Automated refurbishment & end-of-life processes – research approaches in German and Japanese construction

Elisa Lublasser[1]*, Kepa Iturralde[2], Thomas Linner[2], Sigrid Brell Cokcan[1] and Thomas Bock [2]

[1] Chair for Individualized Production in Architecture, RWTH Aachen University, Germany
[2] Chair of Building Realization and Robotics, Technische Universität München, Germany
** Corresponding author (lublasser@ip.rwth-aachen.de)*

Recently, efficiency in the building fabrication process and on construction sites in terms of energy consumption, sustainability and reuse has become more and more important in the discussion of the building life-cycle and the construction site of the future. In this paper, different approaches for the development of automated refurbishment and end-of-life concepts with focus on robotic deconstruction within the construction sector will be introduced. Whereas RWTH Aachen is researching on the integration of industrial robots in the context of smart building automation and the digitalization of the construction site, TU Munich is researching concepts beyond industrial robots and prefabrication as one solution for preplanned deconstruction. An overview of the proposed concepts and the pros and cons of the various methods will be discussed in this paper.

Keywords: *Automation; Robotics; Deconstruction; End-of-life; Refurbishment; Prefabrication; robot motion programming*

INTRODUCTION

As a basis for the detailed development of automated processes, the following introductory section describes the demand for new refurbishment and end-of-life processes to locate the research aims within a global context.

General demand for new refurbishment & end-of-life processes

Generally, the demand for refurbishment and deconstruction of whole buildings as well as building parts is drastically increasing[1] due to rising vacancy rates and worsening building conditions of the building stock among other criteria. Furthermore, in the past years major changes in society that have modified the requirements of residential architecture have been observed. To meet the new standards while preserving existing built resources, the building stock has to be generally reorganized including the partial and locally defined deconstruction of internal and external building parts such as walls, slabs and facades. In addition, the increasing scarcity and cost increase of resources lead to the demand for future refurbishment and end-of-life approaches for buildings which ensure that the material bound in the building can almost fully be recovered for reuse either within the given building or for other construction projects. This recovering is, however, labor intensive, involves highly repetitive processes, and in some cases is dangerous for human beings. The utilization of robots in this filed is thus imperative.

Moreover, not only the demolition sector but also the construction industry have become more and more affected by intensified recycling and reuse standards such as the Waste Framework Directive (WFD) of the European Union or the German Kreislaufwirtschaftsgesetz (KrWG). Therefore, the building industry is in need of recycling and deconstruction strategies for recent construction setups which often include more complex and intertwined composite elements than in past years due to their highly optimized function based layer arrangement. One example for these elements are external thermal composite systems (ETICS). The acceptance and future application of such system are strongly related to reliable recycling strategies supporting the KrWG regulations but are not yet fully examined.

Although the processing of great amounts of construction and demolition waste (C&D) already reaches a high degree of recycling[2], there is still great potential for high quality element reuse of certain building elements. Therefore, the current deconstruction processes have to be adapted to be able to provide the necessary varietal purity for the pursued element reuse.

All in all, new refurbishment and deconstruction processes have to be developed to be able to not only cope with the described circumstances but also efficiently handle the deconstruction and refurbishment in high-wage countries. The efficiency has to influence the process development to optimize working efforts, working time and costs to guarantee the competitiveness of construction and demolition companies. Concurrently, the working conditions within the process have to be increased while decreasing emission for the working as well as living environment close to or at building and demolition sites to provide safer and more attractive jobs for workers in the building and demolition sector to match the changing requests of the labor market.

STATE OF THE ART DECONSTRUCTION

Considering that future refurbishment and end-of-life approaches for buildings can be characterized rather as *systemized building deconstruction* (which allows for component-reuse and recycling) than as *building demolishing*, the actual process can be subdivided into three major phases, namely the preparation of deconstruction, deconstruction and material separation, and the processing of deconstructed components. The development of automation strategies and robotic technology for all three phases that allow to treat a building as a modular product which can be systematically disassembled increasingly is a topic in R&D in both industry and academia.

Currently, deconstruction takes place at different levels of automation, material separation, manual labor integration and costs. While the application of frequently used hydraulic excavators (HE) with various attached deconstruction equipment offers a fairly automated, time and cost efficient process, it is not able to support the pursued optimization of deconstruction and refurbishment processes with a high quality separation for material reuse. So far, this is only possible with a great amount of manual labor cooperation because the big machinery lacks of necessary local accuracy. [3]

On the other hand, manual demolition work with the support of small machinery such as pneumatic hammers is a rather slow process which is often mentioned as indicator for cost-driving positions of demolition services[1]3. Considering also the working conditions, manual demolition procedures entail more disadvantages which are otherwise mostly prevented by the protection of the HE cabin:

(1) direct exposure to dust, equipment vibrations and unpredictable hazardous situation through uncalculatable material fall off
(2) direct contact to unexpectedly exposed contaminated materials
(3) physical stress because of equipment payload and manual material transportation

However, manual deconstruction is so far the most effective procedure for high quality material separation on site[4]. The human dexterity as well as immediate intuitive adaption of working procedures and adequate tools allow for all degrees of purity of variety of harvested materials and thus allow for controlled and predictable material and building element reuse.

In conclusion, common deconstruction procedures are not yet applicable for optimized refurbishment processes. New approaches have to be developed combining the advantages of various common procedures.

NEW APPROACHES FOR AUTOMATED REFURBISHMENT & END-OF-LIFE PROCESSES

In the following sections, the two different research approaches for the optimization of refurbishment and end-of-life processes overcoming the discrepancies of common procedures as described above are explained in detail.

Prefabrication and deconstruction

This section summarizes the research developed by the Chair for Building Realization and Robotics at TU Munich on necessary frameworks and systems for the automated refurbishment and end-of-life processes based on results of prefabrication research in construction. The research aims and results are accompanied by preliminary research and industry examples of the Japanese sector of automation and robotics in construction.

Holistic approach & sub-systems

Achieving an optimal building stock is a goal of the European Union[5]. For that purpose, there have been several publicly financed projects[6-8] that have been working with several solutions in order to ameliorate traditional ways of gathering a holistic building renovation. An automated and robotic building refurbishment process[8] will facilitate the renovation and maintenance of the building stock.

For conceiving a system for robotic building renovation, three main concepts of three main sub-systems have to be considered[8]8:

(1) Sub-System 1. Adaptable module or element configuration. The bespoke added element or module is adapted to the geometry and physics of the existing building.
(2) Sub-System 2. Robotic manufacturing process of customized elements or modules. This concept leads to flexible or lean manufacturing.
(3) Sub-System 3. Robotic installation process of modules or elements that are placed and fixed onto the existing building. To achieve that purpose, there must be a redevelopment of existing robotic and non-robotic hardware and software tools which then have to be reconceived for building refurbishment.

Under these three main sub-systems, a hierarchized and interrelated chart of sub-sub-systems must be organized. Since the System can grow in complexity, methods such as Axiomatic Design or TRIZ are always necessary[9]9. E.g. focussing on Sub-System 2 (see *Figure 1*), the primary goal is to improve the off-site manufacturing process. Other goals can also be pointed out, such as:

(1) Adapt to different degrees of automation
(2) Adapt to various assembly processes configurations depending on the module or element variations
(3) Adapt to factory reconfigurations
(4) Adapt to various supplying systems.

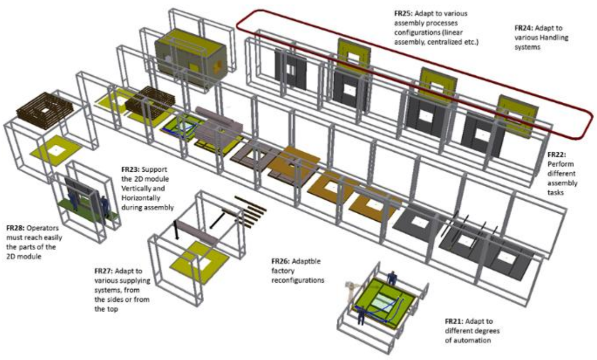


Figure 1. Sub-System 2: Robotic manufacturing system for building refurbishment, a scheme

As it can be observed, the issue of robotic building renovation is complex and needs a holistic vision in order to successfully achieve the goal.

Related robotic technology for construction
Specific and dedicated single task robots (
Figure 2) have already been conceived to work in the interior and exterior of construction sites[10]. Those robots operate different tasks such as dismantling the actual building elements and installing new ones.

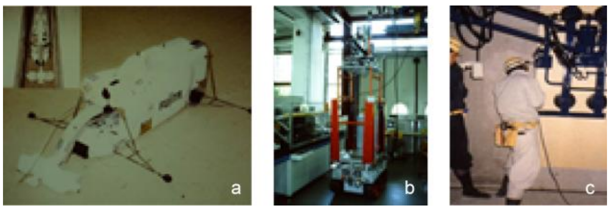


Figure 2. a) Interior Inspection Robot Shinyo Corporation Robot or Fujita Robot b) Interior Refurbishing Robot TB., c) Fig.3. Interior Refurbishing Robot Komatsu (All Copyrights by Thomas Bock, TU Munich)

These technologies, in principle, need to be adjusted for being applied within the building refurbishment process[10].

Preliminary examples for rapid refurbishment
One of the best preliminary examples of rapid building refurbishment is the upgrading of the OMM building in Osaka in 1987. It was led by Takenaka Contractor Company and the YKK curtain wall manufacturer and installer. The main goal of the project was to add a second envelope layer in order to improve the thermal performance of the building. In this case, some relevant characteristics can be found:

(1) Accurate measurement of the existing building envelope.
(2) Accurate positioning of connectors.
(3) Accurate fabrication of bespoke curtain wall prefab modules.
(4) Fast placement system of the new curtain wall using embedded rails
(5) Rapid clamping, fitting and fixing mechanisms.

Although the construction industry of that time period in Japan was highly robotized[12], the used tools were actuated manually in this project. This shows that working in existing buildings due to the unstructured and poorly documented environment is more complex and requires more specific development.

Large scale kinematics for construction and deconstruction
Members of the Building Realization and Robotics Chair at TU Munich have approached a robotic system that is suitable for the installation of flat modules onto facades in order to improve the energetic performance of the building [11,13]. This early stage research has focused on two main issues:

(1) Development of robotic support bodies.
(2) Design of the end-effector system defined as a Modular End-Effector (MEE) System.

Depending on the building typology, some support bodies adapt better to a given building situation. For instance, a support body based on Arial Work Platform is more suitable for low rise buildings, whereas a Cable Driven robot would be appropriate for a high rise building. *Figure 3* a) depicts a connector fixation process with an Aerial Work platform. In this case the MEE is performed semi-automatically and the operator can guide the whole process close to the task. On *Figure 3* b) the MEE is used by an Automated Vertical Bridge crane. It can be observed that the MEE elevates the facade component. As shown in *Figure 3* c), it has also been considered the choice of using the MEE as a cable suspended device by a cable robot.

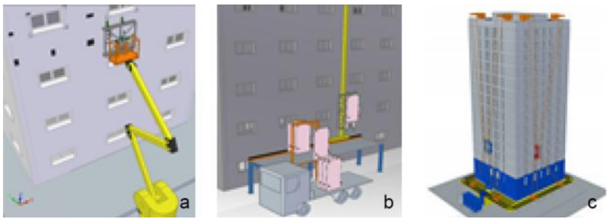


Figure 3. Automated façade element assembly with a) Arial Work Platform b) Automated Vertical Bridge c) cable suspended robot. (Image: Iturralde, Linner and Bock, Chair for Building Realization and Robotics, Technische Universität München)

The MEE system has been simulated using specific software. The simulation has focused on

(1) Structural behavior of the proposed MEE
(2) Operability performance of the MEE system.

For the installation of the modules, the MEE needs to perform several tasks: drilling the existing wall, inserting the connector and placing the fixing and the module itself.

On-site operation site factories

Automated and robot supported deconstruction of buildings is accomplished by on-site operation site factories which are installed on the site as a cover basically move down the building coordinated by the deconstruction time schedule and allow the installation and operation of all sorts of robots and assistive tools. Thereby, a controlled, structured and systemized work environment is created on site. Bock and Linner sub-classified on-site approaches for systemized-deconstruction into three categories[14] (see Table 1).

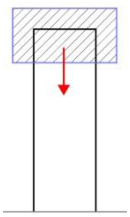
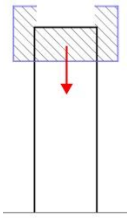
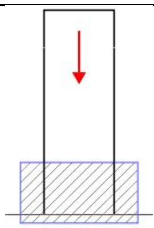
Typology 1	Typology 2	Typology 3
Closed Sky Factory Supported by Building (moving downwards)	Open Sky Factory Supported by Building (moving downwards)	Ground Factory (fixed place) and Building Lowering
		
Systems: Hat Down (Takenaka) TECOREP (Taisei)	Systems: MoveHat (Nishimatsu) RCM (Shimizu) QB Cut-off (Obayashi)	Systems: DARUMA (Kajima)

Table 1 Categorization of on-site deconstruction approaches employing robotic technology

For example, all six major Japanese contractors have developed systems for systemized and at least partly automated/robotic disassembly since 2008[14]. One example is the HAT-Down system by Takenaka Corporation/ T. Bock (
Figure 4). In such on-site factories, the high-level components are disassembled (e.g. from top to bottom), then the harvested components are further process, for example, in a ground factory on-site into sub-assemblies and parts, which can then be handed over to off-site factories for recycling and reuse.

Figure 4. Automated building disassembly for urban mining (Image: HAT-Down system by Takenaka Corporation/ T. Bock)

The processing of lower level components, mono-material parts or raw materials can be efficiently accomplished in off-site factories providing a structured environment for the use of automation and robotic technology. A more extensive example was developed by the Japanese housing manufacturer Sekisui Heim (
Figure 5). They offer as part of their construction system a house reuse program where steel cells and frames that have been disassembled from an old house are "re-personalized" on their production lines and used for a new, individual building[12].

Figure 5. Large-scale deployment of sustainable buildings through advanced prefabrication (Image: Sekisui Heim)

Robotic arms for life-cycle oriented material and element refurbishment

The chair for Individualized Production in Architecture (IP) at RWTH Aachen University is currently researching on robot assisted deconstruction and refurbishment processes for the recovery of building material with a high degree of material separation as well as element reuse. The pursued application scenario of the new processes is based on the refurbishment of wall-construction based buildings especially supporting product recycling for reuse in the building industry[15]. To be more precise, locally restricted and partially executed deconstruction of building elements and relocation of harvested reusable materials or building parts on the same building site within a new context will be sought, which can be referred to as a *life-cycle oriented material and element refurbishment.*

To quickly and efficiently achieve this ambitious goal, the interdisciplinary team of IP is researching on the implementation of well-known industrial robotic arms. The motivation here is to use standardized and reliable hardware to be able to focus the research on detailed software problems such as new task programming as well as human-machine interaction to guarantee a successful implementation in the so far poorly automated construction sector.

Figure 6. depicts an example of initial experiments on robotic arm assistance in the deconstruction process. Here, the robotic arm was programmed for precise stemming of masonry joints as preparation for a refurbishment process including the partial deconstruction of an external wall to gain a new opening and reusing of the harvested bricks for a new internal wall element while recycling other parts.

Figure 6. Robot assisted exposure of bricks via stemming of masonry joints (top) and manual removal of bricks (bottom) at RWTH Aachen construction site (Image: Lublasser and Brell-Cokcan, Individualized Production in Architecture, RWTH Aachen University)

Advantages of robotic arm assistance

It is expected that the integration of robotic arms in the deconstruction process will be able to bridge the gap between common procedures combining their advantages. While relieving demolition and construction workers from the heavy equipment weight and direct exposure to hazardous situations[16], robotic arms are capable of controllable and precise movement, demolition and handling tasks to allow for direct element reuse without the necessity of major post-processing work. The so harvested material can then directly be reused on site in accordance to the refurbishment design. Thereby, the new process not only bridges the gap between different available machineries but also between the different architecturally and resource relevant tasks within a refurbishment project from demolition to construction in a de facto closed loop (see also section 0). Achieving this helps to reduce the consumption of energy and primary resources for construction tasks during refurbishment, since the manufacturing and transportation of new materials becomes superfluous.

Problems of robotic arm assistance

At the moment, standard industrial robotic arms can hardly be used freely for partial refurbishment of residential or public buildings because of their heavy weight, which is necessary to handle the heavy deconstruction equipment. Using large robotic arms endangers structural stability of common building construction. Furthermore, accessibility of the varying operation sites during refurbishment cannot yet be guaranteed. Nonetheless, current developments hold out the prospect of more efficiently usable robotic arms with an improved load to payload ratio (e.g. KUKA iiwa).

Robot programming for complex robotic deconstruction tasks

In order to prepare fundamental skills and software for the pursued robot assisted deconstruction and refurbishment process, the research started out with a couple of experiments focusing on selected aspects. Those initial research approaches are described hereinafter.

Force controlled programming for deconstruction of composite materials

As part of the research project “Robotic Façade Disassembly and Refurbishment System”, a robot assisted process for the deconstruction of external thermal insulation composite systems (ETICS) based on EPS insulation was developed and tested. In general, the deconstruction was focused on uncovering the raw masonry structure for the application of new, ecologically harmless and more easily recyclable insulation material.

The major challenge of the layer separation was the seamless transition of the various construction layers providing no suitable starting position for common deconstruction tools nor grippers. While the separation of those composite materials seems easily manageable for humans due to their described dexterity for even minor material differences during deconstruction, implementing the same sensitivity to robots or other machineries requires additional research and development effort.

Finally, the precise material separation (e.g. of plaster- adhesive composite and insulation) was achieved by using a common multi-tool machine with *force controlled* robot programming through the implementation of a KUKA iiwa and the utilization of its torque sensors. In this case, force controlled programming describes the combination of tool movements linked via movement cancellation criteria depending on forces measured by the robot (e.g. during the collision of the tool and the wall). Thereby, the individual movements can automatically be adjusted according to the spatial settings without interruption or cancellation of the total process. Furthermore, no manual robot movement or relocation has to be integrated in the deconstruction procedure and therefore uncontrolled as well as error-prone actions can be excluded.

Only a small area of the plaster-adhesive composite has to be manually removed from the insulation, afterwards the processes can be continued fully automated. The experimental procedure is depicted in

Figure 7.

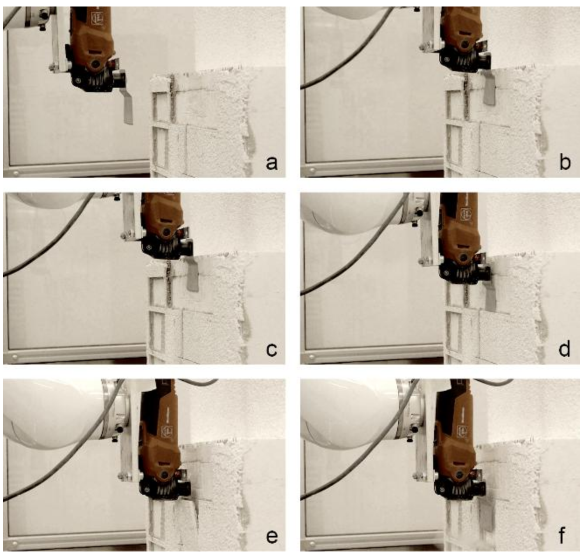


Figure 7. Force regulated movement of the deconstruction tool – Experiment executed in the RWTH Aachen robotic laboratory with a KUKA iiwa and a Fein Multitool (Image: Lublasser and Brell-Cokcan, Individualized Production in Architecture, RWTH Aachen University)

Intuitive human machine interaction through haptic programming

For the implementation of new technology such as robotic assistance on building sites, new ways of programming and machine integration have to be developed to achieve a high acceptance of the technology by unprepared and untrained building workers as well as an efficient human machine interaction on site.

One approach to support simple human machine interaction while alleviating fears for new technology is the "haptic programming" developed during the project "Dynamic & Interactive robotic Assistant for Novel Applications" [17,18] by the chair for Individualized Production in Architecture.

Haptic programming allows for direct and safe machine interaction through targeted integration of teaching options as well as soft motion modes provided by newest robot technology with torque sensors such as the KUKA iiwa. Through slight pushing of the robot by the human in predefined directions, the prepared robot program can be started, manipulated, fast-forwarded and rewound. Furthermore, the robot can be led within locally defined boundaries to capture geometric information which then allows on-site changes of the construction design to the very last minute before execution. The advantage of the haptic programming for simple human machine interaction is that no code-based programming has to be done on-site but the building worker is still able to adapt the construction work and process. For this purpose, no complex additional training in addition to a short introduction to the robot features is necessary.

This haptic programming research has already been tested with various people who are not familiar with robotics and was proofed to be successful. One application was presented at the Hannover Messe 2016 in the course of the KUKA innovation award. Here, bystanders were able to define the geometry of a rod-shaped wood structure which was then immediately produced. Furthermore, they were able to support the robot during the joining process of the rods to gain a higher accuracy of the robotic joining motion.[17] The last described interaction was also tested at the Robodonien Festival 2016 in Cologne. Here, the haptic programming during the process was expanded with the options of program starting as well as fast-forwarding and rewinding to be able to operate necessary predefined movements as often as desired. In both cases, the integrated bystanders were able to interact with the robot with only minor explanations and showed no anxious reluctance in handling the robotic process by themselves.

Global effects of automation and robotic assistance on construction sector

As shown, the application of robotics and automation helps to directly connect different stages of the buildings life cycle. Moreover, automated machinery on site can be implemented as a data and information medium to overcome one of the biggest issues for the implementation of advanced automation on building sites - the lack of a closed *digital* process chain (
Figure 8) from planning to execution on site until the final end of a buildings life cycle[19].

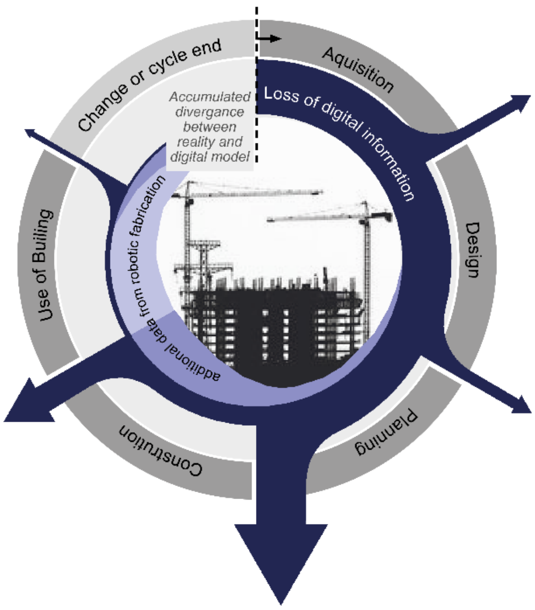


Figure 8. Loss of information during the building lifecycle and additional data through robot integration (Image: Lublasser and Brell-Cokcan, Individualized Production in Architecture, RWTH Aachen University)

By using digitally controlled machinery for building element production, handling and manipulation, connecting various information such as material type and conditions, actual positions of new or inbuilt elements, deviations from planned execution and connecting them with the geometric information of the digital building model will be enabled. Thereby collected information can then be used as data basis for further refurbishment actions or the final building demolition. Furthermore, the data collection helps not only for one building in particular but also as statistic reference material for similar building types.
Additionally, the general setup of automated machinery allows for simple integration of various sensors or camera systems. Collecting additional information with the help of those tools can help to provide a reliable data basis for building refurbishment and demolition especially of old buildings with no digital and little other information on the actual construction setup. Hereby, all building and demolition tasks become more predictable and can be planned more effectively and efficiently.

Conclusion

The paper presented a summary on the various research approaches on automated and robot assisted refurbishment and end-of-life processes in the context of the German and Japanese construction sectors. The different research aims are dedicated to different levels and scales of the general processes development. Thus, an important task for future research is to combine the results of all scales to generate a highly automated and adjustable refurbishment as well as end-of-life process and to generally push the degree of implemented automation in the construction sectors all over the world.

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