A Framework for Robot Assisted Deconstruction: Process, Sub-systems and Modelling

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ABSTRACT

Due to an increasing need for buildings to meet sustainability criteria, the deconstruction and refurbishing market is a thriving market worldwide. Considering that construction and demolition waste account for a large proportion of all wastes produced, novel and scalable solutions for systemised building deconstruction have to be developed. Systemised building deconstruction could serve as the microeconomic basis for improved resource productivity, the recycling economy and urban mining on a macroeconomic level. It also sates a promising field for the application of automated and robotic technology in construction. The advantages of these technologies can be utilized to gain efficiency and finally outperform conventional methods. The presented research explores a development direction that considers the weaknesses and strengths of the real-world company approaches conducted so far and provides conceptual solutions for a compatibility of robot supported, systemized deconstruction with conventional deconstruction methods.

Keywords – systemized deconstruction, Agent-Based Modelling, construction automation, on-site factories, construction robots

1 Introduction

Due to an increasing need to meet sustainability criteria, the deconstruction and refurbishing market is a thriving market worldwide. In the EU it is expected that until 2050 each year more than € 50 billion will be spent for refurbishing and deconstruction. [1]. Considering that construction and demolition waste [3] accounts for 30% (in highly industrialised nations) to 80% (in some developing countries) of all wastes produced, affordable and scalable solutions for systemised building deconstruction have to be developed. The advantages of these technologies (speed, safety, control, accuracy, work flow transparency, etc.) can be utilized to gain efficiency and finally outperform conventional methods. Therefore, this research will identify the key challenges, summarize the existing related work, suggest and evaluate a modular, scalable initial concept and develop a framework for future development.

Up to date plenty of research was done in the field of construction methods for industrialised and automated building construction. In contrast, very few researches focussed on deconstruction techniques. The complexity of a deconstruction and disassembly process is still underestimated by both academia and industry. There are many ways to bring down a building, yet the optimized solution depends on the individual situation and thus on multiple factors such as stakeholders, building type, floors, material, location and safety regulations. The most common practices for building demolition are: (1) manually, (2) balling, (3) by pusher arm, (4) by deliberate collapse, (5) by wire rope pulling, (6) explosion or implosion, and (7) by high-reach excavators. Usually these methods require extreme safety precautions and the associated tasks have to be executed by highly qualified, skilled workers. Furthermore, these methods are associated with disadvantages such as safety hazards, noise, dust, damages to the surrounding buildings, vibration, disturbance of the economic surrounding (surrounding offices, hotels etc. might experience a loss of productivity and can claim for compensation), and ecologic unsustainability.

Major constrains that could affect the deconstruction projects are set out by the imperative of economical return. Commonly, the building will be financed by a real estate investor. Usually the demolishing charge is not considered in the initial build budget of the old building that has to be deconstructed, and therefore the new building has to be so productive that it can cover the deconstruction cost and makes the project beneficial. Financial aspects are key and in particular systemised deconstruction can allow that the new building can be built faster, return on investment (ROI) can start earlier, and that the disassembled components, parts and materials can be sold, re-used, or re-manufactured.

Much research focused on how to increase recycling rates and improve the logistics flow on-site. However, little research focused on the improvement of the whole deconstruction method, its systematisation and the utilisation of novel technological potential. Therefore a framework for a new concept is explored by the presented research and its potentials and objectives are analysed. It will be shown in this paper that it is feasible that in the future buildings will be no longer “demolished” but deconstructed and disassembled in a systemized manner, in on-site factory like environments allowing for the use of automated/robotic equipment, and based on the schedules and system configurations generated by Agent Based Modelling (ABM).

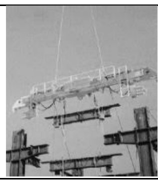
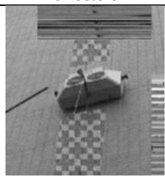
2 Related work

Usually a building is taken down when it reaches the end of its lifecycle by implosion, demolition or the use heavy machinery. The conventional “demolition” methods imply plenty of risks and uncontrollable factors and thus have a significant impact on the safety and operational performance of the public and the surrounding environment, especially when demolishing tall buildings in congested high density urban areas. In Japan, however, due to legal propositions (e.g., some conventional deconstruction methods using explosives are forbidden) and economic and ecologic needs (e.g. rare space for construction waste disposal leads to high cost for disposal of construction waste), alternative methods using (1) Single-Task Construction Robots (STCRs, system deployment started from the 1980s) and (2) semi-automated on-site factories (system deployment started 2008). In parallel, in the context of the optimisation of conventional construction/ deconstruction as well as in the context of automated construction (3) information modelling and waste estimation techniques were developed in Japan as well as in other counties. The state of the art technology in these fields is outlined in the following sections.

2.1 Single-Task Construction Robots

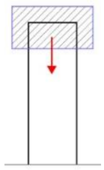
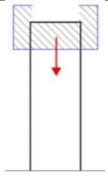
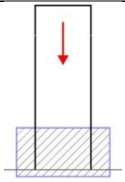
STCRs were developed from the 1980s on by Japanese contractors as a reaction to rising labour cost and quality demands. According to [4] STCRS can be classified into 18 categories. Robots from the categories (1) site logistics, (2) positioning/crane end-effectors, (3) façade installation, (4) interior finishing and material handling, (5) inspection, (6) renovation can be applied and adapted to deconstruction scenarios. In general, a single-task robot consists of three main components: a travel vehicle, a manipulator and an end-effector. Each type of robot is designed to focus on a particular on-site work task Increased popularity of robots can be expected with improved economic incentive, wider applicability [3] and more intensive demand for STCRs in appropriate deconstruction scenarios.

Table 1. Categories of STCRs

		
(1) interior finishing and material handling	(2) crane end-effectors	(3) façade installation
		
(4) site logistics	(5) inspection	(6) renovation

2.2 Deconstruction by on-site factories

Table 2. Categories of on-site factory approaches for systemized deconstruction [5].

Typology 1	**Typology 2**	**Typology 3**
Closed Sky Factory supported by building (moving down)	**Open Sky Factory** supported by building (moving down)	**Ground Factory** (fixed place) and building lowering
		
Systems: Hat Down (Takenaka), TECOREP (Taisei)	**Systems:** MoveHat (Nishimatsu), RCM (Shimizu), QB Cut-off (Obayashi)	**Systems:** DARUMA (Kajima)

Since 2008 the six major Japanese contractors have developed mechanized and partly automated deconstruction systems. Deconstruction systems installed in an on-site factory serve as a basis for controlled and systemized on-site work processes. Most deconstruction sites firstly disassemble the larger (high or low-level) components, then disassemble those components for example in a ground factory on-site into lower level components, mono-material parts or raw materials which can then be delivered directly from the site to the recycling plant. A detailed description of these systems is presented in [5].

2.3 Information modelling and waste estimation

Plenty of research currently focuses on the reduction of demolishing waste. The utilization of information modeling techniques allows to visualize and handle the changes in the design process required to accommodate the different design solutions. To reduce construction waste, it is required to understand the impact of decisions on the type and amount of waste produced, the ‘wastechain', the lifecycle, and life-cycle costs. Furthermore it is necessary to understand the impact of design decisions on the overall construction process. In particular Baldwin et al. present an effective method for reviewing the impact of design decisions on the design process [7]. In terms of waste estimation systems for construction and deconstruction projects, a web-based construction waste estimation system (WCWES) was suggested in [8] incorporating the concepts of work breakdown structure, material quantity takeoff, material classification, material conversion ratios, material wastage levels, and the mass balance principle. WCWES integrates online data input modules and online analytical modules for the quantification of different kinds of waste generated in the construction process at the project level. It facilitates accessibility, interfacing, connectivity and information sharing of users in carrying out a wide range of construction waste estimation tasks for sustainable construction waste management [8].

2.4 Shortcomings and how this research goes beyond the state of the art

STCRs were proofed to be highly flexible; however a major difficulty so far was to use them efficiently in the conventional, unstructured construction environment. [9] Deconstruction by semi-automated on-site factories is highly efficient in terms of time and recycling rates, but the systems are costly and difficult to adapt to the individual buildings [5]. Only typology 3 (Open Sky Factory; actually a trade-off between conventional and completely mechanised/automated construction) can be considered as cost-effective, flexible and compatible with existing, conventional construction processes. Information modelling, optimisation and waste estimation approaches have so far by only be tested in the context of conventional construction and it is assumed that they would be able to unfold their full potential only in combination with more controlled, systemised and automated forms of de-construction. In particular Agent Based Modelling (ABM) can cope with deconstruction tasks which need to deal with complex interactive process as demanded in deconstruction. Therefore, the potential of integration and utilisation of the strengths of each the three mentioned approaches is proposed by the research presented in this paper.

3 A deconstruction approach

An alternative deconstruction approach is introduced in this paper, which aims to provide exemplarily a feasible solution for systematic deconstruction of high rise commercial buildings. The structural details of the exemplarily chosen building (case study) will be described later. The on-site activities will maximise the utilization of the existing construction methods and combine it with robotic technology and modelling approaches. Objective of the proposed solution is to increase the speed of the deconstruction process, decrease the amount of disposal waste generated and improve significantly the recycling and re-manufacturing rate. The approach shall increase marketability of the concept and raise the interest of a variety of stakeholders. It aims at a cost-effective solution that integrates elements of conventional construction (e.g. tower cranes or robotic tower cranes), STCRs, on-site factory elements, a ground factory and ABM. The compatibility with existing elements of conventional construction ensures that existing capacity can be utilised. In terms of on-site factory approaches the Open Sky Factory (OSF) typology is chosen since it is cost effective and compatible with existing equipment as tower cranes. Furthermore, STCRs (in contrast to overhead manipulators as used for example by Hat Down) are highly flexible and adaptable and are thus suggested as the key robot system. Moreover, AMB will combine waste estimation and process modelling and optimisation functionality and thus serve as backbone for the efficient set-up and control of the system. The system is conceived as an open, modular system where new elements can be added in the future and conventional construction elements can be abandoned after a transition period.

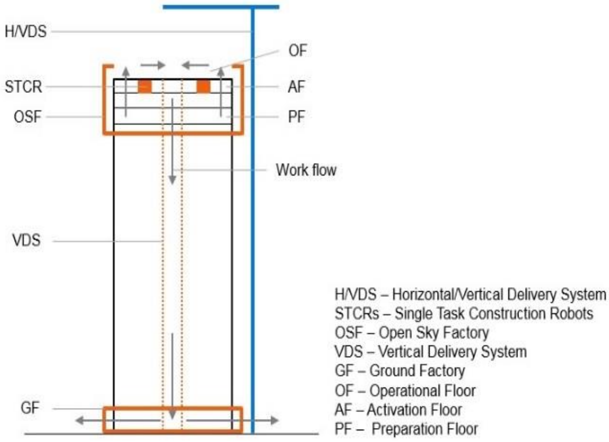


Figure 1. Schematic representation of the deconstruction approach

Key element of the system is the OSF which provides a partially structure environment for the operation of the STCRs on the AF, the disassembly preparation on the PFs and the disassembly of the facade. The OF will be equipped with a climbing system which allows it to be installed on the ground floor, lifted to the operational floors and then lifted down floor by floor. Logistics (tools, STCR delivery, and removal of disassembled material) is done by the VDS (installed in the core shaft of the building) and the H/VDS (upgraded tower crane). In case the shaft of the building cannot be used for installation of a VDS only the H/VDS can be used. The disassembled components are disassembled into parts and mono material elements in the GF.

3.1 Case study and target building

To evaluate the concept a scenario case study is conducted and deconstruction tasks sequences and alternative configurations of the system are analysed. The scenario reveals a number of obstacles and goals and allows exploring potential opportunities. The target building is an abandoned office block with 31 floors which is situated in a downtown area with busy on-ground activities (traffic, pedestrians) and offices and shops that might be affected concerning their operational performance by the deconstruction activity in the direct surrounding. The objectives are to (1) decrease deconstruction time, (2) reduce dust and noise during deconstruction process, (3) increase material recycling and component re-manufacturing rate, (4) develop an adaptable systemized and partly robotised deconstruction system, and (5) evaluate design solutions and the applicability of ABM utilization.

3.2 Deconstruction sequence

The target building is composed of steel frames supported by central reinforced concrete (RC) core. The RC core also contains a service shaft for heating, ventilation, and air conditioning (HVAC) services and vertical transportation. The RC floors were casted on-site when the building was constructed and provided an open office spaces. The external facade is composed of prefabricated curtain wall elements. The building thus represents one of the most common commercial building designs and similar type of the target buildings can be found globally in large quantity.

The exemplarily chosen deconstruction scenario starts with the data acquisition process. Most of the existing buildings are not represented digitally based on a BIM or CAD data base but on 2D data which are necessarily also able to provide sufficient information about the building (such as layout plan, elevations, structural specifications, etc.). This information can be transferred into a relevant BIM application and later integrated with the ABM systems. If necessary the exiting digital representations can be extended and detailed by the application of additional data acquisition methods (e.g. laser scanning, image processing, etc.).

3.3 Task description

In combination with a data transfer approach, additional data related to the used building materials are be gathered and analysed. Building materials can be divided and categorized into a range of categories and specification groups. These categories shall allow predicting the degree of complexity of the disassembly and recycling process. The classifications of the material shall indicate the material type. For example, steel structural elements, metal piping, ventilation ducts, electric wires, and light fittings can be classified as Mc1 (Metal class level 1) (see also Figure 3 for a detailed outline of the component structure of the target building).

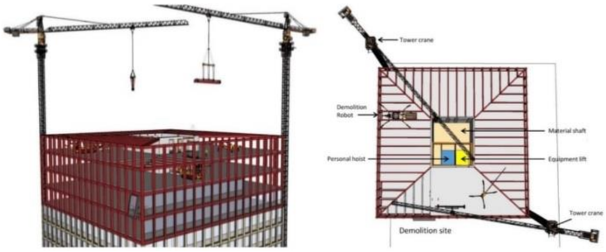


Figure 2. Perspective view of disassembly process of components using the V/HDS (left); A top view of transportation of disassembled components using the V/HDS (right).

This properties can then be transferred into the ABM data base and combined with other parameters such as (1) the location of the material, (2) family type, (3) quantity, (4) weight, (5) assess ability, (6) tooling, (7) man hours needed for deconstruction, and (8) work flow. The next step is then the preparation and installation of the deconstruction equipment. In this particular case, two conventional tower cranes (that can later o be also robotised for the achievement of higher automation ratios) will be installed, which will provide full vertical and horizontal lifting coverage on-site (thus serving as an H/VDS). Once the tower cranes are in place, the next step is the removal of the roof section of the building. In this case the task will be done in a conventional manner. Meanwhile, workers will clear the central RC core, dismount the existing lifts. A vertical transportation system along with a power supply system will be installed in the RC core transforming it into a VDS. During the deconstruction process the RC core will be used as vertical shaft for transportation of materials, workers, and the equipment. Keeping material flow inside the building will significantly reduce noise and dust caused by the deconstruction process. In addition, a vertically movable, partial cover (the OSF) is installed to create a controlled, structured environment on the OFs.

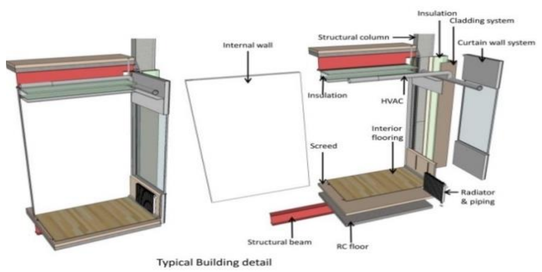
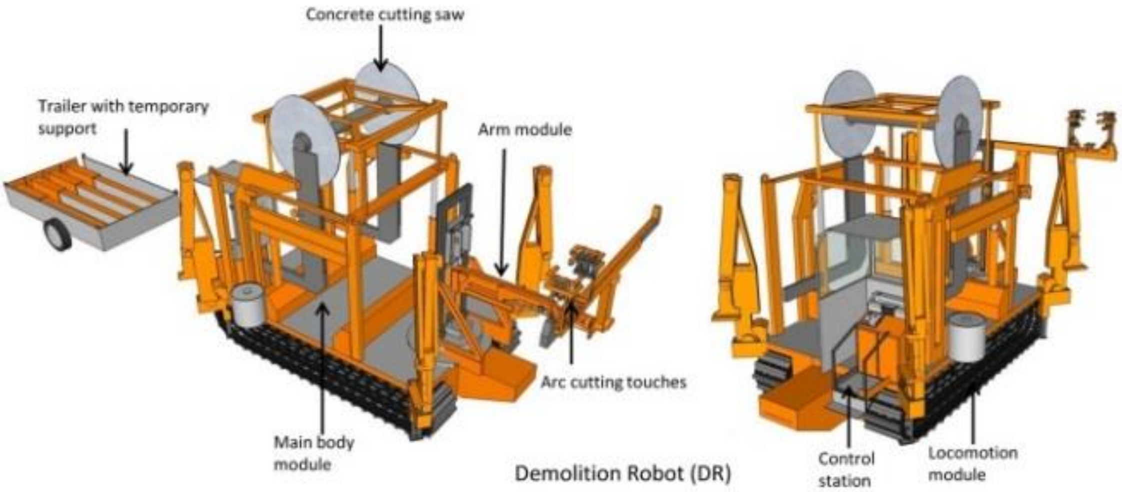


Figure 3. A detailed view of building components assembly.



Then the removal of electrical installations, gas/ water infrastructure, sewer device/components and all other building services follows according to the schedules and operational sequences generated by the AMB sub-system. Furthermore the curtain wall system is removed (using outside platforms of the OSF). All these tasks are conducted manually. Subsequently, novel types of deconstruction STCRs will be assigned to the correct job locations and sequences. The STCRs will operate under the operational floor (OF) on a dedicated activation floor (AF). The actual disassembly tasks take place on the OF and the AF functions as the traveling zone for the STCRs The travel path of the STCRs is pre-defined by the ABM sub-system and single task operations are executed semi-automatically supervised by human workers. The tower cranes work complementary to the STCRS and assist them to remove the disassembled elements (e.g. transport the disassembled elements through the vertical shaft). Once one floor is fully disassembled the STCRs, are transferred to the next floor below. On the ground floor, the dismounted parts and materials are further processed in the GF and prepared for transfer to appointed re-cycling/re-manufacturing locations and facilities. An efficient Just-in-time (JIT) and Just-in–sequence (JIS) logistics strategy will be achieved with the help of the ABM. In this paper, the demolishing of the foundation will not be considered.

4 System description

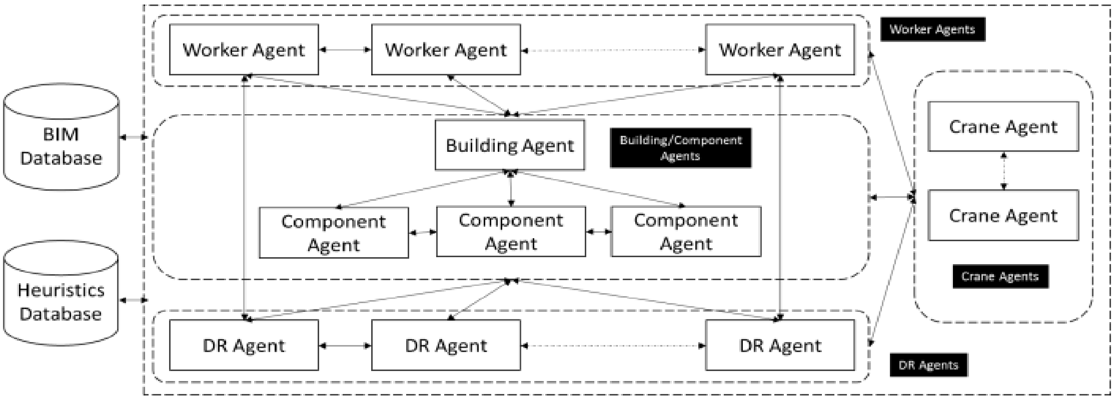
The proposed system attempts to transform conventional deconstruction sites into an on-site disassembly factory which facilitates sustainability by providing a safer work environment and minimising work hours. Conventional tower cranes, STCRs and a number of sub-construction systems are applied in parallel for the project. Each system is designed to execute certain deconstruction tasks. The STCRs, H/VDS and ABM are described in more detail in the following sections.

4.1 Deconstruction STCRs

The STCRs are designed for the cutting and disassembling of floors, beams and column elements. The numbers of the STCRs deployed depends on the size of the floor space and budget of the specific demolishing project. It consists of four modules: (1) locomotion module: the module offers a traveling platform that based on a tracked excavator providing mobility for the system; (2) main body module: the main body provides a structure frame for the system as well as the control and power resources for the robot. The control platform also protected by galvanised steel sheet cover to protect against any debris, dust etc; (3) arm module: the arm module provides positioning control and end effector support when handling, cutting building elements; (4) end effector module: there are two end effector modules, sawing module and cutting module, both are adaptable, upgradeable and interchangeable based on the specification and the position of the saw or arc cutting component can be adjusted according to each task. The concrete saw which is located on the top of the STCR is equipped for cutting through RC floor.

Figure 4. An image of anchoring and slab cutting process.

The arc cutting torches located on the tip of the arm module allow for cutting through structural beams and columns. Moreover, depending on the type of building structures and materials contained in the building to be deconstructed, the end effector module can be replaced.



The STCRs are assigned to the starting location on the AF level. The robot travels then on a pre-defined (through ABM optimised) route down the span direction of the beams. The concrete cutting saw will extended upward and cutting through the OF level areas between the beams. Cross span direction cutting tasks need to be done by human workers from the OF level downward. During the cutting process, temporary support will be placed between the OF level and the AF level just to prevent any structural collapse during the operation. The dismounted RC floor section is then lifted away by the H/VDS. A similar sequence is applied for the disassembly of the beams and columns (Figure 5).

4.2 H/VDS

The main purpose of the vertical shaft is to provide an internal logistical path for all material, workers and equipment, yet without any disturbance to the external environment. The first option is, the STCR has an integrated climbing mechanism which allows the robot to climb up and down between floor spaces. The second option is an opening on the RC floor is cut and prepared on the AF level so that it can then be transported through the opening once the task is completed on the floor.

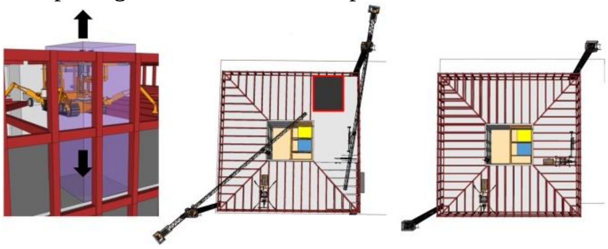


Figure 5. Case analysis for vertical transportation.

4.3 Deconstruction process modelling

Deconstruction scheduling represents the process of assigning resources and situating them time phased in the deconstruction process plan. Conventional approaches for solving scheduling problems encountered many difficulties when applied in real-world situations, because they used simplified models and the conventional deconstruction site is unstructured. Through the use of and OSF and STCRs the suggested approach will encounter this and structures the site to a larger extent. The ABM technique can then provide feasible support for modelling, simulation and realisation of the deconstruction process. To shorten the duration of the disassembly process by optimally allocating and operating resources such as STCRs, cranes, and workers is a key requirement. Even with an OSF unexpected events (such as machine malfunctioning temporality) can occur and scheduling and resource allocations might have to be changed to a certain limited extent. In this case pre-defined scheduling may fail if the number of entities to be controlled becomes too large. Static approaches (such as Critical Path Method; CPM) are not a proper tool in this case. However, based on the ABM method [10], the deconstruction process can be modelled by considering each entity's properties, behaviour and interactions. For example, the disassembly order of the building components can be prepared on the basis of the BIM data of the project, and motion planning regarding the STCRs becomes possible in order to reduce and simplify the necessary movements of the STCRs as well as the interactions of STCRs with the H/VDS. Therefore, work tasks (and thus man hours), time and work hours consumption can be minimized and at the same time the disassembly sequence can be optimized for achieving the maximal recycling or re-manufacturing rate. Furthermore, a body-in-white simulation of the deconstruction process based on ABM can prevent work place overlapping between entities and lead to enhanced safety and reduced disturbance of the surrounding economic environment.

5 System validation and evaluation

Using conventional demolition methods a recycling rate of 55% can be reached. In contrast, more than to 90% [11] can be reached using an alternative method. Deconstruction involves multiple complex processes (such as project planning, automated and robot assisted tasks, manual work tasks, deconstruction management, human resource/machinery procurement, on-site logistics, material recycling, disposal, etc.). Depending on the deconstruction method, energy, money and time can be saved while minimizing the occurrence of fatal casualty and disturbance of the economic environment. So far, traditional project scheduling techniques (e.g. CPM) have been accepted by the construction industry as useful tools for deconstruction. But these traditional scheduling techniques have functional-computational limitations (such as inability of accounting for resource-driven activity relationships). In the following sections a first preliminary framework for the validation evaluation of robot and ABM assisted, systemised deconstruction and the used devices and sub-systems is presented.

5.1 Definition of performance indicators

Following the definition of indicators for the evaluation of automated/robotic on-site factories [5], a first attempt is made to adjust this evaluation system to the development/evaluation of deconstruction projects. Used, for example, in a value analysis the individual indicators can be assigned different weights in order to consider the view of a specific stakeholder.

Table 3: System for evaluation of systemized, automated deconstruction approaches [5].

Phase		Performance indicators
R&D	1	R&D spending
	2	investment in equipment
	3	investment in ROD (deconstruction) standards
	4	investment in component/unit connectors
	5	necessary rate of adaptation of processes
Development	1	clear definability of cost
	2	clear definability of quality
	3	clear definability of de-construction time
	4	clear marketability
Planning	1	deconstruction planning complexity
	3	use of existing building typologies/standards
	4	necessity of integration of phases and players
	5	necessity of complex deconstuction planning tools
Construction planning and simulation	1	planning complexity
	2	necessity of complex deconstruction simulation
	3	time necessary for deconstion planning/simulation
On-site deconstruction system set-up	1	complexity of on-site system set-up
	2	necessity of tests and certifications
	3	time necessary for system set-up
Actual deconstruction phase	1	high de-construction speed
	2	high work productivity
	3	control of quality
	4	resource productivity and recycling rate
	5	transparency of cost and time
	6	working conditions/ safety/ health

5.2 Mock-up of STCR for deconstruction

One of the biggest barriers in introducing robotic technology to building (de)construction is the huge cost of R&D and therefore construction companies are reluctant to participate in projects targeting automated/robotic construction. Moreover, it is challenging to implement traditional industrial robots in a deconstruction environment. One of the key issues is human-robot-interaction and collaboration. In other industries, sensors are used to guide robot during its operation, and often the robot work station has to be isolated from the human worker to avoid risk. However, deconstruction tasks involve many highly coordinated, physically demanding movements which are difficult for either robot system or human worker to operate alone. The optimized solution is to consider efficient human-robot collaboration in the design of the de-construction STCRs.

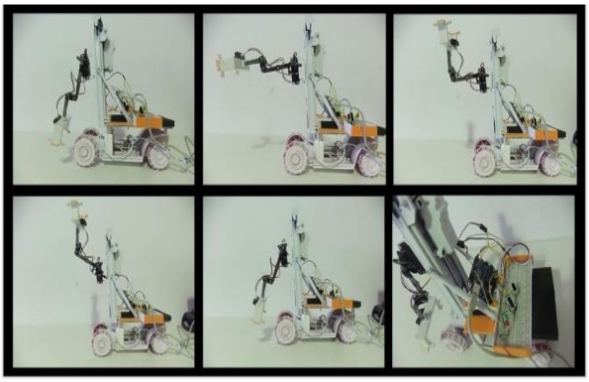


Figure 6. Prototyping process using Arduino micro controllers.

Lately, the development of a new breed of open source electronics prototyping platform, such as Arduino, has changed the research trend of many engineering sectors. Arduino is based on flexible, easy-to-use hardware and software and it can easily be attached to Ethernet Shield, sensors and servos. In order to demonstrate the feasibility of the prototyped simple construction robot, a demolishing robot mock-up was built by using an Arduino control platform. The proposed robot can be used as a sub-system in the proposed concept and also has potential market demands. The prototype consists of four modules (see also Figure 6): (1) Travel platform module; (2) Manipulator module; (3) End-effector module; (4) Control module. Automation and robotic technologies can bring positive impact on the construction industry, yet due to the vast R&D investment of R&D it is essential to introduce the new method one step at the time. It is economical feasible to evaluate and upgrade existing machineries and slowly achieve high degree of automation in the future. The built mock up shows that this is a relatively manageable, cost-effective and efficient approach to engage in robotic research with limited resources and experiences.

6 Conclusion, future research

The proposed system is conceived as an open, modular system where new elements can be added in the future and conventional construction elements can be abandoned after a transition period. Furthermore, in a next step the application of the Robot-Oriented Design

(ROD) method can be considered and contractors can foresee in the design of the building features which make the operation of the deconstruction system more efficient (e.g. through façade integrated rails which simplify operation of the OSF) or which simplify component disassembly. The proposed concept and the case study demonstrate an alternative method for building deconstruction. Innovative concepts were suggested by the use of a cross-disciplinary approach; challenges but also potentials for the (de)construction industry were identified. In the future, building should be designed considering the deconstruction phase [12] and the application of robot supported, systemized deconstruction following the principles of ROD. From early designing stages, the architects and engineers should be aware of the methods, work sequences and tools/devices/robots/on-site factories that will be applied during the deconstruction process. The building components should be compatible with robotic applications. Connectors and joints between components should provide easy access for the equipment during the disassembly phase. Furthermore, the proposed method can subsequently be adapted to other types of buildings to provide a competitive solution in the thriving global deconstruction market.

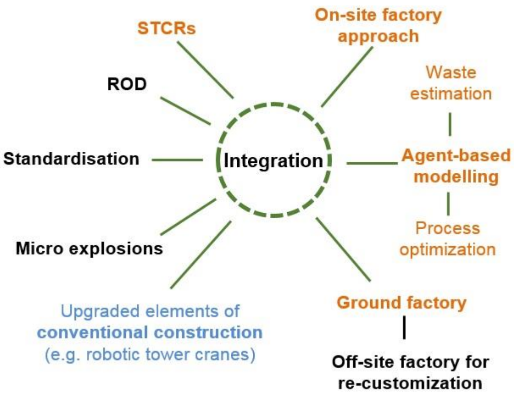


Figure 7: The proposed system is conceived as an open, modular system.

To realise a disassembly oriented design, standardisation activities, economic incentives and an adaptation of building codes or regulations have to be considered. In the future, it might be possible that building standards as LEAD or BREEAM include criteria for systemized, industrialized deconstruction in their certification system in the future as resource productivity (besides CO2 emissions, etc.) more and more gains importance. Standardization on a large scale would justify intensified research and development. In context of a workshop in Munich, representatives of the Kajima/DARUMA team confirmed the importance of such standardisation in order to guarantee the re-usability of complex deconstruction equipment. It was also discussed that through ROD, for example, dedicated wholes in concrete structures could be foreseen in the design of the building for the injection of micro explosives which could then be used in the safe and controlled environment of an on-site factory. Furthermore, following the idea of an off-site production line for component re-customisation as realized by Sekisui Heim, the on-site ground factory can be logistically linked to dedicated off-site factories that re-manufacture components for use in other buildings.

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