DECONSTRUCTION PROJECT PLANNING BASED ON AUTOMATIC ACQUISITION AND RECONSTRUCTION OF BUILDING INFORMATION FOR EXISTING BUILDINGS

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Abstract

As energetic, health and environmental requirements for buildings are changing, deconstruction of buildings in the course of retrofits or replacing construction is increasingly important. To plan change measures in existing buildings, buildings have to be audited manually which is associated with great effort.

In our contribution, we propose and describe a combined system of a hardware sensor with software modules for building information acquisition, reconstruction and project planning. Furthermore, technical requirements, the acquired data, user interaction and system architecture are discussed.

Our tool enables planner, experts or decision makers to inspect a building and at the same time digitally audit the building room by room. For this purpose, point clouds are acquired, analysed and a 3D building model is automatically derived to record it. Furthermore, the acquired data is automatically analysed in real-time to detect construction elements that are saved in a database. Then, based on the generated building element database building reconstruction and planning algorithms use the information for building inventorying and project planning. This allows integrated planning of decontamination, site clearance, and deconstruction activities, as well as to coordinate secondary raw material recovery, resources, logistics, material storage and recycling options time and cost efficiently onsite.

Results from first field tests on acquisition, reconstruction and deconstruction planning are presented and discussed. Finally, a summary and a conclusion are given. This is followed by an outlook on potential future research and application areas.

1. Introduction and motivation

Buildings are characterized by their immobility, heterogeneity and uniqueness. Due to their long lifecycles and changing users', energetic, health, and environmental requirements, buildings are refurbished, retrofitted, remediated or modernized by generations of users, residents and proprietaries. During their lifecycles, different building elements and products are installed, removed or changed in the course of building modification. Often, these modifications of the building structure, equipment and fittings are not documented properly.

At the end of their lifetime, buildings often undergo deconstruction (and replacement), remediation or modernization processes in spatially limited sites of dense urban areas and with limited resources available. To plan deconstruction or change measures in existing buildings, buildings have to be audited previously. And, planning and performance of change measures strongly depend on the quality of the acquired information. Often, the acquisition of building information of existing buildings is associated with expensive equipment and great acquisition and modelling effort of skilled staff.

In the following section 2 of this paper, we present a short literature review on building information acquisition, reconstruction and project planning. Section 3 describes technical requirements of the hardware and software, the acquired data and the user interaction. Section 4 shows the general model architecture and the module interaction. Subsequently, a detailed module description and first results based on test cases are presented. This is followed by a summary, conclusion and outlook.

2. Literature Review

Research in this area can be divided into two major parts: building information acquisition and project planning in building deconstruction. Literature and recent approaches in these fields are described and analysed in the following sections:

2.1 Building information acquisition

If building information is insufficient for a specific purpose, comprehensive data has to be acquired to conduct (project) planning. If properly done, relevant information for deconstruction are captured such as existing building elements, site conditions, space availability, mass calculation and other conditions (Dt. Abbruchverband, 2015); (Rommel et al., 1999). Previous data capturing methods range from manual, semi-automatic or automatic, terrestrial or aerial techniques. Their application depends on the building or infrastructure size, complexity and budget. Terrestrial building auditing and acquisition is mostly carried out at individual building level, while aerial detection is only performed on larger building stocks, areas or infrastructures.

Recently researched methods are manual measuring, image-based or range-based techniques (Volk et al., 2014). Image-based and range-based techniques extract spatial, colour and reflectivity information to digitally reconstruct a building. In practice, mainly manual auditing is applied including a site inspection, manual measurement of the building and its elements via tape measures or laser distance measures (callipers). Often, also other building-related or element-related information is acquired by deconstruction companies or experts via examination of existing building documentation, photographs, and checklists or in written form (Rommel et al., 1999); (Wangler et al., 2010); (LfU, 2001); (LfU, 2003); Dt. Abbruchverband, 2015). However, this kind of information acquisition is quite costly and leads to unstructured data that only can be processed for planning and inventorying purposes under great efforts.

Also, semi-automated laser scanning techniques for documentation of historic buildings via immobile total stations are on the rise (Hajian and Becerik-Gerber, 2010). However, they are affected by great disadvantages yet such as high equipment cost and fragility, as well as difficulties in scanning reflective, transparent and dark surfaces (Klein et al., 2012); (Bhatla et al., 2012). Also, great effort and skills are necessary to process the data on conventional computers to a digital building model with all required data (Mill et al., 2013); (Tzedaki and Kamara, 2013); (Xiong et al., 2013); (Watson, 2011); (Brilakis et al., 2010); (Tang et al., 2010); (De Luca et al., 2006). And, current methods are restricted to rather low levels of detail. Furthermore, recent techniques do not compile an inventory of buildings' (raw) materials yet e.g. for a buildings' material pass or for deconstruction and recycling issues.

Today, only costly semi-automated or manual acquisition techniques are available for building information acquisition. In most deconstruction projects, buildings are shortly inspected and the whole building size (gross volume or gross area) is roughly estimated. According to Dt. Abbruchverband (2015), deconstruction materials and masses are then derived manually e.g. via percentage of gross volume. And, exceptionalities like specific technical equipment such as swimming pools or air conditioning are noted. Buildings' 3D structures are not acquired and reconstructed yet to calculate a buildings' material inventory. This leads to deviations in expected deconstruction masses (on average ~10%, in some cases much more) and thus to uncertainties in deconstruction planning regarding time (deadlines, resource capacities over project makespan) and cost (increased deconstruction or disposal costs).

2.2 Project planning in building deconstruction

Literature on project planning is vast. However, project management approaches in deconstruction of buildings and infrastructures are limited to a relatively small number. Abdullah et al. (2003, 2008) provide project planning and decision making support in deconstruction via hierarchical multi-criteria decision-making (MCDM) approach. Their approach creates a ranking according to the highest benefit/cost ratio and estimate the demolition cost for the whole project according to the highest ranked demolition techniques per activity. Optimization-based project planning approaches include a building auditing support and an optimization tool for building deconstruction project planning in MS ACCESS 1998 (Schultmann et al., 1997); (Schultmann, 2003); (Schultmann and Rentz, 2001,2003). This work is based on manually pre-measured building element dimensions. Schultmann and Sunke (2007) extend the approach by additionally considering the recycling options of each building element and the related energy-saving effects due to different deconstruction activities. Spengler (1998) formulates an optimization problem (MILP) for the deconstruction of complex products in general, but restricts to deconstruction and recycling cost and maximization of the marginal return.

Further related approaches are disassembly and fuzzy scheduling and capacity planning/optimization of complex products (with uncertain activity durations (Schultmann und Rentz, 2003), with uncertain capacities and cost (Spengler, 1998), with the deconstruction/disassembly of electronic devices and partly related uncertainties (Spengler, 1998); (Schultmann and Sunke, 2005, 2008), or related waste quantification and management (Li and Zhang, 2013); (Cheng and Ma, 2012); Akbarnezhad et al., 2012, 2014). However, only very few approaches account for uncertainties in deconstruction project planning (Schultmann und Rentz, 2003); (Spengler, 1998).

Recent trends show the shift of BIM from design processes to retrofitting and deconstruction projects. Existing operative mass flow models are based on pre-existing BIM models and consider the deconstruction of single buildings (Cheng and Ma, 2012); (Akbarnezhad et al., 2012, 2014). Akbarnezhad et al., 2012, 2014) examine a scenario-based (not activity-based) sensitivity analysis of deterministic costs for deconstruction, shipping, reprocessing and disposal (landfilling) as well as of energy and carbon embodiments (Akbarnezhad et al., 2014). However, these works focus on the quantity takeoff, mass and cost calculation aim at ordering the exact number of hauling trucks and calculating the masses designated for recycling or disposal facilities.

It becomes clear, that although there are some approaches in deconstruction project planning, only separate building information acquisition approaches and project planning (under uncertainty) approaches co-exist.

However, there is no approach that joins both to allow an effective way of documenting existing buildings and planning for their deconstruction, re-use and recycling. Also, approaches in literature refrain from modelling uncertainties. And, their approaches do not allow the automated acquisition of building information. Instead, their calculations are based upon manually pre-measurements onsite and assessments of building documentation (if existent). In practice, mainly checklists are applied to acquire building information and to document a buildings' deconstruction. The project planning itself is performed by skilled and experienced staff, but at the same time underlies uncertainties and considerable deviations.

3. Technical and informational requirements

3.1 Requirements to hardware

In order to allow a deconstruction planner to carry out his building inspecting work in an as natural as possible manner, it is indispensable to setup a mobile and wearable building auditing system. The auditing system should also include a minimum of post-processing effort to generate building information, material inventory and project plans. In the design phase of the building auditing system, the following set of hardware requirements were specified in interviews with practitioners and experts:

- Optical sensing system: During the walkthrough inspection of a building, an optical sensing system should acquire the geometry of the building, the floors, and the indoor scenes and should automatically identify building elements. The acquired 3D model should be consistent and persistent so post-processing building analysis steps can rely on high-quality data. Furthermore, the virtual 3D model of a building serves as a visual communication means for internal project planning, controlling or meetings. Ideally, the virtual 3D model serves as a basis to automatically calculate building inventories and to derive project plans from it.
- Real-time: The system should provide real-time results so the planner can check for consistency and completeness during site inspection.
- Enough battery capacity: The system should be energetically self-sustaining as electricity connections are cut and no other energy sources are available in buildings that will be deconstructed to run the system.
- Robustness: The system should be robust to different illumination conditions, due to lacking electricity and lighting in buildings that will be deconstructed.

3.2 Requirements to software

It is mandatory for the software of the building auditing system to provide natural and comfortable interaction techniques to support intuitive and work-centered operations. This should be supported by non-invasive knowledge augmentation capability, including support for automatic object detection that can significantly influence the calculation of the building inventory. For an intuitive use, the software hides the underlying complex machinery from the end-user.

The acquired images have to be interpreted adequately. For that purpose, images are systematically segmented and semantically analyzed in order to detect relevant objects such as walls, windows, doors or power outlets. Because geometry acquisition and reconstruction via depth cameras entails the creation of huge data volumes, efficient and adequate data filtering techniques are necessary to reduce the point clouds to the most significant points. Adequate interfaces need to be implemented to transfer the outcome of the acquisition and reconstruction to the planning module. The intuitive user interface allows a visual inspection of intermediate building reconstruction results and enables the planner to apply changes to the 3D model such as the later identification of undetected objects.

For adequate deconstruction project planning, general building information has to be documented and parameters for inventorying and project planning are necessary. These information and parameters need to be included into the system and should be easily modifiable by a user. Furthermore, the system output (building inventory and project plan) should be easy accessible. This leads to the requirement for a graphical user interface to depict system results adequately.

4. System architecture and interactions

In the following section, the system architecture, the submodules and their interaction are described and discussed. Building information is generated in two ways: via sensor information and via user input (see Figure 1). Both types of information are processed separately. Sensor information is analyzed and major building elements are reconstructed (such as walls, windows, doors, floor and ceiling) while smaller building elements are detected (such as outlets, switches, lamps, sanitary objects). User input regarding the general building information such as address, construction type, year of construction, gross floor area, gross volume etc. are used to save the building in a database. The inventorying parameters can be manipulated via user input in a graphical user interface. Also, deconstruction and recycling parameters can be modified to define time and cost coefficients and to limit the number and capacity of available resources such as staff, hydraulic excavators, and handheld machinery etc. for the project in question. The entry of these parameters is supported by an underlying database that provides standard values. However, if necessary the user might change these values.

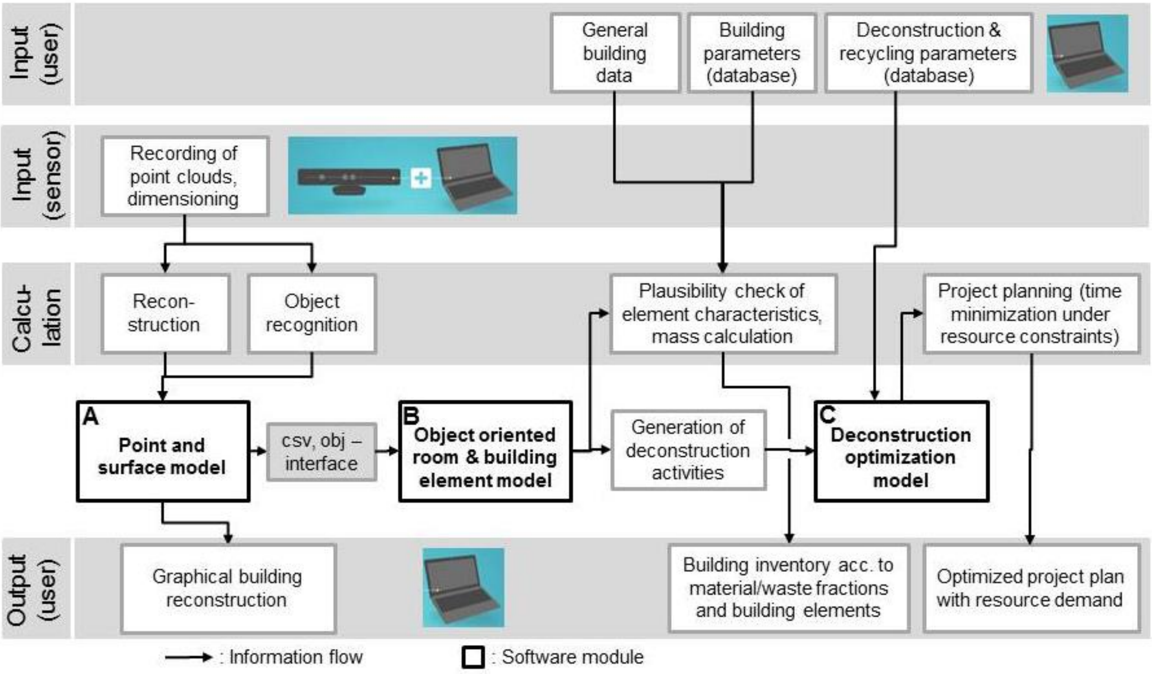

Figure 1 System architecture of ResourceApp prototype

Main elements of the ResourceApp system are the hardware modules and the software modules ‘A: Point and surface model’, ‘B: Object oriented room and building element model’, and ‘C: Deconstruction optimization model’. In the following subsections these parts of the model are further detailed.

4.1 Hardware modules

The ResourceApp hardware setup is a combination of a depth camera equipped with a RGB-D sensor and a laptop with a powerful graphics card to efficiently process the images acquired by the depth camera. In the following we describe both hardware modules:

- Microsoft Kinect - A depth camera equipped with a RGB-D sensor: With the release of the Microsoft Kinect and other RGB-D sensors, depth cameras became available at reasonable prices to the public. Previous to this, devices such as time of flight (TOF), stereo vision and 3D LIDAR sensors were required for 3D perception. The low cost of the Kinect sensor coupled with its high quality sensing capabilities has proven to be an attractive alternative to previous more expensive 3D sensing systems. The Kinect contains two cameras (a RGB camera and an infrared camera), as well as an infrared projector which projects an infrared pattern onto the scene. The infrared camera acquires the pattern in 30Hz at VGA resolution (640 by 480 pixels) which is used to calculate the distance of the depth camera to the acquired object surface. The deformation of the pattern projected onto the three dimensional rooms is then used to infer their three dimensional shapes. This kind of depth sensor also works in poorly lit rooms, which was a main decision criterion for this technology. In the ResourceApp system, the Kinect sensor has been used to implement a real-time 3D reconstruction of rooms and buildings.

Figure 2 Microsoft Kinect: A depth camera equipped with a RGB-D sensor

- Laptop equipped with the Nvidia GeForce GTX 780M graphics card: The real-time capability of the ResourceApp has been achieved by using a laptop with a powerful graphics card (Nvidia GeForce GTX 780M with 4GB RAM and 2,369 GFLOPS). The graphics processor unit (GPU) of the graphics card allows an efficient processing and manipulation of computer graphics and image processing, and its highly parallel structure makes it more effective than general-purpose CPUs for algorithms where processing of large amounts of data is done in parallel.

4.2 Software modules

According to the system architecture previously introduced, this section describes the software modules of the ResourceApp system.

4.2.1 A: Point and surface model (3D reconstruction and object detection)

The point and surface model module is dedicated to the real-time building information acquisition and is a virtual 3D model of an indoor-scene which is automatically acquired during an audit of a building. To build the point and surface model a mobile low-cost depth camera equipped with a RGB-D sensor is used. Because the used sensing system is able to capture visual images along with per-pixel depth information, it is possible to build automatically 3D reconstruction of rooms, sections of buildings and entire buildings with real dimensions. The creation of the point and surface model includes the detection of objects which have to be carefully taken into account during the calculation of the building inventory. The final point and surface model can be exported via a pre-defined CSV/OBJ interface.

The building information acquisition comprises two sub-modules that run in parallel, namely the real-time 3D reconstruction of the building and the detection of significant objects (e.g. switches, power outlets or heaters) that need to be considered in the calculation of the building inventory. In the following we describe both sub-modules:

- 3D reconstruction of building:

  During the inspection of a building, the planner usually goes through the individual floors and audits each room individually. The 3D reconstruction module supports this workflow. As already introduced, the Kinect system is a RGB-D sensor that captures 640 x 480 colour and depth points at 30 frames per second This allows us to create a novel approach to the known research field of Simultaneous localization and mapping (SLAM) that combines the scale information of 3D depth sensing with the strengths of visual features to create a dense 3D environment representation. The depth image of each frame is converted into a 3D point cloud. To register the current frame with the previous frame, our variant of the Iterative Closest Point (ICP) algorithm (Rusinkiewicz and Levoy, 2001) first extracts visual features from the two frames using the RGB images and associates them with their corresponding depth values to generate feature points in 3D. The 3D feature points are considered as significant whereas image areas without visual features are considered as insignificant. Because the insignificant areas do not provide any visual features, the insignificant areas of the point clouds are subsampled. As a result, the point cloud density is reduced. Hence, the reduced point cloud density is then used to estimate an initial alignment in order to find the best rigid transformation between the feature sets of both frames. We then iteratively minimise the nearest neighbour correspondence distances between the two point clouds.

  The point cloud registration is continuously applied during the audit of a room. Because our approach supports a robust camera tracking and matching of visual features, the output of our algorithm is a globally consistent 3D model of the perceived environment, represented as a coloured point cloud. First results are presented in section 5.

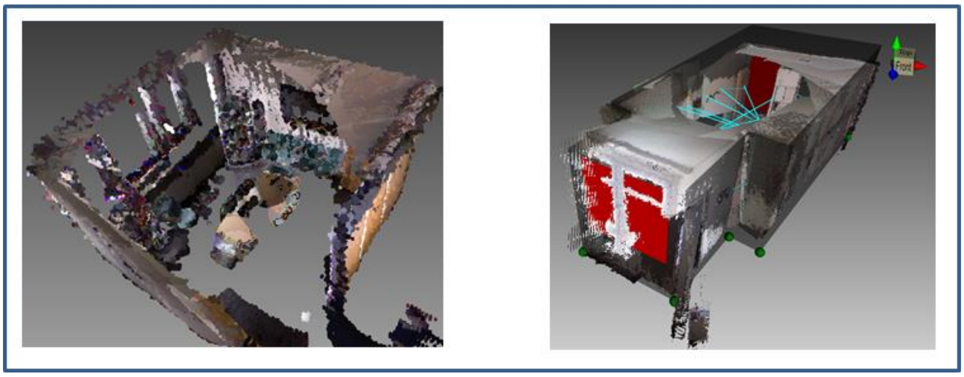

Figure 3 Registered point clouds showing a furnished office room (left) and reconstructed 3D model of a patient room in a hospital produced by our algorithm (right).

- Object detection:

  Besides the 3D reconstruction, the detection of significant objects such as power outlets plays an important role because based on their exact position in the room it is possible to infer how the electrical lines behind the walls are routed. The inference of visually non perceptible information has to be considered as well for the calculation of the building inventory. The object detection module requires RGB images coming from the Kinect sensor.

  One of the challenges we had to address in the project is the detection of textureless objects with low contrast (e.g. power outlets and heaters). For this purpose, as object recognition method Dominant Orientation Templates (DOT) were chosen in our approach (Hinterstoisser *et al*., 2010). As power outlets, light switches and many other objects that have to be recognized have few high-contrast corners, edges, or surface patterns, such as in the case of white light switches mounted on a white wall, classic feature-based methods such as SIFT are ill-suited. DOT was instead developed with the goal of recognizing untextured objects. Although methods based on machine learning, often used to recognize people or faces, can be more robust, they require large image databases consisting of many thousands of positive images containing an object as well as similarly large numbers of negative examples per object category that is to be recognized. As a large number of object categories have to be recognized this would be infeasible. The DOT method is better suited as 5 to 10 examples (templates) per category can be sufficient. To reduce false positives the method was extended to check object scales by using the Kinect's depth to verify that an object's size in the image matches its expected physical dimensions. As object detection relies on template matching, for each object category a set of DOT templates have been created. When parsing the RGB images, those categorized DOT templates are applied on the image stream to quickly find objects and label them according to their category. Since our algorithm maintains the correspondence between the colour and depth images through interpolation and averaging, the position of the detected objects in the 3D model is determined.

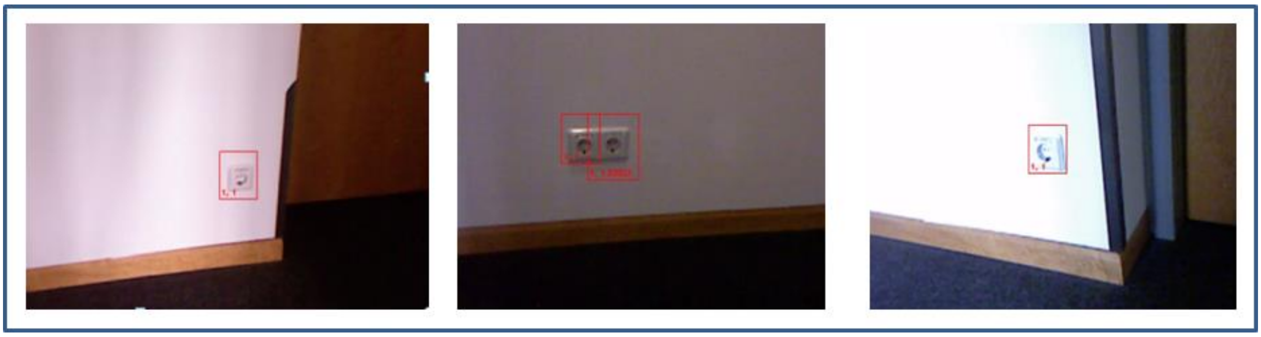

Figure 4 The DOT templates used in ResourceApp are robust to illumination change and can detect non-textured objects (here power outlets) in real-time without relying on feature point detection

Once the 3D reconstruction and the object detection is completed for a building or a section of a building, all acquired information are exported via the CSV/OBJ interface and is used in the downstream process steps to calculate the building inventory.

4.2.2 B: Object oriented room and building element model

The object-oriented room and building element model is based upon the point and surface model (A) that is transferred by the CSV/OBJ interface. Each captured building element is analyzed with respect to its kind and its material information. Depending on these, further invisible but nevertheless existing building elements are automatically inserted. Further, the building element masses are calculated of both visible and invisible objects. Then, the building inventories are created both for material/waste fractions and building elements. This allows further processing and project planning with respect to inventorying, necessary deconstruction and material/element separation activities.

The detailed construction of the object-oriented room and building element model and calculation of the building inventory is depicted in Figure 5 and described in the following. The CSV/OBJ interface lists all detected and visible building elements with their coordinates and material information. Based on this list of building elements, further invisible building elements are derived. E.g. if the list presents a wall, in a first step plausible wall values (such as length, height) are checked on plausibility. However, if the building element information is not characteristic, it is adjusted to plausible values generated from standards.

When it comes to technical building equipment, wiring, piping and tubes often are not visible to the eyes or to sensors. However, often their outlets such as switches, lamps, outlets, sanitary devices, etc. are visible and allow a reconstruction of their runs For example, if a power outlet is detected and listed in the interface, first the related type of equipment has to be clarified. Then, the respective wiring is created and its length is calculated. The reconstruction of the supply line starts that is calculated vertically or/and horizontally calculated depending on the type of technical equipment and the position of the technical outlet as well as on the position of the next technical distribution box for the apartment or building. The coordinates of the apartments' distribution box as well as the house connection point can be manually assigned by the user to allow the reconstruction. Similarly to the wiring reconstruction, pipes and tubes are reconstructed and their volume and mass is calculated.

Or, if a wall is a reinforced concrete wall, a steel reinforcement element and a concrete matrix element are automatically created by the software. If openings had been found on a wall, they are subtracted from the wall surface. Then, the wall surface is multiplied with an assumed wall thickness parameter (which cannot yet be acquired automatically) to calculate the volume of the wall. If the wall consists of a 'single or homogeneous' material (e.g. brick, concrete, timber), the wall volume is multiplied with its respective material density. Else if the wall is made of reinforced concrete, the reinforcement is calculated via standard reinforcement coefficients per square meter wall surface. Then, the reinforcement volume is subtracted from the total building element volume. For both reinforcement material and matrix material, masses are calculated with their densities and listed in the building inventory. Here, a further detailed calculation might be possible but is far more complex.

The generated building inventory consists of three major listings: aggregated inventory (= all building elements that were detected), detailed inventory (=all detected building elements plus all assumed (invisible) building elements) and material inventory (=aggregation of all building element masses according to their main material). The detailed building inventory is used to derive necessary separation, deconstruction and sorting activities during a deconstruction project. The activity derivation and the project planning are described in the following subsection.

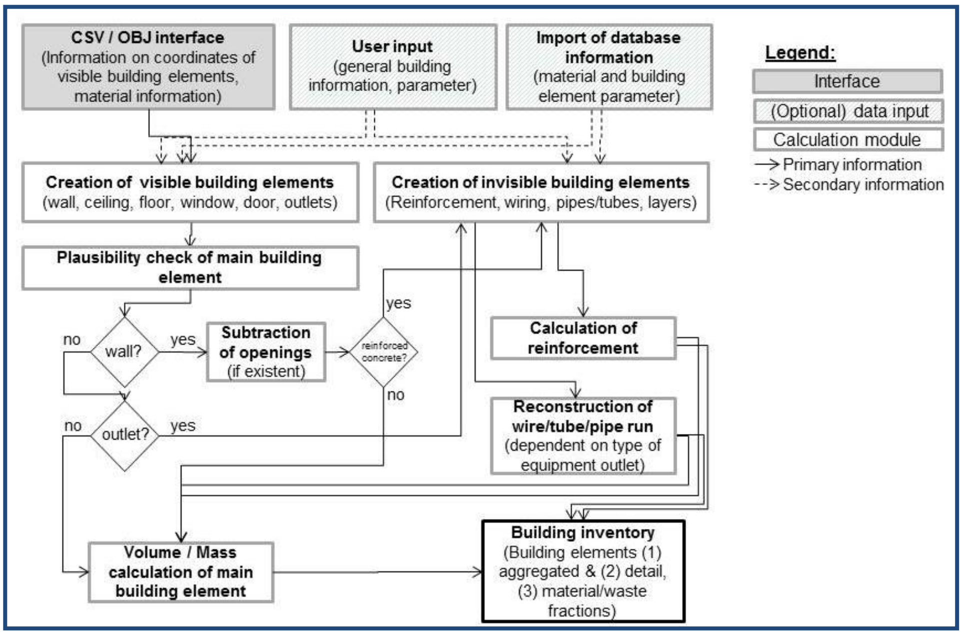

Figure 5 Building inventory calculation logic and plausibility checks

4.2.3 C: Project planning in building deconstruction

Based on the building inventory, activities are derived that are necessary to deconstruct the building elements (see **Error! Reference source not found.**, left). Deconstruction activities can be performed in different modes that differ in their resource usage of staff, machines, time and cost. These activities form the basis for the deconstruction optimization model that calculates an optimum schedule for the deconstruction project. Standard deconstruction activities include separation, deconstruction, crushing, sorting and loading operations that require different amounts of constrained resources (machines, staff, cost). As single activities can be performed in different modes (see **Error! Reference source not found.**, right), e.g. deconstruction of a wall can be done with a hydraulic excavator, dragline excavator or pneumatic hammer, a simultaneous planning of activities in different modes on resources has to be done.

Tabel 1 Exemplary deconstruction activities derived from CSV/OBJ interface (left) and considered modes and their resource requirements (right)

ID	Deconstruction activities	Modes	Resources
1	Start	1 – Grabbing	Hydraulic excavator, sorting grabs, 2 W*
2	Deconstruction of Foundation	2 – Driving	Cable excavator, steel mass, 2 W*
3	Deconstruction of (Exterior) Walls	3 – Pressing	Hydraulic excavator, demolition stick, 2 W*
4	Deconstruction of (Interior) Walls	4 – Tapering	Hydraulic excavator, steel cable, 2 W*
5	Deconstruction of Ceiling Slabs	5 – Tearing	Hydraulic excavator, demolition stick, 2 W*
6	Deconstruction of Doors	6 – Mortising	Hydraulic excavator, demolition hammer, 2 W*
7	Deconstruction of Windows	7 - Disassembling	Hoist, 4 W*
8	Deconstruction of Small Distr. Boxes	8 - Manual deconstruction	Hydraulic excavator (electric hammer), 1 W*
9	Deconstruction of Large Distr. Boxes		**W=Worker*
10	Deconstruction of Wiring		
11	End		

To calculate the optimum schedule, further information and parameters are necessary that have to be predefined by a user, such as available resources, technical applicability of modes on building elements and on materials, activity precedences based on technical constraints, as well as activity cost and activity duration per mode. Partly, this information is stored in a database such as the applicability matrices, precedence constraints, cost and duration and can easily be modified by the user. Also, the user can modify his individual resource constraints. Furthermore, technical constraints such as the activities' precedence (see Figure 6, right) or the applicability of specific techniques on elements or materials are respected.

Thus, in the developed model ResourceApp a multi-mode resource-constrained project scheduling problem (MRCPSP) is formulated with the objective of minimum project makespan. It is solved for the previously calculated building inventory and its derived activities plus dummy start and end activities with the durations and resource demand of zero. The model is implemented as a binary, linear integer problem (BILP) in

MATLAB R2015b. The commercial CPLEX solver from IBM ILOG Optimization Studio 12.5.1 is used to solve the problem. Then, an optimal deconstruction schedule is calculated for the derived deconstruction activities and the available resources and presented as Gantt diagrams (see Figure 6, left) and resource capacity plans. In first test it showed that this method is limited to smaller problem sizes due to high computational effort. Thus, the generated deconstruction activities were grouped and the time slices of the model were reduced to enable solvability or the system.

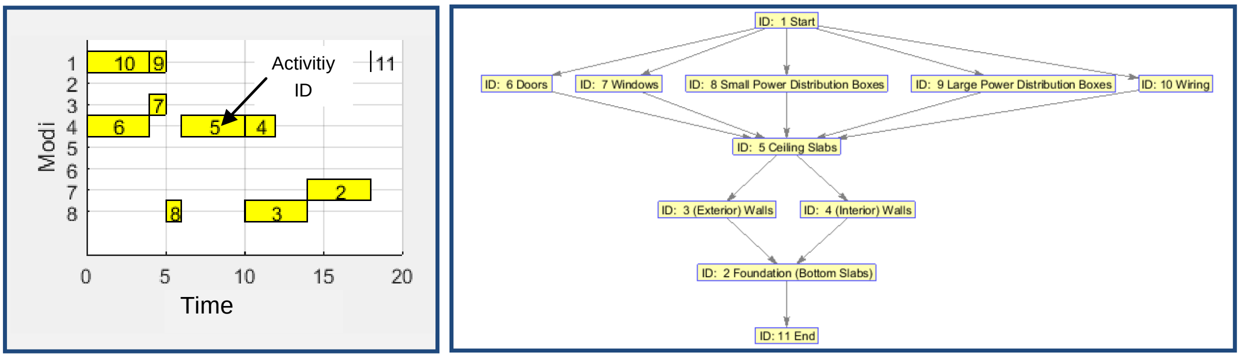

Figure 6 Exemplary Gantt diagram with the scheduled activities (x-axis: time, y-axis: modes) (left) and the underlying precedence graph (right) of a fictive deconstruction project with 11 activities on 8 modes

5. Summary, conclusion and outlook

In our contribution, we presented an innovative system consisting of a sensor and software modules on a laptop that allow data analyzing and project planning for building deconstruction projects. To audit a building designated for deconstruction, the mobile sensor records a buildings' indoor condition. The recorded data is then analyzed to detect objects and building elements. This is followed by a 3D reconstruction of the building interior. Based on the analyzed sensor data, a building inventory is calculated and necessary data for building deconstruction are derived. Subsequently, deconstruction activities are generated and planned on constrained resources with the objective of minimum project makespan. This allows users to audit and document buildings efficiently and to automatically create deconstruction plans and bids. Building owners might also use this application to calculate the building inherent mass and waste fractions and its potential secondary raw materials.

We investigated how the Microsoft Kinect, as a representative of low-cost depth cameras, developed mainly for gaming and entertainment applications can be used for the generation of dense 3D maps of buildings. The key insights can be summarised as follows: (i) a tight integration of depth and colour information can yield robust frame matching and 3D reconstruction, (ii) best practices in SLAM and computer graphics makes it possible to build and visualize accurate 3D maps with such cameras, and (iii) our variant of the ICP algorithm might fail in areas that lack visual information, such as very dark rooms. Further research work will be necessary to increase the robustness of our ICP algorithm. Furthermore, to extend the reconstruction capabilities of the ResourceApp prototype we plan to consider non-rectangular room geometries. The inclusion of further sensors in order to detect hazardous and carcinogenic substances such as asbestos into the ResourceApp prototype is envisioned for the future.

Concerning the object detection, the DOT template representation based on locally dominant gradient orientation has shown that untextured 3D objects could be detected using few templates from different viewpoints in real-time. One notable advantage of the DOT approach is that it does not require a training set. However, since the creation of the DOT templates requires manual work further research is needed to investigate how the template creation can be automatized, possibly with a marker-based approach. With respect to the transferability of the ResourceApp system to mobile phones and tablets, we are following with keen interest the results of the Tango project where Google and Intel are developing a smartphone with an integrated depth camera. Our algorithms are based on the Point Cloud Library (PCL) which is cross-platform and has been successfully compiled and deployed on Android and iOS.

Furthermore, uncertainties regarding the completeness of captured objects in a building and with respect to multiple layers and invisible building elements in older buildings need to be considered. Also, the variability of the optical information and the uncertainty in the identification of building elements has to be tested and statistically evaluated. In the course of our work, also system tests in larger case studies are planned in the near future. The project planning of building deconstruction is possible although the problem sizes that are solvable in a finite time frame are limited. Thus, a reduction of problem size by activity grouping or time slice reduction is necessary and will be further developed. Alongside the test, sensitivity analyses would be useful to identify influence factors on our system results. The named issues will be addressed in our further research in the course of our joint research project.

As an outlook, this tools' capability might be extended to facility management application or to building refurbishment and renovation/modernization projects of buildings and infrastructures. Also, the functionality might be extended to performance measurement in construction and deconstruction projects both in buildings, technical appliances and infrastructure. In these cases, further research and detailing on building elements and types of construction (e.g. regional differences) is needed. Furthermore, the ResourceApp systems' functionality might be transferred to the deconstruction of infrastructure or large technical plants such as nuclear power plants. However, this will require further research on the inherent technical appliances, equipment and materials.

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