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APPLICATION OF GPR-TECHNOLOGY FOR IDENTIFYING THE MATERIAL COMPOSITION OF BUILDING COMPONENTS

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ABSTRACT

Currently various technologies are used in order to determine the geometry of existing buildings, however there is no established technology to identify the material composition of buildings. The traditional material identification of existing buildings is conducted manually through destructive methods, which is not accurate enough and cannot be applied in the operation phase. Within this paper, ground penetrating radar (GPR) technology is applied on a real use case to determine the material composition of buildings. The traditional and GPR method are compared regarding costs and time effort. Results show, that the GPR method has great potential, but requires further optimizations.

INTRODUCTION

The construction industry is the world's largest consumer of raw materials and accounts for 25% of the total solid waste generated worldwide (Yeheyis et al., 2013). In many European countries, the secondary stock is even larger than the primary resources, as for example in Austria, which is a country that strongly depends on imports due to the low amount of primary resources (Brunner and Rechberger, 2016). Thus, it is of utmost importance to reduce the consumption of virgin materials and increase the reuse and recycling of materials in the stock. The systematic reuse of anthropogenic materials from the existing stock is a new approach towards recycling, an approach labelled as "Urban Mining" which is one of the main strategies within Circular Economy (CE) (Klinglmair and Fellner, 2010). However, the main problem that the construction sector is confronted with, is the lack of information about the existing building stock (Brunner, 2011), since in general planning documents are either not available or do not comply with the actual state of the building. Thus, due to lack of information on existing buildings, planning the end-of-life stages of buildings as well as enabling reuse and recycling of the existing material stocks is difficult.

In order to obtain the geometry of existing buildings various digital capturing methods are available, such as photogrammetry and laser scanning, both established methods in the AEC (Architecture, Enginering and Construction) -industry. However, there is lack of digital technologies for the identification of materials embedded in building components. The traditional material assessment of buildings is conducted manually through knocking and drilling. These methods are mainly conducted at the end-of-life stage of buildings in the scope of a pre-demolition waste audit in order to assess the amount and type of waste that will occur at demolition of the building, without paying attention on the recycling and reuse potential. Usually, this information is not accurate, since it is based on general assumptions from planning documentations and random samples. Moreover, the traditional assessment of existing buildings through knocking and drilling is only possible at the end-of-life stage, when the users moved out of the building. However, in order to assess the reuse and recycling potential of materials embedded in buildings as well as the material value of the building, schedule the thermal renovation of buildings, plan sustainable waste streams, and make these materials available publicly, the information on the exact material composition is needed prior the end-of-life stage of a building. Accordingly, non-destructive methods are needed to capture the exact material composition without destroying the existing building, which would enable the development of a digital urban mining platform consisting of relevant information of buildings.

Within this paper, Ground Penetrating Radar (GPR) technology is used for material identification, which enables a non-destructive characterization of the material composition of building components. GPR is a near-surface geophysical tool which is applied for multiple purposes ranging from geological studies and geotechnical engineering to environmental contamination and biomonitoring (Zhao et al., 2013). Through the GPR, a non-destructive characterization of shallow subsurface targets is enabled, based on changes in the electro-magnetic properties of the materials (Davis and Annan, 1989). Due to its non-destructive character, the GPR found broad application in archeological studies in the last decades. The GPR enables mapping of the spatial extent of buried cultural heritage as well as pre-excavation subsurface imaging without destroying essential archaeological evidences (Trinks et al., 2018). A GPR device consists of a transmitting and receiving antenna, whereby the transmitting antenna sends electromagnetic waves into a subsurface, where the waves are reflected from interfaces or scatter off from point sources and travel back to the receiving antenna. The time the electromagnetic wave needs to travel to an interface and come back tho the surface is called travel time, which allows to make assumptions about the distance of the detected target. The amount of energy, that comes back from the electromagnetic wave, depends on various characteristics such as the permittvity of the material, which allows to make assumptions about the electrical conductivity and dielectrical constant and accordingly the material type (Davis and Annan, 1989).

Terahertz spectroscopy is a promissing non-destructive method, which did not find a broad application in the AEC-industry yet, as it is mainly used for pharmaceutical products and biological tissues, such that it delivers results on small-scale (trace mineral) (Abina et al., 2015).

This paper is based on the funded research project SCI_BIM "Scanning and data capturing for Integrated Resources and Energy Assessment using Building Information Modelling" (grant number 867314), which was conducted with industrial partners and research institutes of TU Wien. Within SCI_BIM various methods for generating an as-built BIM-Model of an existing asset are tested and evaluated regarding the applied technologies as well as their cost and time efforts.

Within this particular paper, the potentials of GPR-technology for material identification of building components will be explored. The aim is to demonstrate the application of the GPR on a real use case and determine the correctness and precision of the obtained results. A further aim is to evaluate the costs and time effectiveness of the GPR method in comparisson with the traditional material chracterization method. The novel contribution of this paper is the application of the GPR-technology for a semi-automated material identification of building elements, thus closing a gap, since research dealing with this content is lacking.

EXPERIMENT

The application of the GPR is demonstrated on a real use case – a facility of TU Wien. For obatining the geometry and generation of the as-built BIM, laserscanning technology was applied. The point-cloud obtained from laser scanning built the basis for the manual creation of the "geometrical" BIM-Model, which consists of the exact dimensions of each building component as well as a unique element ID for each component. The manually generated BIM-Model served as reference model for the GPR-measurements, which were carried out after the BIM-Model was created. Since the focus of this paper lies on the identification of the building`s material composition through GPR, the process for generating the BIM with exact geometrical information is not further explained. The building was to be demolished in the near future, thus destructive methods could be applied to identify the real material composition of the building, enabling the comparisson of the results as well as calibration of the GPR-measurements. The GPR and traditional method for material identification were assessed and compared regarding costs and time efforts in order to estimate the potentials for a broader future application to enable the generation of a digital urban mining platform.

Use Case

The investigated building (Figure 1) is located in the third district of Vienna and has a total area of 1265m². The facility of TU Wien comprises of three parts: the office, lab and storage, which can be distinguished from outside due to their varying heights. The highest part of the building is the storage, whereby the lowest is the office. Between the office and the storage, the lab is located. The building was occupied at the beginning of the investigations in the building. After the move out of the occupants, destructive methods were applied to identify the actual material composition of the building components.

Figure 1: Aerial image of the facility

GPR method

The GPR-measurements were conducted on all walls and floors of the use case, however, a verification of the material composition was only possible for the walls, which is the reason why only the reuslts of the walls are presented in this paper. 89 measurements were conducted on the walls with a 1.6 GHz GPR-antenna. Most of the walls were measured on three varying heights (bottom, top and in between at a height of 1.1 m) horizontally. Following a horizontal line, a measurement was taken every centimeter. To obtain a final result per wall, the mean value of the measured parameters was assessed. Some of the measurements were only conducted on one height of the wall, since the composition did not differ from bottom to top, thus one measurement was sufficient. Figure 2 shows the floor plan of the use case (lab and

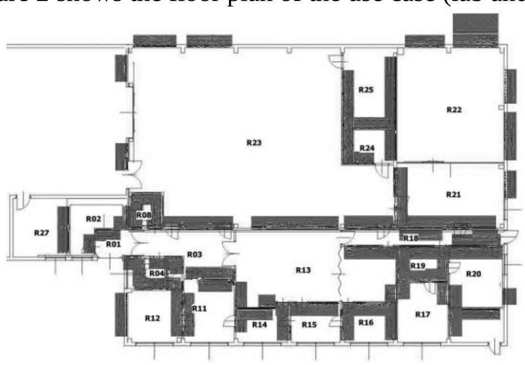

Figure 2: Floor plan with corresponding radar images (©ZAMG Archeo Prospections)

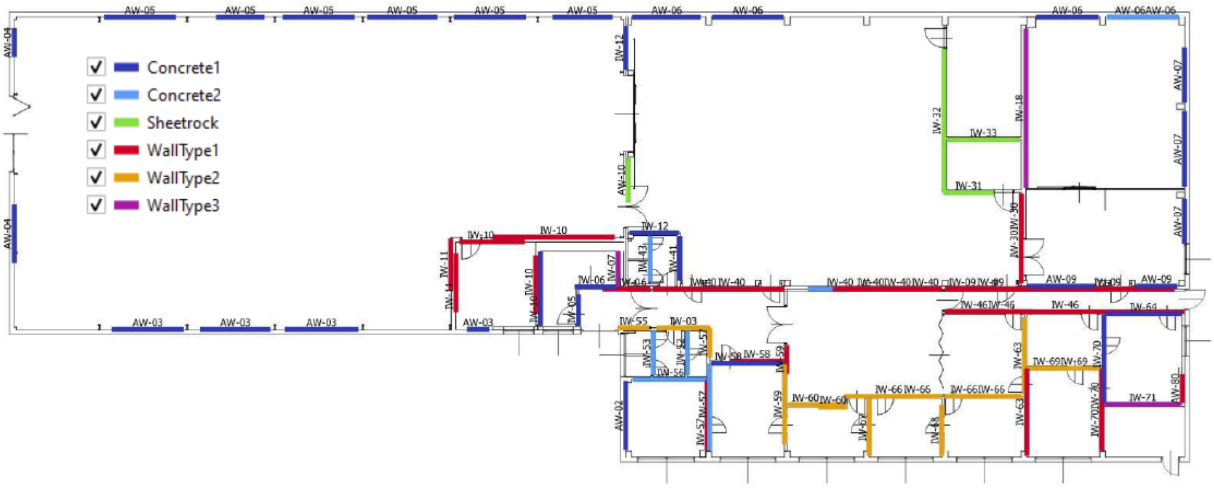

Figure 3: Initial classification results (©ZAMG Archeo Prospections)

office part) with the corresponding radar images of the walls. All GPR-measurements are referenced to the "geometrical" BIM-Model via the element IDs, and shown in a GIS (Geographic Information System).

For the classification of the walls regarding their material composition, three parameteres were meausured from the received GPR wave: the energy of the first local maximum in the measured signal (E1), the energy of the second local maximum in the measured signal (E2) and the main frequency of the first maximum wave (F). In previous research, the amplitude of the first arriving wave was used e.g. for identifying probable pathological areas within timber and for monitoring and mapping the permittivity properties of shallow surfaces (Rodríguez-Abad, I., Martínez-Sala, R., & Mené-Aparicio, 2015, Comite et al., 2015). Our experimental set up bears a close resemblance to previous work, since E1 refers to the amplitude of the first arriving wave of previous work. However, within this paper, further parameters are used to identify materials (E2 anf F).

It can be assumed that two different walls that comprise of the same material composition, deliver the same measurement results, thus the values for E1, E2 and F are similar. Figure 3 displays the first results of the wall classifications. The classification was performed through analysis of the three parameters and grouping of similar measurement results. The existing planning documents, were also taken into consideration for the classification of the wall types. Accordingly, 6 different wall types were identified, whereby only one of them was identified unambiguously: the plasterboard wall ("sheetrock"), which could be identified easily by checking the radar images without a deep analysis of the measured parameters due to its inhomogeneous composition. Plasterboard walls comprise of metal profiles and insulation, which is positioned between two metal profiles. Metal has a higher density (density of e.g. steel sheet is 7800 kg/m³) in comparison with insulation (density of e.g. mineral wool is 18 kg/m³), thus the energy of the electromagnetic wave that comes back from the metal surface is significantly higher than the energy from insulation since the electromagnetic wave penetrates through the insulation. A differentiation of these two materials, thus the characterization of a plasterboard wall, is easily possible. Figure 4 shows the radar image of a plasterboard wall. The bottom of the figure is the side of the wall on which the GPR was applied, where also the corresponding drawing of the wall is shown. In the radar image it can be seen that the electromagnetic wave cannot penetrate through the metal profiles, whereas in case of the insulation, the waves penetrate through it. The other five wall types could be differentiated from each other due to the measured parameters as well as through comparisson of the results with the planning documents ("concrete 1" and "concrete 2"). However, for a clear identification, the real composition was required. Thus, for selected walls, destructive methods such as drilling and cutting were applied in order to define the exact material composition and calibrate the GPR-results.

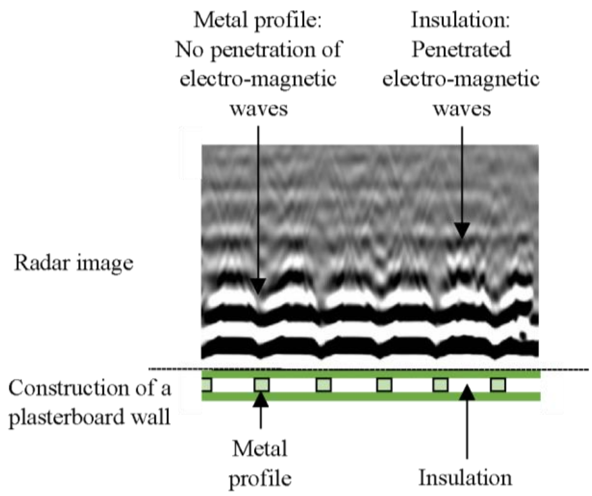

Figure 4: Radar image with the corresponding plasterboard wall

Traditional method: knocking, drilling and general assumptions

The traditional material characterization was conducted twofold – in the scope of a pre-demolition waste audit, which is a mandatory analysis prior demolition of buildings in Austria, and from an urban mining assessment perspective, where the aim was to identify the material composition as accurate as possible, which in general is not obligatory, but was required for the verification of the results obtained from the GPR. The state-of-art assessments were conducted on three days by using manual tools such as a hammer and chisel. However, not every building component was analyzed through destructive methods, thus, assumptions were made for some of the components. As a result, two spreadsheets with the material composition of each building component were generated, namely in form of a pre-demolition waste audit and from the urban mining assessment perspective, thus in the scope of a very accurate analysis. The results were compared and improved, whereby some mistakes could be avoided. As a result, one final spreadsheet with exact material composition of each building component including the properties of each material such as the density was generated.

Table 1 shows the wall types as determined through traditional methods. In total, six different wall types were identified through destructive methods, which do not all comply with the classifications from the GPR-measurement. There is one type of exterior wall (EW), namely EW 1, which is a multi-layered wall consistitng of three layers. Four of five interior walls are mono-layered, whereby the plaster layers of all walls were considered, since they cannot be reused or recycled. Interior wall (IW) 3 is the inhomogeneous plasterboard wall, which could be identified immediately, as described within this section.

Table 1: Wall types as determined through traditional methods

Wall type	construction
Exterior wall 1 "EW 1"	*multi-layered wall*: aerated concrete/mineral wool/steel sheet
Interior wall 1 "IW 1"	aerated concrete
Interior wall 2 "IW 2"	concrete
Interior wall 3 "IW 3"	*inhomogeneous wall*: plasterboard/mineral wool/metal profile
Interior wall 4 "IW 4"	precast concrete block (hollow)
Interior wall 5 "IW 5"	solid brick

Calibration of the GPR-assessments

The initial results of the GPR-measurements were calibrated based on the classification of the traditional material identification. Since on almost all walls destructive methods were applied, the wall types were determined through conventional methods. Thus, the results comply with the actual material composition of the building's walls. The parameters E1, E2 and F were assessed by summing up the values of each wall with the same material composition, as determined by destructive methods, and calculation of the mean values for these parameters. Table 2 displays all wall types with their corresponding values for the parameters E1, E2 and F, after the results were calibrated. With the new classification, the IW 3 could be identified unambiguously, as it was the case for the first assessments (4 out of 4 measurements were correct). The distinction between the two aerated concrete wall types EW 1 and IW 1 was not definite, even though EW 1 is a multi-layered element. The GPR-measurements were conducted on EW 1 from inside, thus aerated concrete was the first material through which the electromagnetic waves penetrated through. It is assumed that the ambiguous results are due to the similar construction of the walls, since EW 1 and IW 1 both comprise of aerated concrete. IW 2 (concrete) could be differentiated from IW 1 (aerated concrete), when the frequency of IW 2 was lower than of IW 1 and the energy of the second electromagnetic wave was high in comparison to IW 1, which was not always the case. Accordingly, 7 out of 15 GPR-measurements of IW 2 were interpreted correctly. The other 8 measurements were identified either as IW 1 (aerated concrete) or IW 4 (precast concrete block). IW 4 was mostly classified correctly, namely 7 out of 9 GPR-measurements. The results of IW 5 (solid brick) lie in the center of the values for IW 1 and EW 1, thus, a definite identification of IW 5 was not possible for each wall. Accordingly, some walls were identified as IW 5, some as IW 1 and EW 1.

The final results of all measured walls are illustrated in Figure 5, where the results obtained from the GPR are compared with the actual wall composition, as determined through destructive methods. The results of the GPR-measurements are displayed as dots, whereby the wall types defined by destructive methods are shown as a ring. The colors of the dots and rings represent the corresponding wall type. As Figure 5 shows, the energy and frequency of the first wave of IW 1 is spread throughout the results of EW 1, such that a definite identification of IW 1 is not possible. The same problem occurred in case of IW 5.

Table 2: Classification of the walls through GPR-measurements

Wall type	E1	E2	F
Exterior wall 1 "EW 1"	13000	2844	1350
Interior wall 1 "IW 1"	16345	3550	1350
Interior wall 2 "IW 2"	15315	6500	1150
Interior wall 3 "IW 3"	20000	8000	1480
Interior wall 4 "IW 4"	20000	10000	1100
Interior wall 5 "IW 5"	15441	2502	1250

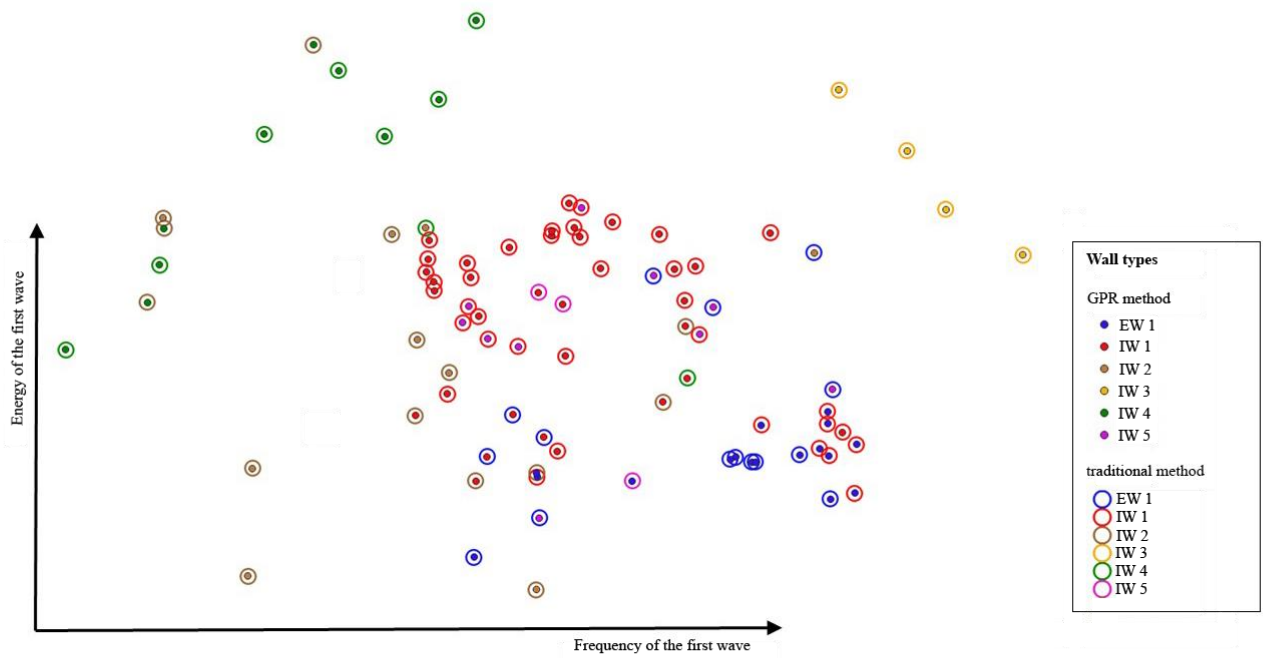

Figure 5: Final classification results (©ZAMG Archeo Prospections)

As-built-BIM

The compilation of the as-built-BIM with the exact geometry and materials information was conducted manually, mainly based on the final result of the traditional method and the existing "geometrical" BIM-Model from the point-cloud. Therefore, multi-layered building components were generated in BIM-Software and assigned to the corresponding elements. For mono-layered components only the material type of the building elements was changed.

Cost and time efforts

The cost and time efforts were assessed for both methods in order to evaluate how much higher the costs and the time effort of the GPR method are, in comparison with the traditional method. The assessment of the cost and time efforts for both methods is divided in three stages, namely the data gathering, pre-processing and model creation stage.

The data gathering stage refers to the GPR-measurements as well as to the traditional assessment, which were conducted at the use case. The pre-processing stage of the GPR method consists of allocating the obtained data to the coordinates of the building, analysis of the radar images and of the results regarding automated material identification. In the pre-processing stage of the traditional method a chemical analysis was conducted as well as a comparison of the results from the pre-demolition waste audit and the urban mining assessment. In the model creation phase of the GPR method, the final classification was performed based on the results of the traditional method. A spreadsheet with wall types and their corresponding classification was created and the GIS-based presentation of the walls including their material composition (Figure 3) was conducted. The model creation phase of the traditional method comprises of the final wall classifications including the thicknesses and material type of each layer of a wall. Figure 6 displays the costs, whereby Figure 7 shows the time effort of both material assessment methods. In total, the GPR method leads to costs up to 117.000 € and to a time effort of 648 hours, whereas the traditional assessment accounts for about 8.200 € and is conducted

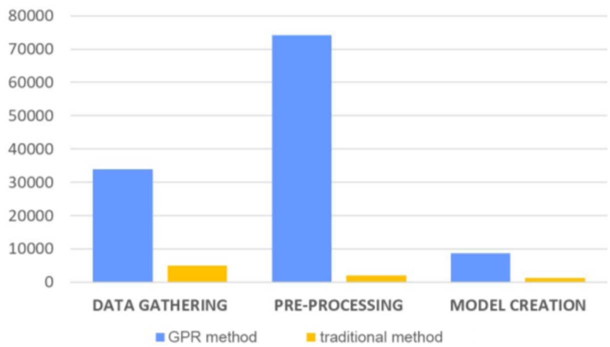

Figure 6: Costs per stage [€]

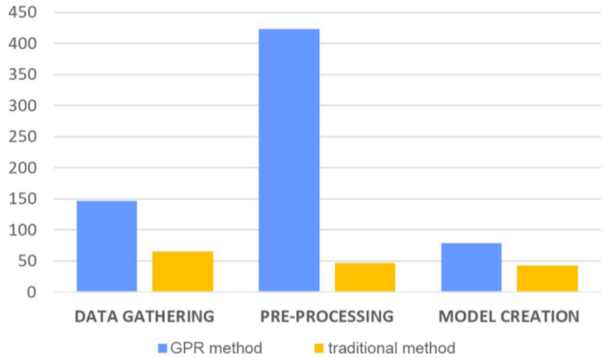

Figure 7: Time effort per stage [h]

in 154 hours. Thus, the GPR method costs about 14 times more than the conventional assessment method and takes about 4 times longer. The largest costs within the GPR assessment method occur in the pre-processing stage and are caused by personnel costs, due to the very-time consuming tasks in this stage. Within the traditional method, the data gathering stage leads to the largest costs and the highest time effort, which is due to the accurate data gathering method.

DISCUSSION AND RESULT ANALYSIS

This paper has shown, that the applied GPR-technology has large potential regarding non-destructive material identification of building components. However, as presented within this paper, the identification of the material composition was not possible for every wall type. Moreover, for the identification of materials with the GPR, the actual material composition is required in order to assign the GPR results to the corresponding wall.

Due to their inhomogeneous character, the plasterboard walls of the use case could be identified unambiguously. A differentiation between the multi-layered exterior walls (EW 1), which comprise of aerated concrete, mineral wool insulation and a steel sheet, and the mono-layered aerated concrete walls (IW 1) was not always given due to the similar values for E1, E2 and F. The same applies for the differentiation between aerated concrete (IW 1) and concrete (IW 2), as well as for the brick walls (IW 5), since the parameters E1, E2 and F of the brick walls (IW 5) are spread between the values of aerated concrete (IW 1) and concrete (IW 2). In order to enable a definite identification through GPR, the measurement of one or more parameters is required. Moreover, for an automated identification, a wall type classification database needs to be built up in order to enable a broader application, wherefore more use cases need to be captured with GPR as well as through the traditional method, to obtain the real material composition.

The as-built BIM-Model was generated manually, based on the point-cloud obtained from laser scanning, through integration of the materials information into the existing “geometrical” BIM-Model. The applied workflow was straightforward; however, the integration of the materials information after the BIM-Model exists, is an effortful task. The integration of the geometry and materials information in an earlier step, would be time-saving. As the GPR can deliver the results as a point-cloud, an integration of the materials information into the point-cloud from laser scanning is possible, but was not tested within this research.

As expected, the GPR method was very cost intensive, namely lead to 14 times higher costs than the traditional method. However, within the data gathering phase of the cost assessment, the hard- and software costs were also included, which would not be necessary for follow-up GPR-measurements. Moreover, most of the GPR-measurements were conducted on three heights as a horizontal line, namely at the top, bottom and at a height of about 1.1 m. Measurements on three different heights are not necessary, since the compositions of walls generally do not vary from bottom to top, such that one measurement per wall would be sufficient. Accordingly, there was more data that had to be processed in the pre-processing stage, which significantly increased the costs. In the pre-processing phase the automated material identification was also tested, which was confronted with obstacles due to lack of comparable GPR-data (no existing classification from GPR available). However, when a wall type classification database is built up, the costs and time effort would significantly decrease, since an automated identification would save a lot of time.

CONCLUSIONS

Within this paper, a novel approach for material identification was tested by applying the non-destructive GPR-technology on a real use case. As shown in the results and in the discussion and result analysis section, GPR-technology has great potential for material identification. For a broader application, a classification database is required, to enable an automated identification without the need for destructive methods. Moreover, the GPR-measurements are associated with high costs, which could represent an obstacle for a broad application in the AEC-industry.

The non-destructive character of this method enables a material identification in the operation phase of a building thus, enabling the assessment of a building`s value, the scheduling of thermal renovations of buildings as well as the planning of sustainable waste streams. In general, the detection of metals (steel, copper etc.), which are materials with high recycling potential, would also be possible. Through the GPR, the exact location and amount of e.g. copper pipes can be defined as well as the reinforcement within concrete.

In order to make the identified materials available publicly, an urban mining platform is required. The urban mining platform would support Circular Economy strategies by making the information on the existing stock availabe publicly, thus enabling reusing and recycling of materials incorporated in buildings, in order to keep materials within the loop and reduce raw materials extraction. The existence of a BIM-Model at the end-of-life stage of buildings comprising of the exact geometry and material composition of a building would support the mentioned strategy and could also be embedded in the urban mining platform. Thus, such a platform would significantly support the switch from the linear oriented processes (“take-make-waste”) of buildings towards a more circular approach (Mining, 2015).

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