Assessing the Viability of Robotic Disassembly of Building Components for Resource Recovery

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Abstract

The transition towards a circular economy will, in large part, necessitate the disassembly and recovery of components from existing building stock. Robotic disassembly has emerged as a technique in other (non-building) industries as a method for efficient and scalable resource recovery. Since robotic disassembly has yet to achieve a similar level of maturity in the building industry, this paper presents an assessment framework towards this aim. This framework harmonizes the demonstrable capabilities of robotic systems (via literature synthesis and currently available hardware) with suitable deconstruction applications (using a case study of a large institutional building). The results yield strategic paths forward for enabling robotic disassembly of building components.

Keywords –

Robotics; Demolition; Circular Economy; Computing; Literature Review; Deconstruction; Machine Vision; Resource Recovery

1 Introduction & Background

With global raw material consumption set to double by 2060 [1], and the fact that the building sector is already the largest consumer of materials globally [2], it is imperative to find alternative ways to source and conserve materials for building construction. Recovery and reuse of building materials is an alternative to the current supply chain feedstock of new materials; for which disassembly is a fundamental operation to perform.

In contrast to manual disassembly, automated disassembly has emerged as a viable method in many applications for its ability to increase disassembly efficiency, be implemented at scale, combat labour market concerns, minimize costs for retrieving high-value items, and to perform complex disassembly processes (e.g., bespoke fixturing, multiple disassembly tools and very small geometric conditions and interfaces), among others [3]. Robotic disassembly has been successfully applied to numerous products including automotive (e.g., batteries, electronic control units, printed circuit boards, etc.), electronics (e.g., cell phones, circuit boards, LCD monitors, computers), and mechanical products (e.g., aerospace components, chassis, industrial manifolds, etc.) [4], [5]. The societal value created by robotic disassembly includes landfill diversion, material conservation for new products, creation of new local jobs [6], and functions as a key step in the growing the re-manufacturing industry.

Robotic disassembly in the building sector has yet to emerge at a scale similar to consumer and industrial product sectors. If realized however, it can overcome several key impediments: deconstruction often has heavy impacts to humans for the noise, dust, vibration, contaminated materials (e.g., asbestos) and debris generated, safety concerns, labor shortages, and inefficient resource recovery rates [7]. While currently ambitious, the ability for robots to initiate or augment current disassembly activities presents significant opportunities.

1.1 Robots for Demolition

Single-task construction robots that are deployed for dismantling structures are called demolition robots [8]. They are "all-terrain" machinery with a relatively small size, which allows them to operate efficiently in the challenging conditions of a demolition site. Demolition robots are not yet autonomous, due to the complexity of their work environment. However, they can be guided with remote controls from on-site or off-site personnel [9]–[11]. This function is beneficial both from an economic and safety perspective. To be specific, demolition works are hazardous and highly repetitive, thus utilizing robots minimizes the risks for the personnel and at the same time increases productivity [9], [11], [12].

Demolition robots often have a hydraulic-powered arm mounted on wheels, crawlers, or tracks to which shears, breakers, crushers, drills, buckets, cutters, grapples, and even high-pressure water jets can be attached [8], [10]. The first one launched was by PE Holmgren and Rivteknik in Sweden, back in 1976. In

1981, Brokk produced the first mass-produced model (Brokk 250), which was remote-controlled. Brokk still continues to manufacture similar models. TopTec has specialized in demolition robots since the late 1980s. Aquajet and CONJET have developed models for hydrodemolition since the late 1980s and early 1990s respectively. Husqvarna has also been offering various options for high ambient temperatures since 2009.

The presented demolition robots are some of the currently available products in the industry. However, the research is still ongoing, with the goal being to develop fully autonomous ones. This might be possible in the future as shown by the use of autonomous vehicles for excavation, transportation, and finish grading [8], [13]. Researchers are still exploring ways to make this happen by combining sensors and lasers with sophisticated algorithms [9], [12], [14]. The potential autonomy of demolition robots would greatly enhance the feasibility of deconstruction techniques, thereby facilitating the reuse of materials such as concrete [15].

2 Proposed Methodology

This paper assesses the viability of robotic disassembly of buildings as a method for supporting greater reuse and resource recovery of building components.

Figure 1. Active demolition project

The proposed methodology uses a three-tier assessment to determine the viability of robotic disassembly for building components (Figure 2). First, we review prevalent robotic disassembly applications and tasks (focusing outside the construction industry, where such work is more mature). Next, we assess current mobile robot hardware capabilities (using manufacturer catalogues) and software requirements specifically in the context of on-site selective disassembly of building components. Finally, we evaluate the viability of specific building components that could be subject to on-site robotic disassembly within a local geographic context (we analyse materials from an institutional building).

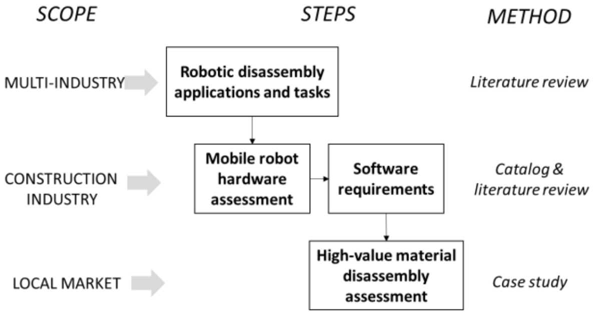

Figure 2. Methodology for assessing the viability of robotic disassembly of buildings

2.1 Robotic Disassembly Applications/Tasks

In their comprehensive review of robotic disassembly applications (which includes digital assistance e.g., sequence planning, decision making, vision systems, and physical assistance e.g., robotic systems and human-robot collaboration), Poschmann et al [3] identified 41 unique robotic disassembly applications. These include robotic disassembly of vehicles and electronics; of which, the majority of robotic tasks focus on handling, removing and separating components. Vision systems emerge as a key aspect of robotic disassembly for identifying target components, fasteners or conflicts along the disassembly path. Another key trend in robotic disassembly is the setup and deployment of entire cells which bring assemblies (e.g., waste electrical and electronic equipment) into a controlled environment to perform disassembly operations. It is typically in this context that human-robot-collaboration (HRC) systems are most prevalent. HRC is often favored even when a-priori geometric data is available for assemblies, since a key challenge centers on the uncertainty of other conditions (whether items are clean, have deviations, or if they are still in good working condition) [16]. Across existing applications of robotic disassembly, the following trends are noted in the literature: (a) maximizing the practical use of robots for disassembly occurs in HRC workflows [17], (b) the vast majority of applications (>90%) rely on accurate and up-to-date a-priori information on the assemblies, coupled with high-repetition across tasks [3], (c) robotic disassembly is optimized when planned upfront in product design [6], and (d) one of the most common robot tasks centers on removal of fasteners [18].

Reviewing the state of existing robotic disassembly applications, the following insights can be made for application to building components. First, HRC is likely required, since buildings possess more variability than manufactured products, greater constraints for robots (in terms of reach and payload), and less up-to-date digital information (e.g., 3D models) for disassembly planning. Second, void of accurate a-priori information on buildings, additional considerations are required for to program sensors and to perform learning in order to aid in efficient disassembly operations.

2.2 Mobile Robot Hardware Considerations

Following the guidance for construction robots outlined in Dritsas et al. [19], mobility criteria are considered feasible when robot weight (including platform) is less than 1 ton (1000kg), and when the robot reach is equal to or greater than 1m (in the horizontal axis direction). From this criterion, we analysed off-the-shelf mobile robots (using a library outlined by RoboDK© software) which fall into the following categories: 5 DOF (degree of freedom) robots, 6 DOF robots, 7 DOF robots, Delta robots and Palletizing robots. Without delving into the feasible disassembly tasks that each of these robots (and robot typologies) can perform, we identified 352 unique payload vs. reach datapoints from which to identify potential disassembly tasks (Figure 3). While the reach of each robot examined ranges up to 3280 mm, the use of a mobile platform can provide extended mobility on-site where needed for certain activities (e.g., mobile co-bots, compound robots).

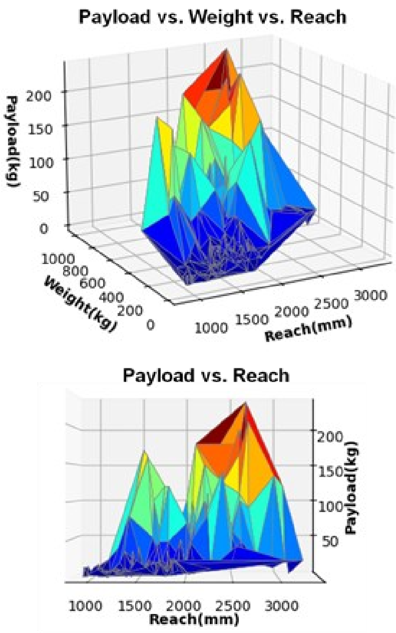

Figure 3. Mobile robot hardware capability assessment of 352 unique off-the-shelf robots

The next step in assessing robot hardware capability for disassembly is understanding (classifying) which types of tasks can be used. Based on general robot motion primitives for construction tasks as outlined by [20] (e.g., grasping, cutting, drilling and screwing), we propose a series of distinct disassembly operations that these robot motion primitives can be used for, as outlined in Table 1. While these robot primitives require custom end-of-arm tooling and programming for unique disassembly operations, it can be shown that many primitives already used in non-disassembly operations can also be used specifically for disassembly operations. For instance, screwing primitive could be used for removal of fasteners with operations including de-screwing and unbolting.

Table 1. Robot motion primitives for disassembly

Robot Motion Primitives	Robot Disassembly Operations
Grasping	Holding/supporting/prying/pulling
Cutting	Selective destruction for removal
Drilling	Access for cutting tool
Screwing	De-screwing, unbolting (removing fasteners)

2.3 Software Architecture Considerations for Robotic Disassembly in Construction

Construction robots generally need to be highly adaptable and agile due to greater environmental uncertainty and complexity as compared with manufacturing applications [21]. This section discusses the requirements of the high-level decision-making layer of their software [22], and the first two workflows of common software programming: environment perception and planning [23], as shown in Figure 4.

For environment perception, robots use various sensors such as cameras, laser scanners, and radio-frequency identifiers (RFID) to collect data. Building information modeling (BIM) serves as an additional valuable information source for understanding the built environment [24]. Robots need to interpret, sense and localize based on collected data, detecting objects or estimating motions through deep-learning models or predefined algorithms, for instance [25]. [26] also has proposed a graph-based multi-modal sensor data integration approach to enhance real-time state and location awareness. Considering how unstructured and dynamic construction and demolition sites typically are, real-time sensing is crucial, accordingly heightening the need for efficient data processing models.

In terms of the planning and decision-making process, construction robots should efficiently update their pre-trained and predetermined motion plans in response to changing (and sometimes unknown) environments. Software requirements are influenced by various factors such as autonomy level, the number of tasks, and required functionalities. For example, fully autonomous robots, driven without human interventions, often rely on artificial intelligence [8], while non-autonomous robots, including pre-programmed and teleoperated robots, are operated by deterministic software modules or human operation. Regarding the number of tasks, multi-task robots demand higher flexibility and learning efficiency than single-task robots [27]. Likewise, robots require different system configurations based on task types (e.g., on-site monitoring, on-site assembly, off-site prefabrication) and mobility types (e.g., gantry systems, aerial, and terrestrial) [28]. Building disassembly tasks, in particular, present additional challenges due to significant variations in target components' conditions, type, and geometry compared to the assembly stage [29].

To enhance the planning process, previous studies have introduced various solutions. BIM has been actively explored for task and motion planning, as shown in the studies utilizing it to provide detailed task descriptions, spatial information, and point calibration for tasks such as brick assembly, structural components assembly, and indoor wall painting [30]–[32]. Similarly, leveraging rich project information from BIM will assist in automating detailed disassembly sequence planning. A hierarchical reinforcement learning training strategy has been developed for more generalized control policies [33]. The efficiency of a demonstration-based motion sequence learning module in multi-task motion sequencing has also been demonstrated [27]. For the teleoperation of construction robots, a multi-user immersive environment has been explored for interaction during excavator teleoperation [34], and a brainwave-based teleoperation system has been proposed for workers in limited movability environment [35].

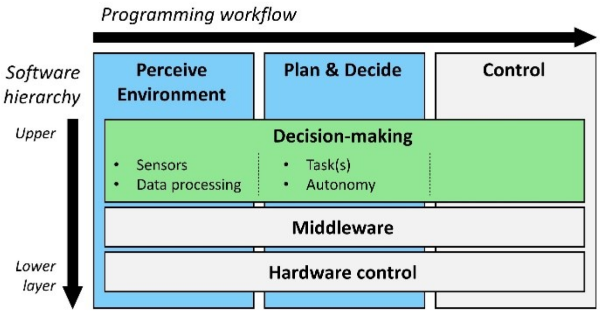

Figure 4. Software hierarchy and programming workflow of construction robots

2.4 Robotic Disassembly Feasibility Scale

In light of the high-level hardware and software considerations for robotic disassembly of building components, we posit a Likert-based robot feasibility scale for assessing initial feasibility. This scale uses five unique categories: RF0 (no robot feasibility), RF1 (limited robot feasibility, i.e., 1 task can be supported), RF2 (some robot feasibility, 2+ tasks can be supported), RF3 (strong robot feasibility, but requires human intervention or collaboration) and RF4 (strong robot feasibility, requiring little-to-no human support, e.g., a fully autonomous solution is probable). To help define each of these robot feasibility levels, we consider key constraints for disassembly tasks, drawing on experience the lead author has from industry work overseeing robot cells for fabrication in construction and experience with disassembly operations. The considered constraint categories are organized into those related to components (torque (T) and payload (P)), and those related to environment or hardware (reach (R) and spatial (S)), with examples defined below:

- (T): rusted/broken fastener, stripped head on fastener, overtightened bolt
- (R): end effector required location exceeds reach capability. For instance, commercial and residential buildings often have a floor-to-ceiling height between 8-12 feet (2.44 m to 3.66 m). In the case where a robot needs to reach the ceiling for disassembly, a custom platform might be required for current robots.
- (P): object being moved is too heavy, and or task moment (force*distance) exceeds capacity
- (S): robot arm and end effector hardware does not have ability to navigate in confined spaces adequately to perform disassembly task

It is important to note that the proposed robot disassembly feasibility scale is based on a specific material in isolation from its overall quantity within a building. As such, determining overall viability of resource recovery potential for a given material may also need to account for a minimum threshold of quantity (e.g., for supply-demand mapping of specific reuse items).

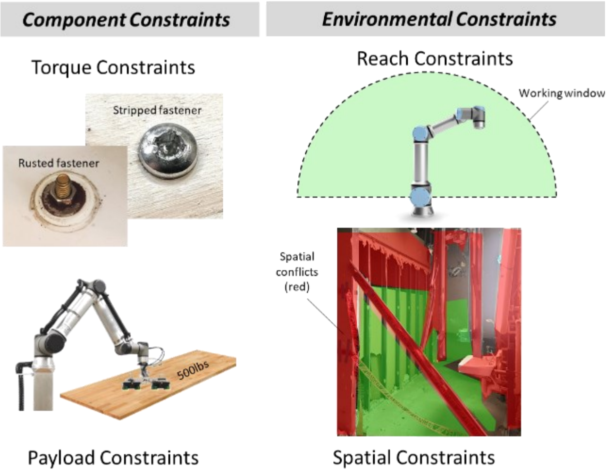

Figure 5. Overview of specific robotic disassembly constraints for resource recovery of building materials

3 Case Study

3.1 Background

The Erwin Center is an events center located in Austin, Texas, built in 1977, and is comprised of a steel-framed structure, with a precast concrete panel enclosure (Figure 6). In addition to its structure, there is a wide range of materials and components which can be potentially reused including doors, windows, chairs, fixtures (electrical, plumbing, mechanical, HVAC), gypsum board, electrical equipment, etc. It underwent deconstruction and demolition starting in 2023, during which time, the authors participated in a building material reuse audit with a third-party consultant.

As part of conducting this audit, priority was given to items which were found to have the highest potential for reuse based on local market factors, quantity and condition of components. Examples of the highest reuse valued materials include interior doors, ceiling tiles, carpet floor tiles, cabinets, mechanical and electrical equipment, light fixtures, network infrastructure and newer-condition appliances. Additionally, during the demolition phase, selective demolition and disassembly were performed to separate and sort many building materials for the purpose of recycling, including auditorium seating, piping, conduit, plumbing fixtures, and light gage wall framing.

Figure 6. Aerial view of the Erwin Center

3.2 Robotic Disassembly Assessment

The authors assessed robotic disassembly feasibility of specific materials using the proposed framework, identifying potential disassembly operations, known constraints and an estimate of overall quantities (we adopted a simple low (0-50 items), medium (50-500 items), and high (500+ items) approach, where overall robot feasibility was best for a high quantity of materials recovered since the return on investment of a robotic system is highest where it can be deployed in a highly-scalable manner). In cases where there is high value for specific material recovery but existing in a low quantity, it is assumed that manual (non-robotic) extraction is more cost-effective and preferred. The result of this overall assessment is shown in Table 2, where the best candidate materials for robotic disassembly are highlighted in green, candidates with moderate potential are shown in yellow, and candidates with poor potential are shown in red.

Table 2. Assessment of robotic disassembly feasibility

Salvage Component	**Disassembly Operations**	**RF***	**Known constraints****	**Quantity**
Interior doors	De-screwing, supporting/ handling, pulling	RF2	T, P: Hollow core: 25lbs, Solid core: 50lbs	M
Exterior door	De-screwing, prying, supporting	RF2	T, R: 80" height to upper screws, P: 100lbs	M
Decorative lighting	De-screwing, prying, supporting	RF2	T, R: ceiling height (8-12')	H
Carpet tile	Handling, prying	RF3	T	H
Ceiling tile	Handling	RF3	R: ceiling height (8-12'), S: framing for tiles	H
Cabinets	De-screwing, cutting, supporting	RF2	T, P: 200+lbs, S: cabinet geometry	M

Sink top with fixtures intact	Cutting	RF1	S: sink geometry	M
Light fixtures	Supporting	RF0	S: ceiling system geometry	H
2x4 wood	Cutting, De-screwing	RF2	T, P: 20lbs	H
Mechanical pump	De-screwing, supporting	RF0	T, P: >500lbs	L
Motors	De-screwing, supporting	RF0	T, P: >500lbs	M
Controllers	De-screwing, supporting	RF0	T	M
Transformers	De-screwing, supporting	RF0	T, P: >500lbs	M
Plumbing fixtures	Cutting	RF1	S: plumbing geometry	H
Fire doors	De-screwing, prying, supporting	RF2	T, P: 100lbs	M
Electrical panel box	De-screwing, handling	RF1	T, S: panel geometry	M
Exit signs	De-screwing, handling	RF1	R: ceiling height (8-12')	M
Wood fibre panel	Handling, prying	RF1	T, R: ceiling height (30'+)	H
Auditorium seating	De-screwing	RF1	T	H

**RF = Robot Feasibility Factor*
***T is listed generally for a range of conditions included stripped or rusted fastener, unknown tactile movements, etc.*

4 Discussion

Based on the robotic disassembly feasibility assessment, carpet tiles, ceiling tiles and auditorium seating were found to have the best overall potential for resource recovery supported by robots (Figure 7). Of the building components reviewed, ceiling tiles and carpet tiles had the highest robot feasibility (RF) factor. Both of these materials incorporate achievable disassembly operations as they are predominately gravity-installed (ceiling tiles being supported by a supporting frame, and carpet tiles being mounted using a special removable double-sided tape). Moreover, the vast majority of robots reviewed in Figure 3 can be used to support the removal because these components do not have a notable payload constraint: ceiling tiles are 2.2kg and carpet tiles are 0.63kg. The quantity of both materials also plays a significant role in its robotic disassembly feasibility (there were approximately 22,200 carpet tiles and 41,000 ceiling tiles). Although both building components are increasingly being supported by take-back programs (either through the original manufacturer or by third parties), current programs typically require the owner or onsite contractor to palletize tiles (which includes the labor for removal and stacking). This implies that robotic disassembly can even contribute to promoting readily available resource recovery programs by reducing the need for substantial manual disassembly.

The third building component identified as being viable for robotic disassembly was auditorium seating. While this component had a very low robotic feasibility (RF) factor, and despite its potential for reuse being low (due to poor item quality), extraction of auditorium seating was found to be a significant source of manual labor during demolition. Given the necessity to recycle the steel in the seating (i.e., many local jurisdictions require a minimum waste diversion rate for C&D projects), during demolition, 100 workers were brought on site for 5 continuous days to remove fasteners and grind the base connection of each seat. The labor cost for this is estimated at USD $100,000 (based on local market labor rate and contractor markup fees). In this case, the use of a robotic system to support disassembly not only could be used to address the high cost of fastener removal, but also reduces safety risk on site for the contractor.

The study demonstrated the potential of the proposed viability assessment framework, grounded in existing research and industry resources, to identify the feasibility of robotic disassembly and the most suitable building components. The framework was initially applied to one institutional building but can be utilized to evaluate the various other building components with different contexts.

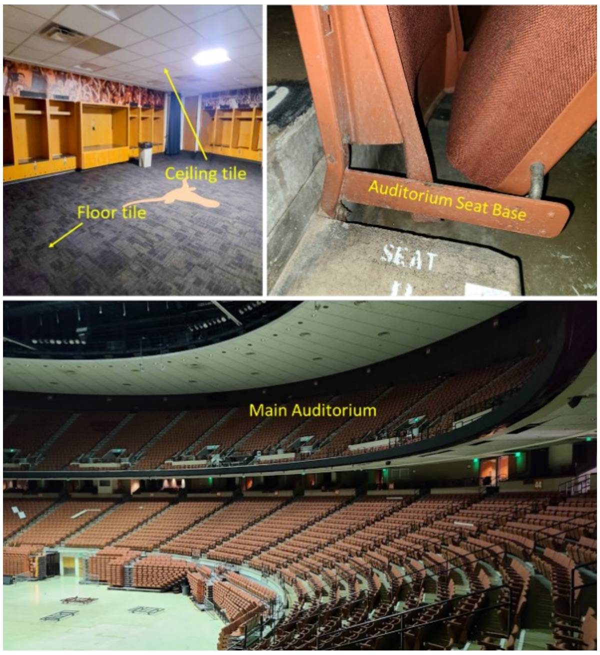

Figure 7. Carpet tiles, ceiling tiles and auditorium seating

5 Conclusions

In summary, this paper explored the potential to incorporate robots to support the resource recovery of building materials at their end of life through disassembly. Current approaches for resource recovery in the construction industry are driven by either manual labor tasks (which include the manual operation of various mechanical equipment). Other industries are beginning to see the prevalence of robots to aid in disassembly operations, however the same level of maturity is not currently seen in the construction industry. To fill this gap, we proposed a conceptual framework that looks at broad applications for disassembly, understanding both hardware and software requirements and finally looking at the specific constraints posed by different building material removal processes. Since the purpose of this framework was only to assess high-level feasibility for robotic resource recovery, additional design and engineering are required to develop robotic systems. A case study of a large institutional building found that three potential building components could be supported by robots for disassembly tasks. In all three cases, manual labor was found to be the primary driver for adopting robotic support.

5.1 Recommendations

A challenge for robotic disassembly in the construction industry is that compared with other applications (e.g., consumer electronics, automotive assemblies, batteries, etc.) the quantity of like-products is not as vast and given the physical size and bespoke nature of construction techniques, geometric variability can be more prolific. As a result, developing fully robotic solutions for disassembly of building components is likely too prohibitive to pursue from an economic and technical standpoint. In fact, fully robotic disassembly approaches are also considered to be prohibitive in many other manufactured product applications [17]. For this reason, human-robot collaboration (i.e., co-bot) solutions are often pursued as a pragmatic approach for many disassembly applications. Based on our assessment of robotic disassembly for buildings, we also recommend such collaborative approach. While there are many potential applications of robots to aid in disassembly planning, it is necessary to consider the practical constraints regarding robot torque, reach, payload and spatial maneuverability when selecting and designing systems. A key limitation in this paper was the robot feasibility based on quantity was only based on a single building. Given the case study explored was a very large structure, with select building materials existing in large quantities, one could potentially argue that justification of a new robot for disassembly support could be based on this building's material alone. While this of course does not factor in numerous prototyping and deployment feedback, we recommend that surveying building material quantities should be done across a wide range of building stock rather than exploring a single building at its end of life. Such review will necessitate that specific building materials have a high degree of standardization in order for the development of robotic systems to be used across multiple buildings. Other practical considerations need to be factored into the deployment of robotic disassembly solutions which we did not explicitly cover such as how robots can navigate in dynamic/cluttered environments, that need to be considered in a full-scale solution.

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