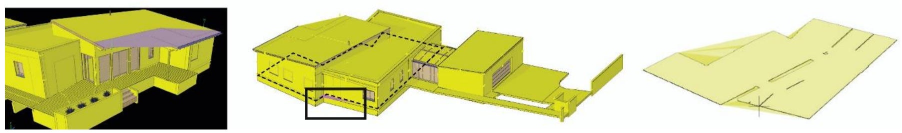

Figure 8. The house imported in cadwork: IFC import coming from ArchiCAD with our exporting profile.

Information handover – To deliver to carpenters a model that only contains the structural parts of the walls in order to not overload the IFC file, a selection must be made by the architects before the IFC file export. They have to check the "only structural parts" option in the model visualization in ArchiCAD (c.f. fig. 9).

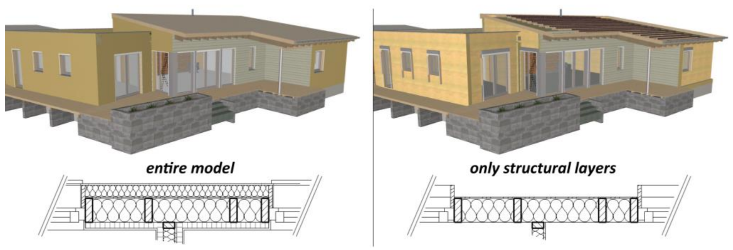

Figure 9. Selection of information in ArchiCAD before the IFC export

Unfortunately, the bad quality of the imported geometry (in breps) doesn't allow carpenters to use it directly to define the house structure. They can only use the imported file as a background base for re-modelling clean basic volumes. Howerver, it makes it possible to carpenters to avoid units reading errors.

4.1.2 Carpenters to architects: an alternative to interoperability problems

We chose to realize this task by using the freeware Tekla Bimsight (c.f. fig. 10.). We decided to use this specific tool and not overweight the manipulations in the architects' software (ArchiCAD). This particular tool allows an easy overlay of many IFC models.

On the figure 10, we can first observe on the left the architects' IFC model with only the global volumes of the construction elements, a wall in this case. Then in the middle is the IFC model detailed by the carpenters with all structural parts constituting the wall. This model is generated from the model drawn by the architects. Lastly, we can see on the right of the figure the two models overlay. In this case, they overlap perfectly and this shows that the architectural conformity is fulfilled.

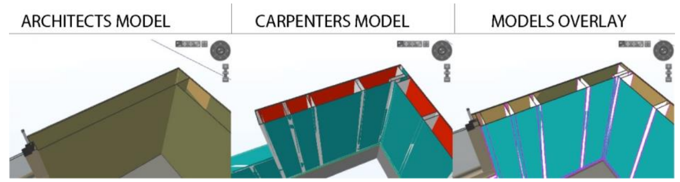

Figure 10. Models overlay done

The modelling process has an influence on the possible exploitations of the model. Sometimes, to ensure a correct geometrical representation, it is necessary to adapt the modelling process. On the opposite, get a proper 3D model to share with partners may alter the geometrical side. This mutual impact of both stakes prevents the development of their full potential and requires an adaptation of the initial goals.

4.2 Final Process

As what we supposed before the experiment, we had to adjust our objectives to fit the possibilities of the software programs used instead of defining new infrastructures. The practical problems today stay linked to interoperability and to the ability of software programs to read and write IFC files. But there is one important step missing in our method: it would be useful to check the quality of the IFC file before it is shared, to see if the DMU matches with the expected LOD, and if no error is detected in the file.

5. CONCLUSION

It is quite rare to get the opportunity to realize an experiment with two SMEs in collaboration with a research laboratory. Our work demonstrated the importance of taking into account usual practices in SMEs in order to implement a BIM exchange process.

This experiment allowed us to set up a first draft of a method for BIM implementation in SMEs. For that, new notations and new practices for architectural conception and construction process have been tested and the relevant information of the DMU that can be shared between the concerned actors has been determined and described.

Notwithstanding the interoperability problems we experienced, carpenters spontaneously asked architects to send them a partial DMU in IFC standard after the end of experiment. The actors are satisfied by the experiment results: they are now ready to invest time and money to set up new changes and integrate more advanced BIM uses. This is an indicator that makes us conclude that implementation is accepted and that "freeze" happened.

This common master student work is resulting in the beginning of two theses about BIM practices integration in SMEs. The first one concerns intelligibility of architectural processes and procedures, and the second one is about usage and technology changes.

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Une approche pédagogique par les modèles pour la sensibilisation au concept de BIM (Maquette Numérique)

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RÉSUMÉ. Les pratiques de projet autour du BIM nécessitent une bonne compréhension des notions liées à la différentiation des formes de modèles impliquées dans cette technologie. L'expérience pédagogique évoquée ici fait suite à deux enseignements : le premier porte sur la modélisation géométrique et la programmation visuelle en Grasshopper et le second sur la modélisation sémantique et la mise en oeuvre de bases de données relationnelles. Le mixage de ces deux enseignements nous permet de proposer un travail pédagogique portant sur la différenciation des différents types de modèles manipulés lors d'un travail simplifié de conception partagée à l'image de ce pourrait être une pratique collective autour d'un outil BIM. Le but de cette sensibilisation est d'offrir aux étudiants une meilleure compréhension des enjeux des différentes pratiques nécessaires à la coopération tant dans les étapes de conception (production) que de partage (communication).

MOTS-CLÉS : Conception collaborative, Maquette numérique, Modélisation conceptuelle, Modélisation paramétrique, expérience pédagogique.

ABSTRACT. The BIM project practices require a good understanding of concepts related to the differentiation of model types involved in this technology. The educational experience mentioned below follows two courses: the first is about geometric modeling and visual programming with Grasshopper and the second addresses semantic modeling and relational databases implementation. The mixing of these two courses offer an educational work on the differentiation of the different model types handled in a simplified work of shared design similar to what could be a collective practice with a BIM tool. The purpose of this outreach is to offer students a better understanding of issues on practices needed to cooperate both in the design stage (production) and in the sharing stage (communication).

KEYWORDS: Collaborative design, BIM, Conceptual modeling, Parametric modeling, pedagogical experience.

1. Introduction

Le bon usage d'un outil numérique par un nouvel utilisateur est conditionné par la minimisation de la distance existant entre le modèle cognitif construit par l'utilisateur et le modèle fonctionnel proposé par l'outil numérique (Norman 86). L'assimilation du concept de BIM et surtout les usages qui en découlent sont également fortement conditionnés par le modèle cognitif que les futurs acteurs vont se construire relativement à la compréhension des notions inhérentes à ce concept. L'enjeu des enseignants, délivrant des enseignements autour du BIM, est de permettre aux étudiants architectes, futurs acteurs de projets BIM, d'assimiler toutes les notions nécessaires à la réalisation d'usages métier pertinents. Cela nécessite une bonne compréhension des différentes formes de modèles impliquées dans cette technologie. Nous présentons dans cet article une expérience pédagogique portant sur la différenciation des différents types de modèles manipulés lors d'un travail simplifié de conception partagée à l'image de ce pourrait être une pratique collective autour d'un outil BIM. Le but de cette sensibilisation est d'offrir aux étudiants une bonne compréhension des différents niveaux d'abstraction et de représentation manipulés dans les pratiques nécessaires à la conception coopérative, tant dans les étapes de conception (production) que de partage (communication). Cette expérience fait suite à deux enseignements : le premier porte sur la modélisation géométrique et la programmation visuelle en Grasshopper et le second sur la modélisation sémantique et la mise en oeuvre de bases de données relationnelles. C'est le mixage de ces deux enseignements qui nous permet de proposer ce travail pédagogique.

Avant de présenter l'expérience et son bilan, la première partie de l'article tentera de définir la notion de modèle et de représentation pour s'attarder sur une identification de différents modèles présents dans le concept de BIM.

2. Notion de modèles et BIM

La compréhension du BIM est multiple, elle contient les notions de géométrie 3D, d'objet paramétrique, d'information, de partage, de processus, et plus globalement de modèle. Toutes ces notions sont convoquées à des temps différents de la conception coopérative entre les acteurs du projet, mais elles sont toutes présentes dans le résultat final que représente la maquette numérique et les pratiques BIM qui permettent de la réaliser collectivement.

L'assimilation de ces notions par un étudiant nécessite un apprentissage progressif où chacune d'elles puisse être identifiée séparément relativement à son rôle dans l'activité coopérative de conception. Pour formaliser cette compréhension, la notion de modèle doit être également assimilée afin de pouvoir décrire et représenter les concepts ou abstractions manipulés par chacune des facettes du BIM.

2.1. Modèle de représentation

Afin de définir la notion de modèle qui nous intéresse, nous nous appuierons sur les écrits et travaux réalisés dans le domaine de l'IDM (Ingénierie Dirigée par les Modèles) (Favre 2006)(Bézivin 2001)(Kleppe 2003). Un modèle décrit une partie d'une réalité, d'un système ou d'un objet selon un point de vue donné d'un observateur. L'observateur peut être une personne (acteur d'un projet), il peut être également l'ordinateur qui va manipuler les données du modèle. Pour construire le modèle, il faut utiliser un langage avec une forme définie (syntaxe) et un sens attaché à la forme (sémantique). Le résultat de cette description est bien un modèle qui prend la forme d'une représentation textuelle ou graphique (ou les deux), compréhensible par l'observateur visé.

À ce niveau les notions de modèle ou de représentation en tant que résultat de l'activité de modélisation sont souvent confondues. Cependant, la représentation est la forme prise par le modèle, mais cette représentation ne peut avoir le statut de modèle que s'il existe un observateur (humain ou machine) qui, par la connaissance du langage utilisé dans la représentation, est capable d'attribuer un sens aux formes présentes et ainsi de comprendre le contenu du modèle : « pour un observateur B, M est un modèle de l'objet O, si M aide B à répondre aux questions qu'il se pose sur O » (Minsky 1965).

Toutes ces notions sont abordées dans le cours portant sur la modélisation conceptuelle avec comme champs d'investigation principaux : le modèle Entité/Association, le modèle relationnel, la transformation du modèle E/A en modèle relationnel et l'interrogation d'une base de données relationnelle en SQL. À l'issue de ce cours, les étudiants doivent être capables de construire un modèle conceptuel décrivant une réalité restreinte à un domaine particulier, de le traduire sous la forme d'un modèle relationnel et enfin de l'exploiter dans une base de données avec un SGBD (Système de Gestion de Bases de Données).

L'assimilation de ces notions sur les modèles en général, les modèles conceptuels, et les modèles de données permettront aux étudiants d'aborder, dans cette expérience, au travers d'un modèle conceptuel et d'un modèle de données mises en oeuvre dans un SGBD les différents niveaux d'abstractions auxquels l'usage du BIM se réfère. C'est ces différents niveaux d'abstractions que nous nommons « les modèles du BIM ».

2.2. Les modèles du BIM

L'appellation BIM couvre à la fois les aspects données, activités, et ressources que génèrent les pratiques et usages métiers du bâtiment. D'ailleurs l'acronyme BIM et plus particulièrement l'interprétation de la lettre 'M' peut se décliner suivant l'objectif visé en « Model » pour prendre en compte l'aspect donné, en « Modeling » pour décrire les activités et en « Management » pour la gestion des ressources (acteurs, temps, coût,..). Ainsi, l'usage des outils BIM nécessite l'assimilation de différents modèles qui interviennent tout au long des activités de la conception coopérative. Dans le cadre de cette expérience pédagogique, nous avons identifié cinq types de modèles numériques que nous souhaitons illustrer et faire assimilés aux étudiants du Master. Ces modèles sont les suivants :

Modèle géométrique :

Ce modèle est créé par des outils de CAO géométriques (Rhinocéros, Sketchup,…), la sémantique repose sur la géométrie. Les éléments représentés sont des volumes, des surfaces, des segments, des points. Ces modèles décrivent une réalité géométrique qui peut être interprétée par un observateur humain initié comme une représentation d'un bâtiment, mais qui demeure au sein des outils numériques un modèle géométrique dépourvu de sens « métier ».

Modèle géométrique sémantique :

Ce modèle, qui visuellement a la même représentation que le modèle géométrique, est issu des outils CAO orientée métier (ArchiCAD, Revit, ..). La sémantique est celle de la construction, les formes présentes dans le modèle représentent des ouvrages (mur, poteau, panne, plancher,..) décrits par leur géométrie (hauteur, largeur, position,..). Généralement, il est communément admis que les usages du BIM commencent à ce niveau d'abstraction.

Modèle géométrique sémantique enrichi :

Ce modèle est construit comme le précédent, mais chaque élément du modèle peut être décrit ou enrichi par des informations complémentaires qui ne sont pas liées à l'aspect géométrique de l'ouvrage, mais qui sont utiles à la mise en oeuvre, aux évaluations et estimations ou encore à la maintenance. Ces propriétés sont attachées aux ouvrages représentés et éditables via l'outil numérique exploité : « The building information model is a three-dimensional geometric model that is data rich » (Kensek 2014).

Modèle géométrique sémantique enrichi partagé :

C'est à ce niveau que les activités et les actions des acteurs sur le modèle précédent sont prises en compte. Ce modèle, exploité essentiellement dans les outils BIM qui offrent des services d'accès partagé à la maquette numérique (Archicad server, Revit server, BimServer,..), permet de répondre notamment aux questions du type : qui a fait quoi ? Quand a été réalisée cette action ?

Modèle de processus :

Ce dernier modèle décrit l'enchainement d'activités, réalisées par les acteurs, mais aussi par les outils numériques, qui contribue à la réalisation du projet coopératif de conception. Les concepts représentés par ces modèles sont les acteurs, les activités, les événements, les informations échangées,... La représentation peut prendre plusieurs formes. Ce peut être le formalisme normalisé BPMN (Business Process Model and Notation) (Dijkman 2008) utilisé dans les outils numériques dédiés à la modélisation des systèmes d'information (Bonita, VisualParadigm,...). Ce type de modèle est également présent dans les outils de programmation visuelle dédiés à la définition de processus paramétriques de conception de formes géométriques (Grasshopper, Dynamo,..). Les éléments de ces processus sont des modules paramétrables générant principalement des formes géométriques. L'agencement de ces éléments entre eux définit un processus de construction d'une forme paramétrable. Les modules peuvent également réaliser d'autres fonctions comme notamment la sauvegarde d'information, le calcul d'une estimation ou d'une évaluation, l'accès à une source d'information.

L'expérience pédagogique que nous présentons dans la prochaine partie se propose de faire assimiler les caractéristiques de ces modèles ainsi que leurs différences par l'exploitation d'un Modèle géométrique sémantique enrichi partagé. L'ensemble du modèle étant décrit par un modèle sémantique (Entité/Association), implémenté dans une base de données relationnelle (SGBD Mysql) et accessible par un modèle de processus de conception de formes paramétriques (GrassHopper).

3. Expérience pédagogique

L'expérience pédagogique, présentée ici, se déroule depuis 4 ans à l'ENSA de Nancy dans le cadre du master AME[1]. Elle est divisée en trois phases : une première phase théorique qui cherche à définir et à caractériser un contexte de conception à travers la réalisation d'un modèle Entité/Association. La deuxième phase est plus expérimentale matérialisée par la mise en œuvre d'un ensemble d'outils de modélisation et de gestion de données de conception (géométriques, sémantiques et collaboratives).

La troisième phase est une évaluation du niveau d'assimilation des concepts présentés et mis en œuvre par les étudiants participant au cours.

Phase théorique

Le contexte de conception mis en œuvre consiste à créer un espace architectural formé de quatre entités architecturales : un plancher, des poteaux, des murs et des plafonds. Le positionnement et le dimensionnement de ces éléments doivent respecter un gabarit défini par les enseignants. Ce dernier définit une emprise au sol structuré en deux parties ainsi qu'une contrainte de hauteur de bâtiment.

[1] AME : Architecture, Modélisation, Environnement

Le scénario de conception prévoit de travailler en binôme pour proposer une réponse architecturale commune et conçue à distance (binôme physiquement éloigné). Un gabarit, composé de deux zones, a été affecté à chaque binôme en leur laissant la possibilité de choisir la zone d'intervention. Ces gabarits (zone d'intervention) sont accompagnés de règles de conception simplifiées matérialisées par des hauteurs de bâtiment à respecter.

L'étude théorique a commencé par un travail collectif de définition d'un modèle Entité/Association structurant le contexte coopératif de conception proposé à savoir : les entités architecturales de différent type peuvent être créés ou annotées par chacun des étudiants ; ces entités sont représentées par un volume composée de faces à quatre sommets. Ce processus a permis la définition d'entités sémantiques (Volume, Etudiant, Face, Sommet et Annotation). Chaque entité a été analysée afin définir les propriétés qui permettent de l'identifier et de la caractériser. Par exemple, l' entité « Annotation » est identifiée à travers la clé « IdAnnotation » et caractérisée par les attributs « Text » et « Type » décrivant respectivement le contenu de l'annotation et son type (remarque ou action).

Ce modèle a ensuite été traduit sous la forme d'un schéma relationnel afin que les données soient gérées par un SGBD relationnel, ici MySQL.

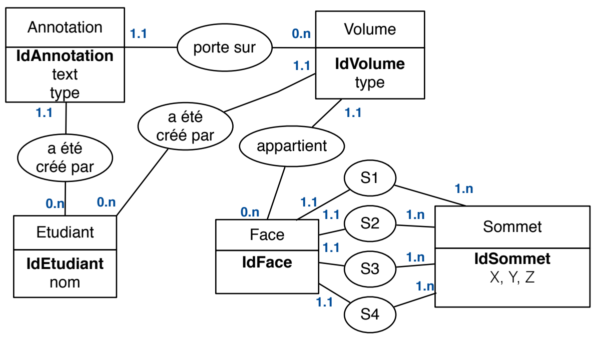

Figure 1. Modèle relationnel (Entité/Association) structurant la base de données

La base de données ainsi construite est utilisée comme une interprétation simplifiée d'un serveur BIM. Elle est composée de cinq relations (ou tables) caractérisées par un ensemble d'attributs et de clés étrangères matérialisant les associations entre les entités :

Volume (idVolume, type, #idEtudiant)
Face (idFace, #idVolume, #S1, #S2, #S3, #S4)
Sommet (idSommet, X,Y,Z)
Etudiant (idEtudiant, nom)
Annotation (idAnnotation, text, type, #idVolume, #idEtudiant)

Phase pratique

La phase d'expérimentation pratique est divisée en plusieurs volets.
Dans le premier volet les étudiants créent une base de données MySQL selon la structure proposée, ils mettent ainsi en œuvre les connaissances acquises durant le cours de Modélisation Conceptuelle. Ces bases sont nommées « BIM-n » avec « n » correspondant au numéro du groupe concerné. Cette activité confronte les étudiants à la précision que demande les outils de gestion de données (typage et nommage).
Le deuxième volet consiste à utiliser un outil de modélisation géométrique 3D (Rhinoceros) afin de proposer une configuration architecturale composée de Murs, Planchers, Plafonds et Poteaux. Les étudiants sont appelés à utiliser des formes parallélépipédiques pour modéliser les différentes composantes du projet. Cette contrainte cherche à simplifier et à accélérer la phase de modélisation.
Le troisième volet est orienté vers le partage des données et la mise en place d'un dispositif de conception collaborative. Ce processus est matérialisé par des modules ou *« Clusters »* crées sous l'environnement de programmation graphique *Grasshopper* (plugin du modeleur 3D *Rhinoceros*). Ces modules créent des passerelles avec la base de données et le modeleur 3D générant ainsi un cadre d'échange et de partage des informations de conception. Trois modules d'échange sont proposés : BIM-IN, BIM-LIST, BIM-OUT.

BIM-IN est un module de sauvegarde des éléments du projet dans la base de données qui prend en compte le type de l'objet et le nom de la personne qui l'a créé. Une étiquette indiquant l'identifiant, la nature de l'objet ainsi que son créateur apparaitra sur l'interface du modeleur 3D confirmant ainsi la sauvegarde de l'objet dans la base de données. Les étudiants répètent cette opération pour l'ensemble des objets constituant leur conception. L'entrée « Lien Connexion BD » de ce composant permet de définir les paramètres de connexion à la base de données (nom de la BD, url, login et mot de passe).

BIM-LIST est un module de sélection des objets sauvegardés dans une base de données (cf. Figure 2). Il permet d'afficher la liste des objets d'une base de données créés par un étudiant et de les trier par type. Ce module permet aux étudiants d'identifier les objets crées par le partenaire. Cette identification se matérialise par l'affichage des identifiants « idVolume » des objets dessinés et sauvegardés dans la base de données.

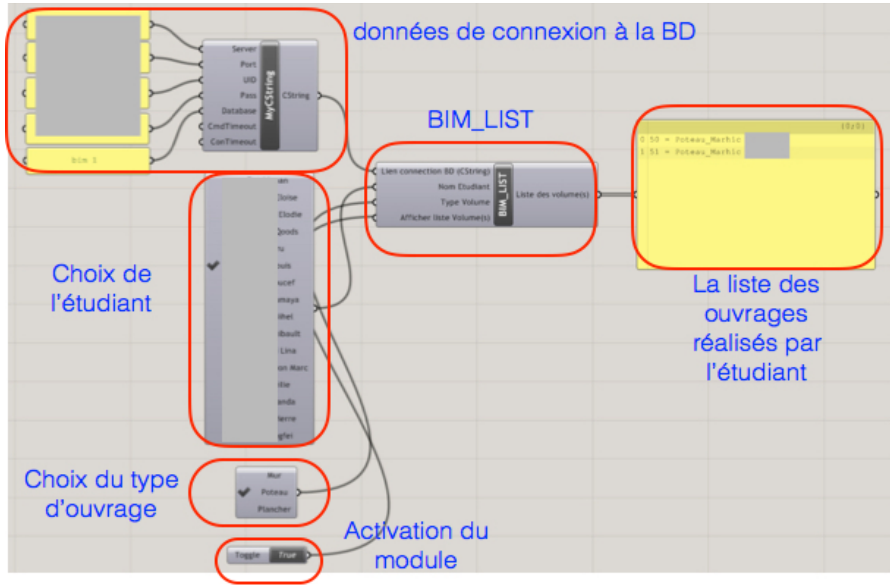

Figure 2. Le détail du composant BIM-LIST

BIM-OUT est un module d'import et de visualisation d'objet sauvegardés dans la base de données. Les étudiants sont appelés à utiliser ce module pour importer et visualiser la géométrie crée par leur partenaire et ainsi afficher le projet dans sa globalité. Ce module offre la possibilité d'attribuer une couleur déterminée aux objets importés. Ce module nécessite un lien de connexion pour identifier la base de données à partir de laquelle les objets seront importés ainsi que l'identifiant de l'objet à récupérer.

Le quatrième volet de cette expérimentation est orienté vers les échanges entre les mêmes membres du groupe pour discuter (à distance) du projet en cours de conception. Nous avons mis en place un ensemble de modules qui offrent la possibilité aux étudiants d'associer des commentaires à un objet conçu ou importé à partir de la base de données. Chaque étudiante peut ainsi saisir des commentaires, mais aussi afficher ceux de son partenaire créant ainsi un espace collaboratif. Ces annotations sont classées en deux types : *« remarque »* ou *« action »*. Les activités d'annotation et d'échange sont matérialisées par deux modules : Annotation-IN et Annotation-OUT.

Annotation-IN est un module de saisie de commentaire ou de remarque associé à un objet bien défini et formulé par un concepteur donné. Ce module doit être connecté au composant *« MyCString »*[2] afin de définir le lien de connexion à une base de données précise. Chaque annotation crée est associé à un seul concepteur qui doit saisir son nom au moment de l'intégration de l'annotation. Ce dernier doit aussi préciser la nature de l'annotation à saisir.

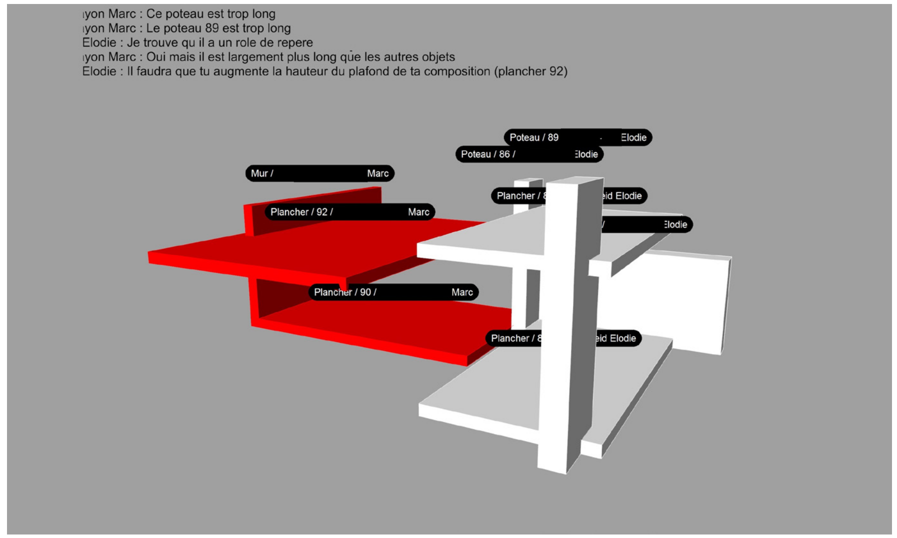

Figure 3. Le résultat de la visualisation des annotations et du modèle 3D sémantique avec le module Annotation-OUT

Annotation-OUT est un module de récupération et de visualisation des annotations formulées par un ou plusieurs concepteurs et portant sur une ou plusieurs entités architecturales (cf. Figure 3). Ce module nécessite un lien de connexion à la base de données ainsi que la saisie d'un ou de plusieurs noms de concepteurs. La saisie de plusieurs identifiants permet de

2 Module faisant partie du plugin SlingShot créé par Nathan Miller et permettant de créer une passerelle entre Grasshopper et MySQL

récupérer les annotations concernant plusieurs objets en les filtrant par type (choix du type d'annotation à afficher).
Les étudiants sont appelés à communiquer via ces modules pour corriger les erreurs de conception et améliorer leurs propositions architecturales.

Phase d'évaluation

Dans cette phase d'évaluation qui fait suite à la phase pratique, nous proposons aux étudiants de répondre à un questionnaire. Nous cherchons, à travers ce questionnaire, à identifier le niveau d'assimilation des étudiants des différents modèles du BIM mis en œuvre dans l'expérience. Les questions portent sur la nature des modèles manipulés, mais aussi sur les activités réalisées durant les deux précédentes phases de l'exercice.

Le questionnaire révèle que les étudiants sont arrivés majoritairement à identifier les différents modèles manipulés. Ainsi, 80% des étudiants arrivent à identifier les éléments du modèle sémantique E/A (Entité « Annotation ») nécessaires à la manipulation d'un modèle géométrique 3D sémantique enrichi (à partir d'une liste de propositions). Dans le même sens, 65% des étudiants ont réussi à identifier le moyen utilisé pour intégrer la dimension sémantique dans cet exercice (propriété type de l'entité « Volume »). Ce constat est confirmé avec le même taux pour les activités intégrées à cet exercice : 65% des étudiants ont réussi à identifier le moyen utilisé pour matérialiser la dimension collaborative (Entité « Etudiant » et associations « a été créé par »).

La dernière partie du questionnaire s'est intéressée aux types d'outils mis en œuvre pour créer cet environnement BIM. Les résultats montrent que plus de 75% des étudiants ont identifié les outils ayant une orientation BIM, dont « Modeleur géométrique orienté objet », « Serveur de maquette numérique », « Éditeur collaboratif de maquette numérique », « Éditeur visuel de programme pour l'exploitation de maquettes numériques ».

4. Conclusion

Cette expérience montre que l'approche par les modèles permet aux étudiants d'avoir un certain recul face aux outils et aux usages qui leur sont proposés dans le cadre d'un enseignement. Ainsi par cette progression allant du théorique, c'est à dire la modélisation du contexte coopératif et à la pratique par la mise en œuvre du modèle dans des outils simplifiés, mais néanmoins proches de la réalité, les différents modèles du BIM ont pu être identifiés. Même si la démarche, les outils et l'évaluation mise en œuvre sont perfectibles, l'expérience demeure pertinente puisqu'elle motive les étudiants en les plaçant dans un processus d'apprentissage théorique et pratique cohérent et compréhensible. Le modèle explique l'expérience, les outils lui donne une réalité.

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THÈME 6

Visualisation et interaction dans les espaces virtuels

THÈME 6

Visualisation et interaction dans les espaces virtuels

Dans cet article, nous présentons un projet de recherche dont l'objectif est d'exploiter avec des interactions naturelles des outils numériques collaboratifs d'aide à la décision. Le travail porte en particulier sur la simulation 4D (modélisation 3D d'un projet associé à un planning pour la simulation du chantier) collaborative synchrone (même lieu). Nous présentons une première proposition de prototype et une étude de cas de planification de chantier issue d'une situation réelle.

La numérisation et la restitution virtuelle des maquettes de la collection de Louis XIV (les plans-reliefs) sont un enjeu important pour la préservation et la valorisation numérique de ce patrimoine imposant, fragile et méconnu. Cet article présente le projet de numérisation du plan-relief de Verdun actuellement enfermé dans des conteneurs à Paris. Après avoir décrit les spécificités de ce patrimoine particulier, l'article s'attarde sur la méthode exploitant les cahiers de développements (documents historiques dédiés au constructeur de la maquette) ainsi que sur les outils numériques interactifs de valorisation du modèle 3D obtenu.

Cet article décrit une interface de navigation par survol dans une reconstitution urbaine numérique en 3D d'un plan-relief. Cette navigation s'effectue en utilisant la métaphore de l'avion mimé à partir d'une main libre de tout dispositif physique, et dont l'acquisition de sa position et de son orientation se font à partir d'un périphérique de repérage et de suivi 3D. Ce mode de navigation a été mis en place dans le cadre d'une valorisation grand public du plan relief de la ville de Verdun en Meuse, France (maquette à l'échelle 1/600e). Deux évaluations ergonomiques ont été menées afin d'évaluer ce type d'interface, d'en révéler les défauts, et d'en corriger certains.

Supporting collaborative decision in architectural design with synchronous collocated 4D simulation and Natural User Interactions

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Abstract. The work presented in this paper is part of a more comprehensive one which aims to propose appropriate natural user interactions to support collaborative decision making in synchronous 4D simulation. It presents the issue and previous works on natural user interfaces in 4D simulation. It also introduces a first prototype and a 4D case study from a real construction site.

Keywords: CSCW, 4D simulation, Human-Computer Interfaces, Natural User Interaction, Decision support, Architecture, Engineering and Construction, Collaborative 4D.

1 Introduction

According to Kvan, “in discussions about computer systems for collaborative design, their behaviours, specifications and implementation, the most fundamental arguments appear to be encountered on the issues of interaction” [9]. This is about both the interaction between participants and the interaction with the systems, and the issue have been well discussed in related literature [9, 10, 12]. But during the last decade, new devices (smartphones, tablets, digital tabletops, etc.) are appearing with new interaction capabilities. Construction practitioners are increasingly using such devices including, in addition to common mobile devices, the VCE [13], the TATIN [1], the ValueLab [7], and the iRoom [6]. Because of the diversity of innovative devices, it is important to take into account the novel interaction mechanisms they provide users with.

2 Previous works on natural user interfaces in 4D simulation

In the line of Building Information Modeling (BIM) approaches, collaborative 4D simulation is being increasingly used to visually simulate the construction process in order to detect constructability inconsistencies in the planning or in the design [3]. 4D simulation consists in linking a 3D model to the construction activities planning (time) to simulate the construction process over time [11]. In synchronous 4D simulation, all collaborative work participants are working on the 4D model at the same place at the same time [3]. If the interaction with 3D models has been extensively discussed in the literature, the interaction principles with the fourth dimension are much less studied [4, 8].

After Command Line Interfaces and Graphical User Interfaces, the last evolution in the Human-Computer Interaction paradigm lies in Natural User Interfaces (NUI). NUI reuse the human capabilities, behaviors and gestures to interact with IT systems [2]. NUI are not really new in 4D simulation. In 2002, Waly and Thabet proposed a virtual construction environment (VCE) for pre-construction planning [13]. They introduced an Interactive Virtual Interface (IVI) where users can graphically "drag and drop" elements from the 3D model and rebuild the building by putting side by side the components in the order received for the actual construction. The IVI offers intuitive and interesting interaction mechanisms such as 'click to take' or 'release to place' or 'navigate to the walk through' [13].

3 A NUI me-fi prototype to support collaborative 4D decision

In Human-Computer Interfaces design, "prototype fidelity expresses the similarity between the final user interface and the prototyped UI" [5]. Medium-fidelity (me-fi) tools "support designing UI mock-ups giving more importance to the contents than the style with which these contents are presented" [5]. The proposed prototype is composed of:

- a digital tabletop (Fig. 1c), used to display the 3D model, allowing all participants to visualize the model and providing the designer with appropriate natural interaction to make changes on the model (using a CAD software);
- 4 digital tablets (Fig 1a), used to display the planning, allowing each practitioner to make changes on his part of the planning. The validations performed by Zaidi [14] on lo-fi prototypes showed that interactions with the 3D model on tablets are not useful and actors prefer to interact with 3D on the tabletop;
- a whiteboard (Fig. 1b), used as viewer, displaying the 4D model resulting from the 3D model and the planning sequences.

The prototype business scenario is based on a case study from a real construction site in Luxembourg. The studied detail is about the construction sequence of wooden wall which is built through many steps with various subcontractors (woodwork, insulation, and cladding). Moreover windows have to be installed during and after the assembly of the wall itself. A smooth coordination among actors is then necessary to drill accurate reservations within walls and to ensure that the openings on the wall fit the windows dimensions. A 4D simulation for this case study showed that it is possible to involve at the early construction stage the sub-contractors in the construction process planning, and to provide them with a visual support in order to interact with the model and to find out the optimal construction sequences.

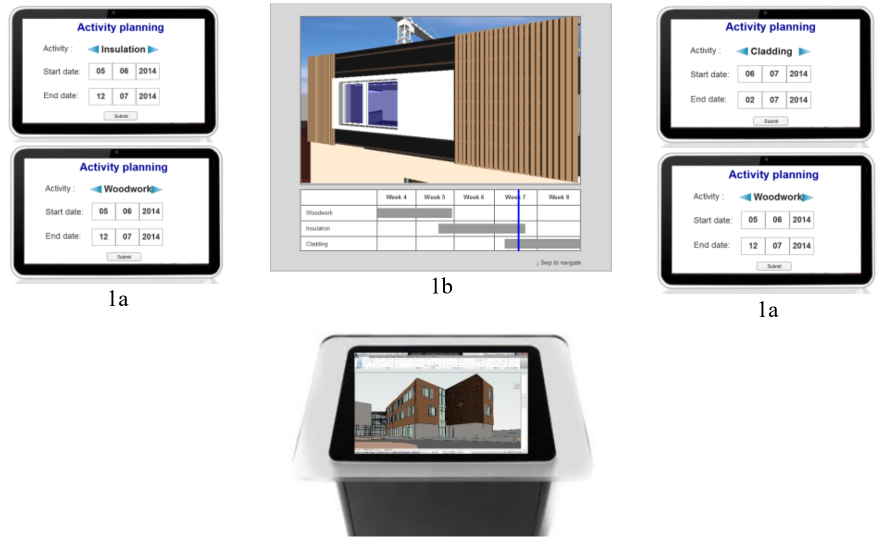

Figure 1 : Devices composing the Me-Fi prototype

On the technical level, a built-in screen is integrated to the tabletop. This screen is multitouch and at least 12 points. A 4D software is implemented on the tabletop in order to manipulate the 3D/4D model with multitouch gestures. The digital tablets are connected to the tabletop and the via Wi-Fi connection.

The research project is still at its beginning and experimentations are planned to be conducted in architecture and engineering agencies. Such experimentations will be studied by some psychologists and specialists in ergonomics in order evaluate the usefulness and the usability of the proposed prototype for collective decision making supported by 4D models in a synchronous and collocated environment.

4 Conclusion and future works

In this paper, we presented the very first steps of an ongoing comprehensive work which aims at supporting collaborative decision making in architectural design with synchronous collocated 4D simulation and Natural User Interfaces. A first prototype and a 4D case study from a real construction site are introduced. These elements provide a good basis to understand the research project approach. Future works will validate the proposed prototype in the line of the business case. It will then be possible to propose a real NUI-based collocated and synchronous 4D system, according to the prototype.

Aknowledgement

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VIRTUAL 3D RECONSTRUCTION OF PLANS-RELIEFS FROM HISTORICAL DOCUMENT ANALYSIS FOR VALORISATION APPLICATIONS

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***Abstract*— The French collection of Plans-Reliefs, scale models of fortified towns, constitutes an awesome architectural heritage. Facing this patrimonial richness, many cities, represented on these plans-reliefs, would like to expose, develop and exploit this historical heritage. However, the fragility, the dimension of the supports and the exposure conditions makes this acquisition difficult. Thus, the creation and the exploitation of a virtual model constitute an interesting alternative. This paper presents a method exploiting historical documentary for the 3D semantic modelling and the valorisation of the virtual Plan-Relief of Verdun. The original Plan-Relief is currently enclosed in containers in Paris.**

***Index Terms*—Historical documents, 3D semantic model, method, scale models, valorization application**

I. Introduction

The French collection of Plans-Reliefs constitutes an awesome architectural heritage. These scale models of fortified towns were built under the reign of Louis XIV of France (Fig.1). From an initial collection of 260 plans-reliefs, only one hundred models are preserved. Most of them are exposed in the "Invalides" museum in Paris and the others are in the museum "Palais des Beaux-Arts" in Lille (France). Facing this patrimonial richness, many cities, represented on these plans-reliefs, would like to expose, develop and exploit this historical heritage for tourism, urban and memorial issues. However, the fragility and the dimension of the supports and the conditions required for their exposure makes this acquisition very difficult and expensive. Thus, the creation and the exploitation of a virtual model constitute an interesting alternative for these cities steeped in history. This creation of a digital model requires the availability of the town scale model as experiments led with Prague [1] and Toul [2]. In this article we present a new approach based on historical documentary resources represented by preparatory documents. These historical documents bring together all the topographic surveys made on the ground by the engineers of the time and were used as specification for the construction of the plans-reliefs. Some of this material has been digitized. The method of 3D semantic modelling of plan-relief presented here proposes to utilize these media as a data source for the reconstruction of a virtual historical city model similar to the original plan-relief which was built manually with this same data source. This paper presents the method exploiting preparatory documents made on the city of Verdun, which is currently enclosed in containers in Paris, to rebuild a virtual plan-relief Verdun. The preparatory documents and the modelling method are presented respectively in Part 2 and 3. Some valorisation applications of this virtual model are presented in the last part of the article.

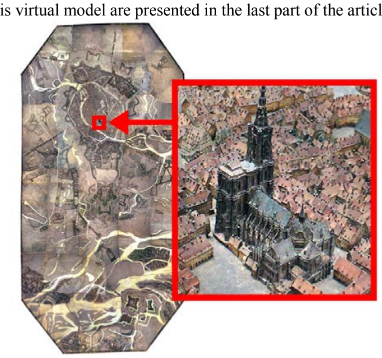

Fig. 1. Although the scale is 1:600, the objects shown on the model are highly detailed (for example, the 24 cm-high cathedral on the plan-relief of Strasbourg made in 1725-1758 and measuring 80 square meters (Musée historique de Strasbourg).

II. The historical documents

The plans-reliefs of the nineteenth century have been built according to several types of historical preparatory documents including many graphic documents. The *épures* are large plans depicting each parts of the scale model (*tables* in French). The drawing limits are irregular as they follow the delineation of the parts of the scale models. Every constructed and landscape elements are drawn on these plans as well as contour lines [3].

Other graphic documents include the elevations and plans of each city block, hamlet, isolated farm or fortification work. These drawings were taken from field measurements that were conducted by topographer artists. The elevation views are in fact developed elevations (the sides of the construction are like unfolded nets), which may explained why these historical documents are called "book of nets" (*cahiers de développements* in French). The drawing scale is 1:600 like the scale-models. These graphic documents are also annotated giving precise knowledge of the nature of the materials used for walls, roofs, grounds, etc. For example, abbreviations are used to identify flat (f.t.) or barrel tiles (b.t.). Color and materials are specified for facades (warm shade, sepia, ochre, new, etc.).
The correspondence between plans and elevations is done through two types of annotations: letters to identify the courtyards and numbers to define portions of the elevations. The example illustrated in figures 2 and 3 shows a courtyard (Y) and elevations (1, 2, 3, 4, 1).

However, inconsistencies, errors and omissions are common and make it necessary to use *a priori* knowledge for addressing interpretation problems. Among the difficulties encountered, we noticed a lack of data. Spending more time to understand and to interpret documents can solve this problem. In addition, these graphics are not always readable and often present contradictions between them.

Another example of problem illustrated in figures 2 (inside the red area) and 3 (under the red arrow on the elevation), shows an inconsistency and parasite lines between the building (4 to 1) in ground plan and elevation. Note that on the plan (Fig. 2) between number 4 and 1 there is a single building, while on the elevation (Fig. 3) there are two buildings side by side. So, we see that the limits of the buildings are not readable and not well defined.

This ambiguity is the most common problem in some city blocks, with random segments and omissions that make it difficult to separate the boundary of the parcel and building type.

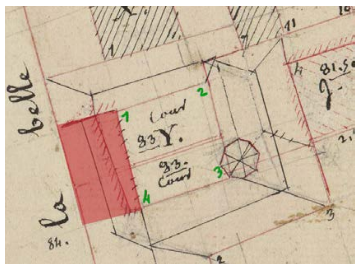

Fig. 2. Floor plan excerpt from a city blocks

Even if significant simplifications have been made in graphic documents, these materials offer a unique documentation on the evolution of cities, fortifications, architecture and countryside. That is why the museum of Plans-Reliefs started a digitizing campaign of its preparatory documents in 2010. Today, only two preparatory documents of six avalaible were digitized and made available on the web. Problems of access to the scale models have led the decision to use the orthographic projections contained in the preparatory documents to develop a new approach of 3D semantic modeling of plans-reliefs.

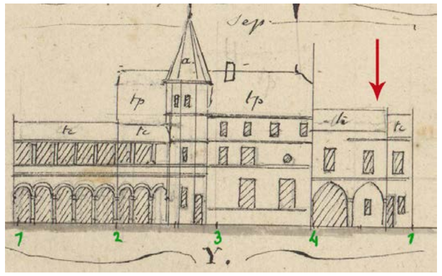

Fig. 3. Elevation overlooking the patio.

III. The 3D semanctic modelling method

Our modeling process is explained in Fig. 4. It is a knowledge-based approach that consists of two steps: the first one is common to all projects, whereas the second one is specific to each scale model.

Step 1: firstly, a knowledge model of the studied architectural elements (buildings and fortification works) is carried out (a) thanks to reference literature (e.g. classical and military treatises). Each kind of element is described in a library of parametric entities (b). This library can be enriched at anytime if required. For more details about the library, you can read [1] [4].

The second step is different depending on the studied elements; buildings or fortification works.

Step 2 for the buildings: secondly the modeling process consists of the following steps:

- semi-automatic step (d): 2D drawing of polygons in the plans : ground outline of the buildings and elevations. This step is manual for the ground plan (some tests carried out by specialists of this domain research did not produced exploitable results). For the elevations, simple algorithms allow us to automatically detect simple facades and their openings.
- Relations between the ground outline of buildings and their elevations are then manually specified. Each segment of the ground outline can be connected to a corresponding elevation (d).
- Finally, from a ground outline and its corresponding elevations, we automatically compute the 3D textured model of the building (e) according to a given parametric object of the library.

Step 2 for the fortification works: an automatic modeling approach (KASTOR) of the fortification works has already been developed for the post treatments of 3D survey data. The adaptation of this process with graphic documents as input data is still a work in progress: the main issue is to automatically extract the outline of fortification works (d) in order to use KASTOR for the 3D modeling (e).

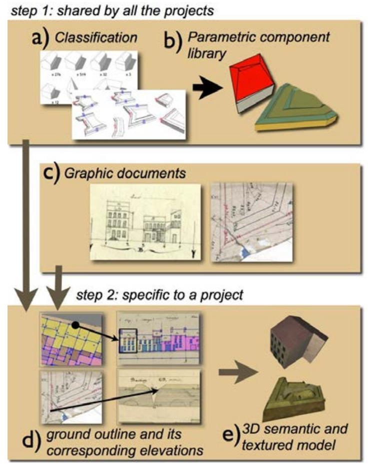

Fig. 4. Modelling process for the creation of the parametric elements.

IV. Valorisation applications

3D models of plans-reliefs can be imported into 3D engine development platforms for creating applications in real-time 3D, such as Unity 3D, Unreal engine, etc (Fig.5). With some adjustments on 3D models when importing and writing a few scripts, it is possible to attach the knowledge related to the semantic modeling we made earlier. From there, the possible applications of valorization of plans-reliefs are many and varied.

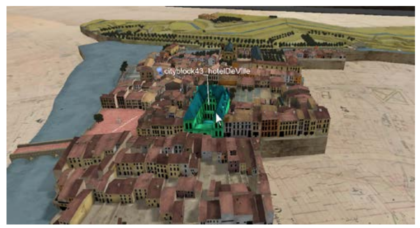

Fig. 5. 3D semantic model of Verdun plan-relief integrated in Unity 3D.

A. Kiosk

Conception of kiosks for visualization of plans-reliefs is possible. Interactive navigation can be done with a free hand gestural interface by using a tiny device called Leap Motion. Thus, through the airplane metaphor [5] allowing a fast and intuitive learning, everyone, even without browsing experience into 3D models, can easily navigate through the 3D model by flying over the plan-relief.

Figure 6 illustrates a free hand travel on a computer using Leap Motion device situated just below the hand.

Fig. 6. Free hand travel above the 3D plan-relief of the city of Verdun using the airplane metaphor.

B. Multi-touch and tangible table

The virtual model of plan-relief can also be used as interactive support on multi-touch tables. The semantic modeling of buildings allows an individual identification of each element. So, actions (such as displaying information, etc.) are possible when an interaction occurs (tap on an element).

Furthermore, multi-touch tables can manage a tangible interface by recognizing objects put on their surface, either by markers (as RFID, 2D pattern) [6], or by using sets of marks stuck under objects serving to simulate fingers [7]. Thus, the pose of an object on the table can launch actions: for example, the pose of a tangible model of church could highlight all the religious buildings (Fig. 7).

Fig. 7. Tangible table : the pose of a 3D printed object, that represents a church, highlights all the religious buildings in the virtual plan-relief

C. Tablet computer and augmented reality

The virtual model of plan-relief can also replace a town map on a tablet computer (Fig. 8). It is then used as support in mobile applications of educational rally in order to visualize the differences between the current city and what it was at the time period of the plan-relief. The virtual model and the knowledge attached to architectural elements can then be used and presented to the user as augmented information on reality.

Fig. 8. Tablet computer : visualisation of the virtual plan-relief of Verdun as a map used in mobile application of educational rally.

D. Augmented 3D printed model

A 3D printed model of the plan-relief can be make in white color with a 3D printer to obtain a physic object serving as screen for a video projector. Thus, the projection of a video on this 3D printed model is able to highlight various locations of the map in a synchronous way with an interactive application showing information attached to architectural elements.

Figure 9 shows a picture of an augmented 3D model. The differences of colors are due to the video-projector showing specific places according to user's interaction.

Fig. 9. Augmented 3D model of Barcelona *(Located at Col·legi Oficial d'Arquitectes de Catalunya. COAC. Plaça Nova, 5, Barcelona).*

V. Conclusion

The creation and the exploitation of digital models of plans-reliefs constitutes for the represented cities a real opportunity for touristic, historical or urban valorization. The under development proposed method uses historical digitized documents. It allows overcoming the high cost and the difficulty of acquisition of a plan-relief and it is able to model most building types present in the different city blocks of the plan-relief of Verdun. More complex buildings like churches and administrative buildings are hand-modelized. The examples of valorization are under experimentation with the city of Verdun, financer of this project. A first studied improvement track concerns the modeling of more complex objects such as religious buildings where a parametric approach is being developed. Concerning the valorization applications, an exploitation of the 3D semantic model is envisaged in a GIS for the purpose of an urban scale usage by the general public or administrative services of the city. We also wish to replicate this experience using this method for modeling the plan-relief of Toul from its preparatory documents. We will then be able to compare this model to the one realized in a first project from a digital acquisition [2] and thus analyze and interpret differences and their origins (historical, technical, human).

Acknowledgment

The authors thank the community of communes of the city of Verdun, which finances the project.

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Navigation main libre dans une reconstitution urbaine 3D : application à la valorisation de plans reliefs

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Résumé

Cet article décrit une interface de navigation par survol dans une reconstitution urbaine numérique en 3D de plan relief. Cette navigation s'effectue en utilisant la métaphore de l'avion mimé à partir d'une main libre de tout dispositif physique, et dont l'acquisition de sa position et de son orientation se font à partir d'un périphérique de repérage et de suivi 3D. Ce mode de navigation a été mis en place dans le cadre d'une valorisation grand public du plan relief de la ville de Verdun en Meuse, France (maquette à l'échelle 1/600^{e}). Deux évaluations ergonomiques ont été menées afin d'évaluer ce type d'interface, d'en révéler ses défauts, et d'en gommer certains. Des perspectives de solutions sont abordés concernant les défauts restants.

Mots clés choisis par les auteurs

Interaction gestuelle ; Leap Motion; Navigation ; 3D ; Échelle urbaine.

Mot clés de la classification ACM

H.5.2. Information interfaces and presentation (e.g., HCI): User Interface.

Introduction

La valorisation du patrimoine architectural et urbain auprès du grand public par l'exploitation des modélisations numériques de celui-ci constitue un réel challenge pour les acteurs de ce domaine (conservateurs, archéologues, historiens, architectes, etc). La mise à disposition d'un mode de navigation à un public comme celui d'un musée, nécessite une appropriation rapide, afin que l'exploitation du modèle 3D soit la plus pertinente et la plus attrayante possible. Hors, le mode de navigation dans un modèle 3D d'un espace bâti, diffère selon son échelle. Dans un bâtiment, une navigation en vue subjective est bien adaptée, alors qu'à l'échelle urbaine, comme les plans reliefs, une navigation par survol offrant une vue d'ensemble est plus adéquate [1].

Avec l'émergence actuelle des dispositifs de repérage 3D à tarifs abordables (Kinect, Leap Motion, …) il devient envisageable de proposer au grand public de nouvelles interfaces gestuelles de navigation dans des villes virtuelles en 3D, sans que les mains n'aient à tenir un quelconque périphérique. L'objectif de cet article est de présenter une navigation main libre, adaptée à la valorisation du patrimoine particulier de la collection des Plans Reliefs [2] (cf. figure 1).

Navigation et valorisation

De plus en plus souvent, le besoin de naviguer dans des environnements 3D reconstitués se pose. Ceci est dû à l'amélioration des matériels informatiques qui permettent l'affichage 3D temps réel d'environnement 3D de plus en plus complexes et réalistes, et à l'accroissement de la facilité de mettre à disposition des modèles 3D (ex. WebGL pour la 3D dans les pages Web). Ainsi, même si Google Earth a permis de banaliser, il y a quelques années, la navigation 3D, il reste une partie de la population qui n'a pas l'habitude des environnements numériques en 3D et qui est de plus en plus souvent confronté à cette situation.

Une problématique est de mettre à disposition de visiteurs, des bornes interactives dans des lieux publiques, pour visualiser et naviguer facilement dans des reconstitutions numériques 3D de plans reliefs [3]. La collection des plans reliefs comprend une centaine de maquettes (cf. figure 2) réalisées généralement au 1/600e et représentant les places fortifiées des frontières du territoire français du XVIIe au XIXe siècle. Hors, faute de places adaptées, elles ne sont qu'une fraction aujourd'hui à être exposées. La création de modèles 3D virtuels de plans reliefs est une réponse aux enjeux de préservation et de valorisation d'un patrimoine riche, mais méconnu [4].

Si plupart des modèles 3D numériques des plans reliefs ont été obtenus par des scans 3D (ex. plan relief 3D de Prague [5]), celui de Verdun a été réalisée par une méthode semi automatique à partir des cahiers de développement [6] (rassemblements de relevés topographiques, de croquis, et de milliers de mesures réalisés sur le terrain par des topographes au XVIIe siècle), parce que sa maquette réelle n'est pas accessible (stockée dans une réserve), et que son coût pour l'en faire sortir s'élève à plusieurs dizaines de milliers d'euros.

La navigation par survol au sein d'une reconstitution numérique 3D d'un plan relief se justifie par le fait que l'échelle de ces plans reliefs et leur taille (53m^2 pour Verdun) ne leur permet d'être vu que depuis une position située au dessus. Et aussi par le fait que plans reliefs sont des maquettes de villes dont l'objectif était d'offrir au roi une vision globale des défenses des villes [4], et ne présentent pas de vue très détaillée, ni très précise, des bâtiments. De ce fait, leur parcours d'un point de vue pédestre est inadapté. Hors, la navigation par survol d'un modèle 3D d'environnement urbain reste problématique [7], surtout pour des utilisateurs

Figure 1. Survol du plan relief 3D de la ville de Verdun par la métaphore de l'avion (ici sur un écran standard).

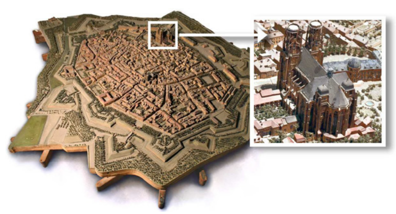

Figure 2. La table principale du plan relief de Toul (2.23m x 2.13m) et un détail montrant la cathédrale d'une dizaine de centimètres.

occasionnels. En effet, la souris a été conçue dans l'optique de parcourir un espace 2D, et s'adapte mal à une navigation 3D intuitive [8], sans parler du risque désorientation spatiale [9]. Afin de palier ces manques, de nombreuses interfaces de navigation 3D ont également recours au clavier (en sus de la souris) comme dans Jankowski et al. [8]. Ou encore, elles remplacent la souris par d'autres périphériques comme la spacemouse, le flystick, etc. Ces derniers nécessitent d'être manipulés par l'utilisateur pour naviguer, ont un coût élevé, et posent des problèmes d'hygiène par leur passage de main en main. Ces aspects induisent souvent des difficultés d'utilisation, surtout pour des utilisateurs occasionnels comme peuvent l'être de nombreuses personnes visitant un musée.

Interface de navigation par survol

La notion de survol est naturellement associée à la notion d'avion. Nous sommes parti du constat que si on demande à quiconque de mimer un avion avec sa main, pratiquement tout le monde effectue un mouvement de roulis pour simuler un virage, et un mouvement de tangage pour simuler une montée ou une descente (cf. figure 3).

Partant de cette constatation de gestuelle naturelle nommée "métaphore de l'avion" dans [10], nous avons décidé d'expérimenter celle-ci dans le cadre du survol de plans reliefs 3D numériques, mis à disposition du public à l'aide de bornes. Nous avons choisi de tester cette métaphore de navigation sur le plan relief de la ville de Verdun. Le modèle virtuel de ce plan relief a été implémenté dans Unity 3D (moteur 3D temps réel dédié à l'origine au jeu vidéo [11]), qui se prête bien à la visualisation et à la navigation dans des modèles 3D urbains [12] comme les plans reliefs.

La nécessité d'avoir un périphérique de repérage et de suivi 3D a donc été envisagé afin de pouvoir détecter cette gestuelle naturelle. De surcroit, il était nécessaire qu'il puisse être ajouté à des bornes tactiles existantes à moindre coût. Parmi les périphériques de repérage et de suivi 3D, la Kinect a été rejetée, car son SDK ne distinguait que l'ouverture/fermeture de la main. L'usage d'une caméra, pour le repérage et le suivi, a également été rejeté pour les nombreuses contraintes que ce système impose (ex. coût élevé, encombrement illumination invariante, fond invariant, etc) [13].

Ainsi, l'usage du boitier Leap Motion [14] s'est rapidement imposé :

- de par son coût très abordable : 90 $ US;
- sa taille réduite : 8 x 3 x 1,2 cm (L x l x h);
- ses capacité de détection, notamment son aptitude à reconnaitre une main et ses doigts et leur orientation respective, et sa précision de mesure (0.01 mm selon la société Leap);
- l'absence d'illumination particulière (fonctionne dans la pénombre grâce à ses leds infrarouges [15]);
- et le fait qu'il est multi-plateformes (OS X, Windows, Linux).

Réalisation

Ce petit boitier, couplé à l'ordinateur d'une borne tactile, nous à permis à l'aide de son SDK pour Unity 3D, d'implémenter la métaphore de l'avion. Le boitier renvoie périodiquement l'orientation de la main détectée sous la forme d'un couple de vecteurs : le premier indiquant la direction de la main, et le second, une normale à la main (cf. figure 4). L'implémentation de la navigation se fait de manière triviale, grâce au

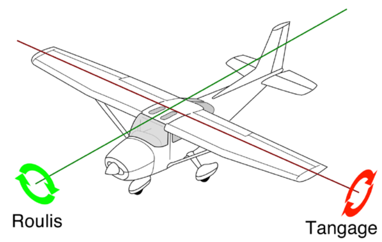

Figure 3. Axe de roulis (en vert) et et tangage (en rouge).

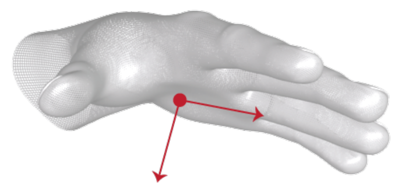

Figure 4. Les vecteurs de direction et normal à la main (source de l'image: documentation SDK Leap motion)

SDK qui permet de calculer, à partir de ce couple de vecteurs, les angles de tangage et de roulis.

Au final l'avion virtuel de la métaphore se comporte de la manière suivante :

- un roulis de la main fait virer celui-ci ;
- un tangage de la main fait lever ou baisser le nez de l'appareil;

L'écran joue alors le rôle de la fenêtre du cockpit de l'avion sur le monde extérieur. Comme la métaphore de l'avion ne requiert pas de translation de la main pour simuler le déplacement [16], nous avons fait le choix d'un déplacement continu de l'avion, dès la détection par le boitier, d'une main ouverte. Le caractère ouvert de la main se fait en regardant le nombre de doigts visibles (c.à.d. déployés) renvoyé par le SDK. De manière réciproque, la sortie de la main de la zone de détection, ou sa fermeture, entraine l'arrêt de tout déplacement.

Ce choix permet de garder une gestuelle simple, où l'utilisateur n'a pas à se soucier de contrôler la vitesse. Il fournit également une meilleur expérience utilisateur selon Nabiyouni [16]. De plus, afin d'éviter que l'utilisateur n'entre en collision avec les bâtiments, ou encore perde l'avion virtuel dans la stratosphère, des niveaux de navigation minimum et maximum ont été choisis afin de borner les altitudes de navigation. Le boitier a été positionné de sorte que la main ne vienne pas obstruer l'écran pendant la phase de survol, afin de conserver une vue complète de l'affichage. De plus, pour limiter une éventuelle fatigue, le boitier est positionné de sorte que l'utilisateur puisse amener sa main au dessus sans avoir le bras tendu [17]. L'écran tactile de la borne reste utilisé pour désigner un objet et obtenir des informations sur ce dernier.

Évaluation ergonomique

Notre objectif est de proposer une interaction perçue comme facile d'apprentissage, pratique, amusante et produisant le minimum d'erreurs et de fatigue. Ces variables renvoient directement aux attributs composant l'utilisabilité comme définie par Scapin et Bastien [18]. Les attributs sont mesurés grâce à une échelle de Lickert à cinq modalités. Notre hypothèse était que la métaphore de l'avion rendrait la gestuelle facile à apprendre, pratique et amusante. En revanche, nous avons envisagé une fatigue des utilisateurs due à la gestuelle.

Le dispositif étant destiné à un usage public, notre but était de le concevoir tel que son temps d'utilisation moyen (passé à maîtriser la gestuelle et à explorer la maquette) soit inférieur à cinq minutes. Nous avons mesuré le temps mis par des sujets à atteindre différents objectifs pour être sûr que ce but soit atteint.

Nous nous sommes placés dans une démarche itérative, en alternant expériences et corrections du système. Le système testé était constitué d'une table interactive ainsi que du boîtier Leap Motion situé à hauteur de main. L'expérience s'est déroulée en trois temps : d'abord présentation de l'expérience et remplissage d'un questionnaire destiné au profilage, puis prise en main du dispositif et réalisation de trois taches de difficulté croissante, et enfin remplissage d'un questionnaire recueillant les avis sur l'expérience utilisateur et les suggestions d'amélioration du dispositif.

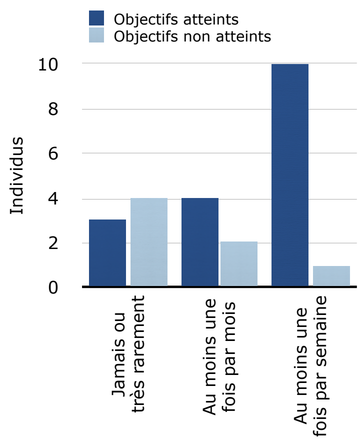

Figure 5. Réussite en fonction de la fréquence de confrontation à un environnement 3D

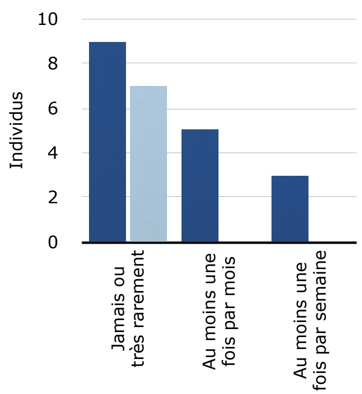

Figure 6. Réussite en fonction de fréquence de confrontation à une interface 3D

Résultats des expériences

Première expérience

24 sujets volontaires de 11 à 51 ans ont passé cette expérience. Elle a duré en moyenne 90 secondes avec de fortes variations entre les sujets (écart-type de 53 secondes). 37,5% des sujets tentent de tourner par abduction et adduction du poignet (changement de l'orientation horizontale du poignet respectivement vers soi et vers l'extérieur). 70% des sujets réussissent à atteindre les 3 objectifs, et 30% abandonnent avant. Les sujets n'arrivant pas à atteindre leurs objectifs sont des sujets ayant pas ou peu d'expérience avec les environnements 3D et les interfaces gestuelles (cf. figures 5 & 6; l'expertise influe sur la performance [19]). Parmi les items renseignés sur l'expérience ressentie, l'affirmation avec laquelle les utilisateurs sont le moins d'accord était « le système faisait ce que vous lui ordonniez de faire » (cf. figure 7). Nous avons alors visé à réduire ce décalage entre gestuelle effectuée et réponse du système.

Seconde expérience

Pour la version suivante du logiciel, la rotation horizontale de la vue peut se faire par abduction/adduction en supplément de la supination/pronation (inclinaison de l'avant-bras pour mimer l'inclinaison des ailes d'avion). Les utilisateurs faisaient instinctivement ce geste lors de la précédente expérience. Une seconde expérience similaire à la première a été menée avec la nouvelle version du logiciel et 12 autres utilisateurs âgés de 15 à 59 ans.

La durée moyenne est semblable (86 secondes au lieu de 90) mais 50% des utilisateurs continuent à naviguer dans le plan-relief après avoir terminé les tâches, ce qui n'est arrivé que chez 4% des sujets au cours de la première expérience. Dans cette passation, 91% des sujets utilisent l'abduction/adduction pour orienter leur vue, ce qui confirme que ce type d'interaction est perçu comme plus naturel pour accomplir ce type de tâche. De plus, tous les sujets arrivent à remplir tous leurs objectifs, qu'ils soient familiers ou non avec les environnements ou interfaces 3D, contrairement à la première expérience. 25% des utilisateurs sont toujours en désaccord ou neutres avec l'affirmation « le système faisait ce que vous lui ordonniez de faire » (cf. figure 8). 50% des sujets demandent à reculer lors de cette deuxième passation, 25% souhaitent changer le niveau de zoom et 8% demandent à changer l'orientation sur place.

Conclusion et perspectives

Les résultats de l'évaluation ergonomique montrent que le dispositif remplit déjà les buts d'utilisabilité chez les utilisateurs habitués aux interfaces gestuelles, et les travaux futurs viseront à ce que ces buts soient atteints chez les utilisateurs non habitués. La deuxième version s'est révélée plus satisfaisante en matière de performance des utilisateurs tout comme de ressenti.

Grâce aux deux expérimentations menées, nous avons mis en valeur les fonctionnalités manquantes qui seraient utiles à la tâche mais incompatibles avec cette métaphore. Le recul, le zoom et le changement d'orientation à l'arrêt sont les fonctions à ajouter en premier d'après les testeurs. Les nouvelles fonctions peuvent être implémentées en détectant la position de la main par rapport au Leap Motion, en supplément de l'orientation qui est pour l'instant notre mode d'interaction principal. L'ajout de ces fonctionnalités nécessitera potentiellement de remplacer la métaphore de l'avion.

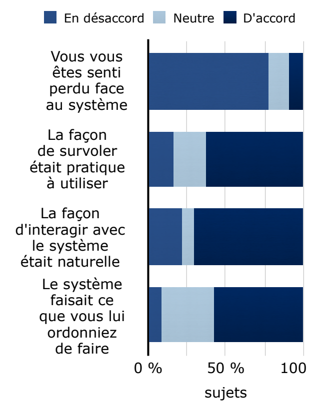

Figure 7. Première expérience

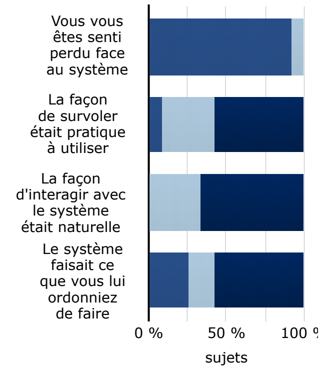

Figure 8. Seconde expérience

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Index des conférences

CIPA 2013, Strasbourg, France. *(p. 13)*
La documentation du Patrimoine CIPA est une organisation internationale qui s'est fixée deux objectifs : suivre les évolutions technologiques et assurer leurs exploitation pour la conservation du patrimoine culturel, l'éducation et la diffusion. Cet organisme organise un congrès international biannuel qui constitue une plateforme d'échange d'idées, des meilleures pratiques et la diffusion de travaux de recherche scientifique.

Digital Heritage 2015, Grenade, Espagne. *(p. 19, 157)*
La première édition de « Digital Heritage International Conference » a eu lieu à Marseille en Octobre 2013, rassemblant des professionnels et des chercheurs dans les domaines du patrimoine culturel et des technologies de l'information dans le but de développer l'utilisation de ces technologies pour le patrimoine.

CAAD Futures 2015, Sao Paulo, Brésil. *(p. 35, 63)*
CAAD Futures est une association néerlandaise créée en 1985 dont le but est de promouvoir, à travers des conférences et des publications internationales, la conception architecturale numérique au service de ceux qui s'intéressent à la qualité de l'environnement bâti. Une de ses principales actions est l'organisation d'une conférence internationale biannuelle.

Creative Construction Conference 2015, Cracovie, Pologne. *(p. 51)*
Les *Creative Construction Conference* sont un espace de rencontre et de discussion pour les chercheurs ambitieux et les praticiens issus des quatre coins du globe qui s'accordent sur le fait que l'industrie de la construction évolue de plus en plus rapidement, vers plus de créativité ; grâce aux technologies, aux matériaux de construction et à la gestion de projet.

CDVE 2014, Seattle, Etats-Unis d'Amérique. *(p. 153)*
CDVE 2015, Majorque, Espagne. *(p. 61)*
CDVE (Conference in Cooperative Design Visualisation and Engineering) est une conférence internationale qui promeut les activités de recherche sur la conception coopérative, la visualisation coopérative, l'ingénierie coopérative et leurs applications dans tous les domaines de l'ingénierie.

eCAADe 2015, Vienne, Autriche. *(p. 43, 119)*
eCAADe 2016, Oulu, Finlande. *(p. 69)*
eCAADe (Education and research in Computer Aided Architectural Design in Europe) est une association regroupant des institutions et des personnes ayant un intérêt commun dans la promotion des bonnes pratiques et le partage d'informations en relation avec l'utilisation de l'informatique dans la recherche et l'éducation en architecture. Elle organise chaque année une conférence internationale. Cette association a créé les archives électroniques CUMINCAD regroupant des publications scientifiques dans le domaine de la conception architecturale numérique.

SCAN'14, Luxembourg, Luxembourg. *(p. 81)*
SCAN'16, Toulouse, France. *(p. 136)*
Le Séminaire de Conception Architecturale Numérique (SCAN), rendez-vous biannuel de la communauté francophone de l'architecture, est une conférence qui rassemble des chercheurs autour de questionnements portant sur les implications du numérique en conception architecturale. Il vise à éclairer l'architecture du point de vue de ses relations aux usages des technologies de l'information et de la communication dans l'intention d'imaginer, de spécifier et de développer de futurs usages et de nouveaux outils adaptés aux spécificités et aux évolutions de la conception architecturale.

CAADRIA 2015, Daegu, République de Corée. *(p. 93)*
L'Association CAADRIA (Computer-Aided Architectural Design Research) favorise l'enseignement et la recherche en conception architecturale numérique en Asie, et compte des membres sur les six continents. Elle organise une conférence annuelle dont la première a eu lieu en 1996 à Hong Kong. Depuis, dix-huit conférences ont été organisées en Australie, Chine, Hong Kong, Inde, Japon, Corée, Malaisie, Singapour, Taiwan et en Thaïlande.

ICCCBE 2016, Osaka, Japon. *(p. 128)*
L'ICCCBE (International Conference on Computing in Civil and Building Engineering) est une conférence internationale qui regroupe des chercheurs du monde entier dans le domaine de l'ingénierie du génie civil. En 2016 avait déjà lieu sa seizième édition. L'ICCCBE est sponsorisée par l'ISCCBE (International Society of Computing in Civil and Building Engineering).

IHM 2015, Toulouse, France. *(p. 161)*
La Conférence Francophone sur l'Interaction Homme-Machine (IHM) regroupe des chercheurs dans le domaine de l'IHM en favorisant la pluridisciplinarité (informatique, psychologie, sociologie). Elle est soutenue par l'Association Francophone d'Interaction Homme-Machine. En 2015 avait lieu sa 27ème édition.

EUROGRAPHICS 2016, Gênes, Italie. *(p. 21)*
Eurographics est une conférence internationale organisée une fois par an par l'association Eurographics. En 2016 avait lieu la 37ème édition. Elle concerne le domaine de l'infographie, des constructions géométriques jusqu'aux représentations photo-réalistes en passant par l'animation et la simulation de phénomènes naturels.