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Emergent digital possibilities for design-led reuse within circular economy

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This paper discusses literature and practice-based case studies in transformative, design-led reuse using emerging technologies. The inability of recycling to manage the assortment and complexity of waste materials within Circular Economy (CE) demands more discrete, attentive and granular approaches to reuse of waste by design professionals. This paper explores emerging and established digital technologies of Building Information Management (BIM), 3D scanning and artificial intelligence (AI) for their capacity to ease and improve transformative, design-led reuse practices for interiors, furnishings, architecture and building. Practice-based research is used to communicate first-hand encounters with the possibilities, benefits and challenges of these digital techniques.

Circular economy (CE), despite an ever increasing body of academic literature and advocacy by government and industry to be the way of the future, is failing. Waste is an ever-increasing problem, with construction and demolition waste comprising one-third of global waste going to landfill[1], upwards of 12 billion tonnes annually[2]. Despite much interest in circular economy, circular practices are actually declining; material circularity dropped from 9% to 7% since 2018, and the volume of raw materials extracted since 2018 is nearly equivalent to the amount extracted across the entire 20th century[3]. A key explanation for these failures are the continuing attempts to fit circular economy practices onto existing linear, waste-making practices in ways that do not substantially change the paradigms of techniques, technologies, labour and practice within the design industry. The industrial emphasis on recycling is a product of this approach because of its intent to 'regenerate' used materials in ways that replicate the capacities of raw, unused materials within the manufacturing and production systems designed to work with such raw materials. The fantasy is that if recycling works, then nothing else needs to change. Designers, trained to design with new materials and components in accessible standardised specification, can continue their practice as normal. Conversely, as we will argue in this article, the techniques, technologies, labour and practice within the design industry *do* need to change in ways that greatly impact, and rely upon, different loops within circular economy, being the smaller loops of repair, repurposing and reuse of products and materials.

In this article we discuss how design-led reuse in interior design and the related disciplines of product design, architecture and building, can improve through the use of emerging and established digital technologies, catalysing shifts in technique, labour and practice. We do this first by exploring the problems with recycling to identify the conceptual issues to be addressed, and then we define our terminology and focus through a review of strategies grouped within design-led reuse (and reuse-led design). We then introduce our aims through explication of our theoretical framework and methods, after which we review literature and case studies for a selection of technologies suitable for design-led reuse. The technologies are chosen due to their importance for conventional design practices and their relevance to our practice-based research. Therefore, we include a discussion of studio experiments to understand their challenges and potential for design-led reuse through intuitive and first-hand perspective.

Circular economy and the fallacy of recycling

The early conceptualisation of circular economy by Walter Stahel envisioned the re-circulation of materials and products across a full spectrum of designed products, but also services and practices[4,5]. Materials and products can achieve longer life through careful design, maintenance, repair and, once a product or its materials have reached a transition point marked by loss in function, value or appropriateness, then reuse. This logical order of circular economy practices aims to minimise entropy, slowing the fragmentation and granularisation of materials, and preserve embodied energy, cost and carbon. Reuse is placed before recycling[6]. Across the range of reuses, reuse that privileges the larger, more complete and less destructive forms of reuse are preferred. To give an example of this, consider remanufacturing, in which products are returned to manufacturers for disassembly into their components for selective reuse into new products. This is a kind of reuse, but one that should be less preferred to reuse of whole products in new uses at local sites.

However, the clear emphasis of industry and government has been on recycling, and often not even recycling that is truly circular. This has failed. To give an example that illustrates the problem generally, in Australia glass waste products, such as glass panels from construction waste and consumer products like glass bottles, are typically crushed and used as substrate for new roads[7]. However, glass is an extremely durable material, glass bottles

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can be washed and reused, and glass panels might have potential for reuse in new buildings. Glass can also be melted down and recycled into new glass products, for potentially many more reuses. Yet, the complexity and cost of managing the assorted glass waste stream for such outcomes is considered prohibitive and this has led to an indiscriminate, non-circular, *down-cycling* solution that granularizes glass and mixes it with asphalt and other materials into a composite material from which the glass can likely never be extracted. In Cradle to Cradle theory, a theory for the technical design of sustainable and circular products, such composites are termed monstrous hybrids[8]. Downcycling here refers to recycling a material or object in a way that loses functional, economic and/or or thermodynamic qualities when compared with the material or object's original quality[9].

Cradle to Cradle, and other examples of early circular economy literature such as Industrial Ecology[10] give credence to recycling as an environmental solution but not without reservation. Cradle to Cradle focuses on 'biosphere' (biological and biodegradable) and 'technosphere' (technological and perpetual) qualities of materials in product design. The capacities of technosphere materials infer recycling, even though its authors, William McDonough and Michael Braungart, recognise recycling as a limited and flawed approach. For Industrial Ecology, which seeks to mimic natural, ecological cycles in industrial processes, the concept of waste becoming feedstock for another industry likewise infers recycling, even though recycling is typically far less materially sophisticated than Industrial Ecology requires. Recycling processes typically implement at scale with minimal sorting of waste, thereby requiring destructive and energy-consuming processing (for example shredding or boiling) that deplete material integrity, such as effecting a build-up of impurities in metals, or shortening plastic polymer and plant fibre lengths. Rather, taking a broader CE approach, we need to discretely apply highly attenuated sorting practices to whole products, components and materials before they are degraded beyond possibility of repair or reuse. In other words, preserving whole products or components and conserving the value-chain of material lifespans.

Circular economy and reuse

Reuse, which better conserves embedded energy, should also advance its own innovations for screening and sorting. Yet, products, once manufactured and released into consumer use, become highly assorted in a maddeningly complex array of typologies, materials and products in an even more complex mix of unique values or states. Solid waste resources such as timber and metals are highly varied and mixed in ways that are impractical or costly to sort. Within any building are numerous different materials designed into hundreds, if not thousands, of components for floors, walls, roofs, and facades, plus "infrastitial" elements often hidden from view, that include piping, wiring and guttering[11]. Building products, fixtures and furnishings, once leaving the factory floor, have different entropic values (in disrepair, good, fair or poor condition), different locality (literally different geographic locations), non-standard sizes (changes to length and width through installation onsite), and are changed by configuration with other products, (fixed with glue, screws or mortar or another fastening system). This is especially the case as architectural or building products become smaller in size, more mixed and more distributed across geographies. This *assortment* of materials in the waste sector is counter to the paradigmatic availability and organised provisioning of raw materials in standardised sheets, slabs and regular units of measurement from online catalogues.

The varied components of buildings have been conceptualised as "shearing layers" defined by timescales of longevity and capacity for change, in which the deeper layers of a building, its "site and structure", may rarely or never change, while the more superficial layers of a building, such as façade, plumbing and cabling, interior layout, furnishings etc, known as "skin, services, space-plan and stuff," change relatively frequently[12]. The shearing layers model presents a rationale for maximising conservation of materials by only changing what may be required from wear or functional obsolescence. However, Stewart Brand argues the superficial layers, that are the remit of interior design, also change frequently according to style and taste, irrespective of how they are worn or aged. The model justifies adaptive reuse of building structures, well-evidenced by the popularity of adapting historical buildings for new purposes[13], but says little about the need for the reuse or repurposing of interior fitouts removed from such buildings. We propose this creates a premise for interior designers to circumvent sustainable reuse of fit-out materials because the building's structural lifespan is prolonged by interior redesign. Yet, it is incumbent on the interior design sector to play a role in reducing this waste burden, as while buildings are only fully demolished once, the interiors of buildings undergo "multiple refurbishments"[14]. Relevantly, Brand's associated design strategy of 'pace-layering', seeks to learn from the resilience of ecological systems and their multiple speeds of biological change[15]. This infers human building practices likewise require processes of reuse mimicking the decomposition and re-composition of natural materials within ecology. This inference augments our aim to address the faster changing layers of the built environment and develop strategies for improving the deconstruction, redesign or repurposing of their materials.

What hasn't been well implemented so far, as Walter Stahel proposed, is that CE economy practices of reuse (but also repair and maintenance) require new practices of labour. Currently, the waste sector is associated with lower socio-economic employment. Waste work is pushed towards the low end of the labour market, such as non-professional trade workers in demolition or scrapyard industries for building products. Waste products shipped overseas can become the task of low-paid workers in polluted, hostile working conditions. Conversely, architects and designers are associated with elite, professional society. This difference illustrates the "significant impediment" that income inequality, industrial exclusion, and educational imbalances are to positive pollution and economic outcomes[16]. Higher labour costs are a barrier to implementation of circular economy practices, even as circular economy initiatives promote investment in human capital to reduce pollution and resource use, support market operation and increase product life expectancy.

Reuse-led design and design for X

An important step towards improving the circularity of building materials and products generally is designing them in ways that facilitate disassembly, deconstruction and reconfiguration so that their structural and functional integrity remains intact through multiple uses. Design strategies that address this issue for manufactured products exist within a group known as Design for X[17]. This group includes design for disassembly, design for repair and design for reuse. Related strategies within the group, such as design for recycling or design for remanufacturing, are likewise important CE strategies but require a greater level of re-processing and, as we have argued for recycling in general, don't conserve material resources as well as reuse. The important consideration for this group is that they are future-facing; they inform the creation of new products in the present with future capacities. This critique also applies to other design for X strategies, such as design for lightweight, reduced production steps, standardised components etc. Following from our definitions for the adjacent practices of repair, in which repair-led design "leverages the future planning" agency of design to ease repair in the future[18], we term future facing reuse strategies (including the design for X reuse strategies) 'reuse-led design'. However, while such strategies are important and play a key role in improving the sustainability of the built environment, the focus of this article is on those techniques and technologies that help designers transform waste and second-hand materials that exist today; we term this 'design-led reuse'.

Design-led reuse

There is a strong history of designers and craftspeople transforming waste back into functional products in isolated works, often short-run products, and the reusing of building shells and structures (adaptive reuse) is well established for architectural and interior design[13]. However, as the large volumes of construction, demolition and renovation waste in landfill indicate, reuse of discrete building components and materials is lacking. Waste management theorists have stated "simple manipulation of object properties is capable of turning wastes into non-wastes"[19]. Yet designers still struggle with the complexity of the task due to the scale of waste, its assortment, and lack of material information they can process in ways that are known to them. To resolve this conundrum, the problem of waste and its assorted complexity must come into the remit of professional designers with skills to not just design with waste, but also design the systems to *capacitate* the design of waste with more efficiency, precision, ease, material (value-chain) conservation, and creativity.

Designers can become better at managing the difficulty of transformation of waste by considering the discrete steps required; disassembly and deconstruction, inventory, specification, design conceptualisation, visualisation, prototyping and fabrication or building[20]. For circular design practices to expand and become paradigmatic, they must become easier and more readily adoptable. In this article we consider, as designers, approaches to make such work easier through alignment with the way designers are generally trained to work. We orientate increasingly familiar technologies used in design, that have made linear, non-circular design and production easier, towards design-led reuse. Following from our studio experiments, these are Building Information Management (BIM) and 3D scanning, alongside use of Computer Aided Design and Computer Aided Manufacturing (CAD and CAM, together abbreviated as CADCAM). We also consider Artificial Intelligence (AI) technologies as nascent technologies that have rapidly progressed in the past few years.

These selections are part of a broader toolset of information communication technologies (ICT) applicable to circular economy[21]. Conversely, the dominant linear modes of design have already greatly benefited from ICT advances, but this itself is problematic as new efficiencies accelerate the levels of waste being dumped into landfill[22]. Relevant to our disciplines, there is less evidence for the use of emerging technologies in design-led reuse of interiors and furnishings. There are some intriguing exceptions, some dating back over a decade, of emerging technologies deployed towards the repair and reuse of waste for furniture and homewares[23,24], however many practitioners of repair and reuse in the furniture and homewares sector are orientated towards craft practice. Perhaps because they value traditional methods of crafted repair and reuse, they have been slow to take up developments in 21st century design technologies[25].

The lack of uptake in digital tools for design-led reuse is a subset of the general lack of design-led reuse within the industry. This lack can be understood through its disbenefits and counter arguments, largely concerning risks in terms of aesthetics, supply, timing, process complexity, return on investment and warranties[26]. The challenges of project planning[27], including procurement[28], is multiplied by the difficulty, “uncertainty” and risk that incorporating used components is said to bring to projects. Second-hand or waste materials may not be available when they are needed, or available when they are not needed[29]. Gorgolewski notes used materials can be sourced early to alleviate supply uncertainty, but this comes with its own logistical and cost burdens[20]. Such risks are almost always assessed against a budget line.

However, Aguiar and Jugend invert the risk of used materials, arguing that design-led reuse creates non-homologous designs that spread risk, increasing “independence from external resources” and “price volatility”[17]. To illustrate, if a series of houses are designed with identical cladding, a supply shortage may be a significant issue. However, if a mix of complementary claddings are specified, the supply risk may be decreased. This is because design-led reuse often tessellates and/or divides surfaces[20], as a practical and aesthetic response to entropic fragmentation (e.g. breakage, offcuts, assortment), and combines varied materials together, fostering if not requiring complementary specifications, and negating the need for long runs of large single uniform quantities, reducing supply risk. Furthermore, while there is complexity in using varied second-hand materials, there is also opportunity; flexible designers can adapt materials to the task at hand, transforming them in form, function or style. Transformative practices in design-led reuse have been termed re-fabrication[29], among other terms.

The perceived and actual financial feasibility of digitally mediated design-led reuse would seem to rest with six cost elements: 1. digital modelling, 2. the cost of the used items themselves, 3. transport, 4. storage, 5. modification, 6. install costs. These budget lines belie the larger financial, health, social and cultural costs and benefits that design-led reuse projects generate, and further still, the costs of *not* practicing design-led reuse. To appropriately assess whether digital design-led reuse is economically feasible, the hidden systemic costs need to be accounted and budgeted. Relevant are resource waste and labour costs saved by not newly creating an item, and waste costs that would otherwise be incurred in not reusing the items, including environmental externalities. While economic assessment is not a focus of this article, there is emerging agreement that “the global market at present does not properly account” for the true price of materials when “the producer does not bear the full costs of production”, including pollution and future interests in which value is not applied to products to account for their impact on future generations[22].

The broad scope of design-led reuse across disciplines of architecture, design and building indicates a paradigm shift is required. In any particular building project, for example, designers or architects will be required to: envision what materials could be reused; identify where and how these materials can be reclaimed; collaborate with actors who can reclaim, transport and store these materials; understand design techniques complimentary to reclaimed materials; understand the functional characteristics of materials in relation to their longevity and reuse; understand the regulation and insurance boundaries the work operates in; acquire skills in digitally modelling, designing and documenting reclaimed materials including new BIM requirements; advocate to clients the use of reclaimed materials and the approval of design-led reuse, and; develop relationships with tradespeople and makers who can materialise design elements that require specialist construction, potentially using CADCAM techniques. Not all of these aspects to design-led reuse will be addressed here, but, significantly, we attempt to address the needs and roles of designers *as* designers (and not as craftspeople or as builders) and as professionals that typically work at desks behind screens, not out on construction sites or scrap yards, or inside workshops. For design-led reuse to flourish, second-hand material, products and components must be intuitively easier to use. It is the way designers can and should manipulate the object properties of waste resources within their professional habits and digital work environments that is the focus of this article.

Theoretical framing

This review is framed by the pressing need for greater implementation of transition design and its strategy of cosmopolitan-localism[30], as a subset of the design for sustainability cannon[31]. Transition design argues that the shift to a sustainable, circular economy is achievable through the expertise of designers to create particular and incremental changes in localised production and consumption[32]. Cosmopolitan-localism[33] proposes such local sustainable practices need to be supported by globally connected knowledge ecologies that leverage digital technologies and communication infrastructures[34]. We especially desire increased capacity to solve local problems of waste by exchanging digital information for virtual transformations; captured locally, designed anywhere, and applied locally, minimising the carbon cost of moving waste, given that global transport shipping accounts for significant percentages of global climate change emissions. This theoretical framing is used to focus on tools, techniques and methods with potential to capture, transfer and exploit digital data on materials and products for waste transformation. These considerations drive our use of practice-based research in our methods described below. The remainder of this article therefore addresses this topic with a focus on the tools of BIM, 3D scanning and AI for design-led reuse in the context of circular economy practices in building, architecture and design, with discussion and focus steered towards techniques for creating and managing inventory, conceptual visualisations, and exploit of entropic qualities.

Methods

Practice-based research is critical for exploring, developing and evidencing new kinds of techniques and methods relevant to industry, emergent in artifacts generated though creative experimentation[35]. As designers and researchers, practice-based research is an integral aspect of our studio processes and we do it to make designing transparent and understandable to the broad audience of the public, professional designers and the academic researchers[36]. Over the past few years, technologies of concern have emerged in our projects. Here we assemble a selection of them, framed as case studies selected through our disciplinary expertise that address our aim to ease and increase professional labour of design-led reuse, correspondent with the concepts of cosmopolitan-localism for digital exchange of techniques and strategies. Our methods therefore include literature review and artefact/process reflection. In the following sections categorised by technology, we introduce literature concerned with that technology's capacity for design-led reuse. We start with summarising systematic reviews, where they exist, and then proceed to applied examples from the literature that align with our experimental practices. For BIM and 3D scanning, we illustrate and discuss our practice-based studio experiments, communicating those findings that especially relate to ease of use and technological uptake. As many of our 3D scanning experiments concerned timber, we discuss it as a material of special interest for design-led reuse, including CADCAM applications. We then introduce the literature on AI technologies for design-led reuse, proposing ideas for future practice-based research, before concluding with summarising remarks pointing to general directions for further research.

Technologies: BIM

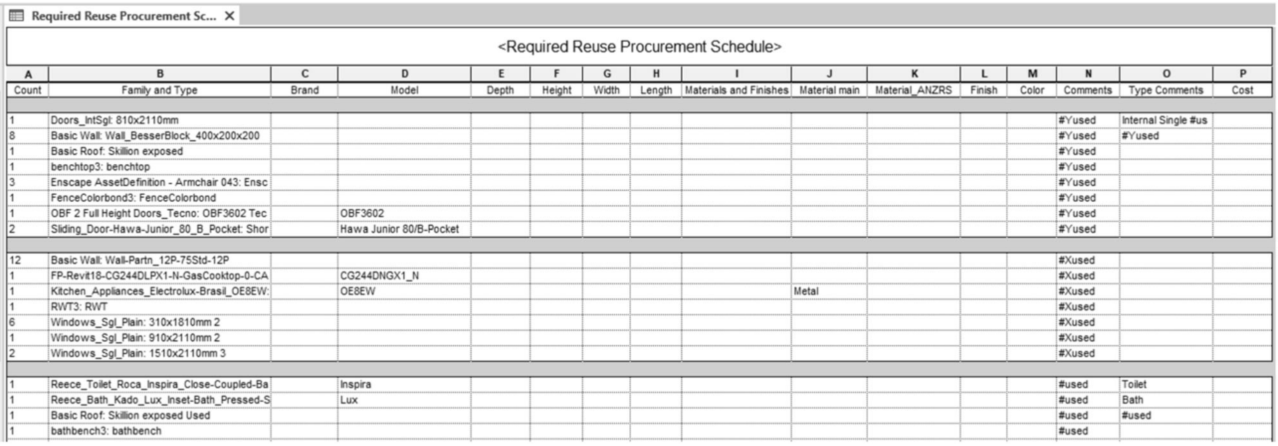
Product design, architecture and construction have embraced emerging digital technologies, but have been slow to implement circular practices. The complexities of architectural design have led to the data-management innovation of BIM and its suite of digital software and practices that store and attach information to virtual three-dimensional object and building designs. This information can include site, material and other metadata beneficial to make cost, materials and logistics of construction more flexible, efficient or detailed. Chen, Feng and de Soto[37] conducted a literature review of sustainable practices in construction across 61 papers (narrowed down from 332 abstract reviews) in which research into use of BIM was identified as the most common driver for construction circularity. They found use of BIM for sustainable specification (including life-cycle analysis information) and use of BIM to facilitate design for deconstruction[38,39], which might facilitate BIM for design-led reuse, but overall explicit mention of BIM for reuse was lacking; this is reflective of their general finding that CE strategies aligned to waste management and recycling outnumber those for reuse. Cheng and Ma's[40] proposed BIM datasets *should* exist for "most buildings, including historical buildings", but developing BIM datasets for historical buildings, though calculation, analysis and/or retrieval of historical information is a significant challenge[41]. From a technical perspective, the frameworks for how to create, maintain and use digital assets within a BIM environment need to be assessed for their capacity to manage second-hand and waste materials and their unique metadata possibilities in ways that foster design-led reuse, and not just recycling. These frameworks include the international Open BIM object standard (OBOS)[42], the international ISO 19650 Standard for Industrial Asset: A Comprehensive Guide to the Five Parts of BIM (Building Information Modelling) series[43], and the Australian National BIM Guide[44].

A related problem is the lack of digital models for second-hand and waste products. Digital models are fundamental tools used by designers and architects but tend to only exist in online marketplaces for new construction items. The concept of digitally identifying used materials is emerging, and one concept is the digital 'material passport'[41,45], another is to catalogue/inventory existing building into 'material banks'. Such material banks, 'internet-of-things' tracking and passport systems, while largely oriented toward recycling, might be implemented for design-led reuse[37,46]; contributing to the data available within online used material marketplaces[47–49], making sustainable design specification easier[14,50–53]. Digitally augmented marketplaces have potential to improve information sharing between designers and demolition/deconstruction/salvage companies[54], with some information sharing already trialled via the Demolition and Refurbishment Information Datasheets and the LEED spatial database[55]. Khadim et al.[56] discuss BIM frameworks that facilitate upload of user-created digital models as a way to build circularity metrics. There is potential for digital models of second-hand materials and waste materials to be created for online marketplaces via 3D scanning.

BIM experiments

For the first practice-based experiment of this article, a simple BIM process was created to provide visual and text information at the design stage, managing the specification of new and second-hand materials within a building (Figs. 1–3). Within the CAD software Revit, a leading BIM platform for architecture, the BIM category "comments" is used to identify, via hashtag, if a component or material in a new build *can* be second-hand (#used), *must be* (#Yused), or *must not be* second-hand (#Xused). A view filter is then set up to recolour the materials/components reflecting their reuse status. Upon doing so, visual indicators and lists can be generated for use in design tasks such as discussions with clients and engineers, for approval, costing or procurement. Other data can be added to the comments property without impacting the functionality of this feature. No special training is required to implement this technique.

While BIM in general capacitates future-facing reuse-led design by providing detailed information about materials and components of a building, facilitating their disassembly and reuse in the future, this particular use of BIM is for design-led reuse, proposing and facilitating use of existing waste materials in the present. Ideally, such a use of BIM would dynamically



<Required Reuse Procurement Schedule>

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Count	Family and Type	Brand	Model	Depth	Height	Width	Length	Materials and Finishes	Material main	Material_ANZRS	Finish	Color	Comments	Type Comments	Cost
1	Doors_IntSgl: 810x2110mm												#Yused	Internal Single #us	
8	Basic Wall: Wall_BesserBlock_400x200x200												#Yused	#Yused	
1	Basic Roof: Skillion exposed												#Yused		
1	benchtop3: benchtop												#Yused		
3	Enscape AssetDefinition - Armchair 043: Ensc												#Yused		
1	FenceColorbond3: FenceColorbond												#Yused		
1	OBF 2 Full Height Doors_Tecno: OBF3602 Tec		OBF3602										#Yused		
2	Sliding_Door-Hawa-Junior_80_B_Pocket: Shor		Hawa Junior 80/B-Pocket										#Yused		
12	Basic Wall: Wall-Partn_12P-75Std-12P												#Xused		
1	FP-Revit18-CG244DLPX1-N-GasCooktop-0-CA		CG244DNGX1_N										#Xused		
1	Kitchen_Appliances_Electrolux-Brasil_OE8EW:		OE8EW						Metal				#Xused		
1	RWT3: RWT												#Xused		
6	Windows_Sgl_Plain: 310x1810mm 2												#Xused		
1	Windows_Sgl_Plain: 910x2110mm 2												#Xused		
2	Windows_Sgl_Plain: 1510x2110mm 3												#Xused		
1	Reece_Toilet_Roca_Inspira_Close-Coupled-Ba		Inspira										#used	Toilet	
1	Reece_Bath_Kado_Lux_Inset-Bath_Pressed-S		Lux										#used	Bath	
1	Basic Roof: Skillion exposed Used												#used	#used	
1	bathbench3: bathbench												#used		

Fig. 1 | Reuse procurement scheme in Revit with hashtags used in the Comments field to specify preference for second-hand materials.

Fig. 2 | Visualisations of a building design using the exterior of a residential building and the Revit template construction file for an interior structure of a commercial building. The BIM hashtag filter is applied to highlight the intent to specify, source and/or construct with used materials. Any materials that have not been tagged, for which a decision has not been made, are coloured grey.

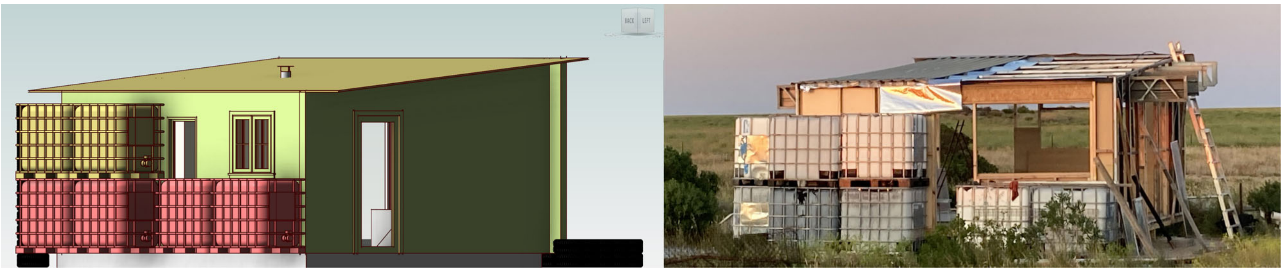


Fig. 3 | The hashtag system used to specify new and second-hand materials, contrasted with the build under construction. In this particular design, two new water tanks were specified for drinking water storage, while four second-hand water tanks were specified for thermal mass, wind break and grey water.

integrate with digital inventories of second-hand materials, helping designers identify which materials and components are currently available. In the meantime, the tagging system can at least initiate conversations between designers, clients and builders, documenting intent and consensus on what materials and components can and should be second-hand.

Technologies: 3D scanning

3D scanning mainly concerns two techniques; Light Detection and Ranging (LiDAR), which uses pulsed laser reflections from the object to accurately capture geometry, and photogrammetry, an older technique that captures both geometry and photographic representations of texture. The techniques are often used together. There is technical review of the practicality of 3D scanning reusable building components with different systems[57].

LiDAR is used extensively across many engineering industries. Examples include use to inform deconstruction methods for buildings[58] and, in conjunction with BIM to estimate waste tonnage of destroyed homes after the Australian bushfires of 2019[59]. It has become widely used for the heritage analysis of buildings, and for adaptive reuse of building shells it can be used to create new interior furnishing that fit the building's internal geometry[60]. The potential of emerging technologies and the synergies between BIM and 3D scanning is noted for understanding waste resources in buildings, an 'urban mining' concept (to complement recycling, primarily)[41].

Yu and Fingrut[61] propose a method for capturing digital models of 'irregular' timber discarded by lumberyards, using two levels of 3D scanning; drone deployed photogrammetry for large-scale capture at lumberyards and hybrid LiDAR/photogrammetry for finely detailed small-scale capture of timber in the lab. This process of using lumberyard by-product is similar to that for second-hand timber products, including the proposal to build material database capacitating entropic and anisotropic details. These concepts are considered more deeply in the discussion on timber below. The virtual architecture model constructed in Yu and Fingrut uses a structural analysis and optimization tool (Millipede for Grasshopper in Rhino) to map structural requirements into voxels and then voxels into components from the database.

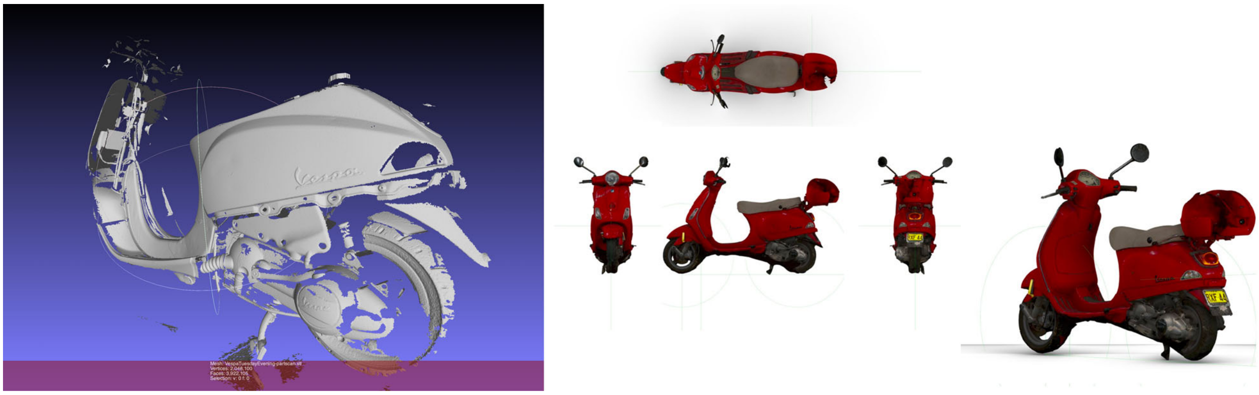


Fig. 4 | Meshlab screenshot of an incomplete but geometrically accurate 3D scan of the Vespa using Einscan Pro+ on Windows 10 OS, 2021, and an iOS app 3D scan of the Vespa (supplied by David Caon, 2022).

3D scanning experiments

Our own need to work with 3D scanning emerged when collaborating with industrial designer David Caon in the transformative repair of a broken Vespa motor scooter (Fig. 4)[62], the first of three practice-based 3D scanning projects described in this article. With Caon, we scanned the scooter before and during disassembly using two technologies. A hybrid laser and photogrammetry mobile app on iOS, Apple's mobile device operating system, was sufficient for Caon to obtain visualisation materials for conceptual development. To accurately obtain the geometry for component attachment points, so that new and refurbished components could designed for the restoration, an Einscan Pro (hybrid laser and photogrammetry) was used, though it was noted to be less useful for capturing the bike as whole for visualisation purposes. 'Stitching' geometry together was a recurrent problem, made especially tedious when working in the field, outside lab or workshop conditions, subject to environmental factors, such as changes in natural light, or difficulties with cables or batteries. The need to carry the devices while scanning the objects made scanning more prone to errors. However, the scans were sufficiently accurate for the attachment of new and second-hand components.

The second project with 3D scanning replicates and extends the work of Zoran and Buechley[23]. Hybrid laser and photogrammetry scanning was used to model a missing chip from a marble lampshade (a rather typical feature of damage for such a product). The virtual model was then leveraged to produce creative designs with backside surface geometry matching the surface exposed by the missing piece. These were then 3D printed to repair the lampshade (Fig. 5). While simpler repairs of chip edges are possible with handcrafted, traditional approaches (using casting and moulding techniques), the use of CAD and 3D printing potentialises faster and more creative possibilities. However, from the CAD perspective, the digital processing work to extract and build the surface geometry was reasonably tedious and required interoperating multiple software applications (Meshlab, Meshmixer, Rhino 3D), additional to the 3D scanner software (Einscan Pro). Theoretically, such a process could be fully or partially automated, possibly with AI tools. The potential here is that automation of repairs might foster virtual offsite repair of scanned building components that could be applied onsite for the repair of damaged components intended for local reuse. While the 3D printing of lightweight polymers shown in this specific experiment is not suitable for larger structural purposes, 3D scanning broken components and objects generally may be used to obtain and manipulate the geometry of voids and areas of damage generally, establishing a base set of data for repair. This emulates the use of X-ray to determine structural viability described in Gorgolewski's study[29], but with less cost and more accessibility; we contend the capacity for a building site or scrapyard to scan broken components potentialises both determination of structural viability and offsite transformation, in a great level of granular detail, without the need to move the material.

In the third 3D scanning project, photogrammetry was used several ways in a case study of a derelict Buddhist temple in Japan[63]. Preliminary community consultation determined that the local community, unable to pay for the repair or upkeep of the temple, were interested in the outcomes of design-led reuse. Hundreds of images taken with a DSLR (digital single lens reflex) camera using a bracketed higher dynamic range (HDR) photography technique were used to construct a photogrammetry model in the software RealityCapture (Fig. 6). While the project was halted by COVID19 pandemic conditions, our intention was to use the visualisation as a starting point in building an inventory of the vast number of objects, furnishings and components within the 300-year-old building. Some practical aspects of this process have now been demonstrated by Yu and Fingrut[61]. In our case study, should the building be deconstructed, we proposed there would be capacity to add metadata annotations to the model for items and materials in ways similar to those discussed in the BIM section above[25]. Should items and components additionally be individually scanned during deconstruction, the resulting digital models could likewise be added to this inventory or material bank, providing accurate geometry and material values information for subsequent design-led reuse of the building's components, which are largely timber.

Timber for design-led reuse: special considerations

Some materials are 'low hanging fruit' for circular practices in the field. Timber is one such material. To give an example from one country, in Australia across 2018–2019 there was 109 kilotonnes of timber in municipal post-consumer solid waste[64] additional to timber waste from construction and building. Furthermore, Australians spent over $7.6 billion on new indoor furniture[65], much of it made from newly harvested timber that potentially could be replaced by reclaimed timber. The relative ease of structural manipulation and reconfiguration for timber is evidenced by many examples of its design-led reuse[61].

A nuance here is that, for timber at least, design-led reuse technologies are better at managing deeper layers of a building, the 'structure' layers, that are more consistent and homogenous in form and materiality than the shallower 'space-plan and stuff' layers of furniture and furnishing. This is suggested by the visual complexity of the 'stuff' in the far right image of the Anyoji Temple case study above (Fig. 6). Waste wood from building and piers, for example, are often repurposed into furniture through subtractive and joinery processes, even if waste timber is less commonly applied in building scale design-led reuse due to uncertainty about its structural integrity. In this regard, waste timber is outcompeted by new timber that is free of structural defects (potential or real) that may, or may not, impact structural integrity calculations.

The repurposing of timber through traditional carpentry methods can be made more efficient through the analogous, automated CADCAM

Fig. 5 | Sequence of images showing the process of repairing a chipped marble lamp (product design by Henry Wilson) including 3D scanning, missing chip reconstruction in Rhino 3D and design iterations for transformative repair that were 3D printed and glued into place.

Fig. 6 | Views of a Photogrammetry model of Anyoji temple constructed using RealityCapture showing the skin and structure of the building, including internal spaces filled with furnishings.

processes of computer numerically controlled (CNC) robotic milling. However, CADCAM processes applied to design-led reuse for second-hand timber is lacking. There seem to be technical reasons for this. CAM technologies tend to operate best with homogenous, defect-free materials. Engineered composite timber products, such as orientated strand board (OSB), plywood or medium density fibreboard (MDF) that allow the smooth operation of automated mill-heads, are particularly popular for subtractive wood manufacturing, often preferred to even raw sawn timber, with its array of anisotropic variables (seasonal growth, branch and knot growth, drying variations, etc)[66]. There are, however, experiments successfully using 3D scanning of forest wood to construct complex toolpathing for robotic CNC mills[67–69].

Comparatively, waste timber can have all these anisotropic complexities plus entropic complexities; wear, mould or damage from use, or they may be problematically fixed to other materials that cause damage during deconstruction. Such complexity slows down the role of the reuse practitioner. Digital technologies in general should be able to speed up circular practices just as they have sped up linear practices of design, by mapping and managing this complexity. One example in practice is a project in which AI machine learning was used to detect knots in photos of reclaimed

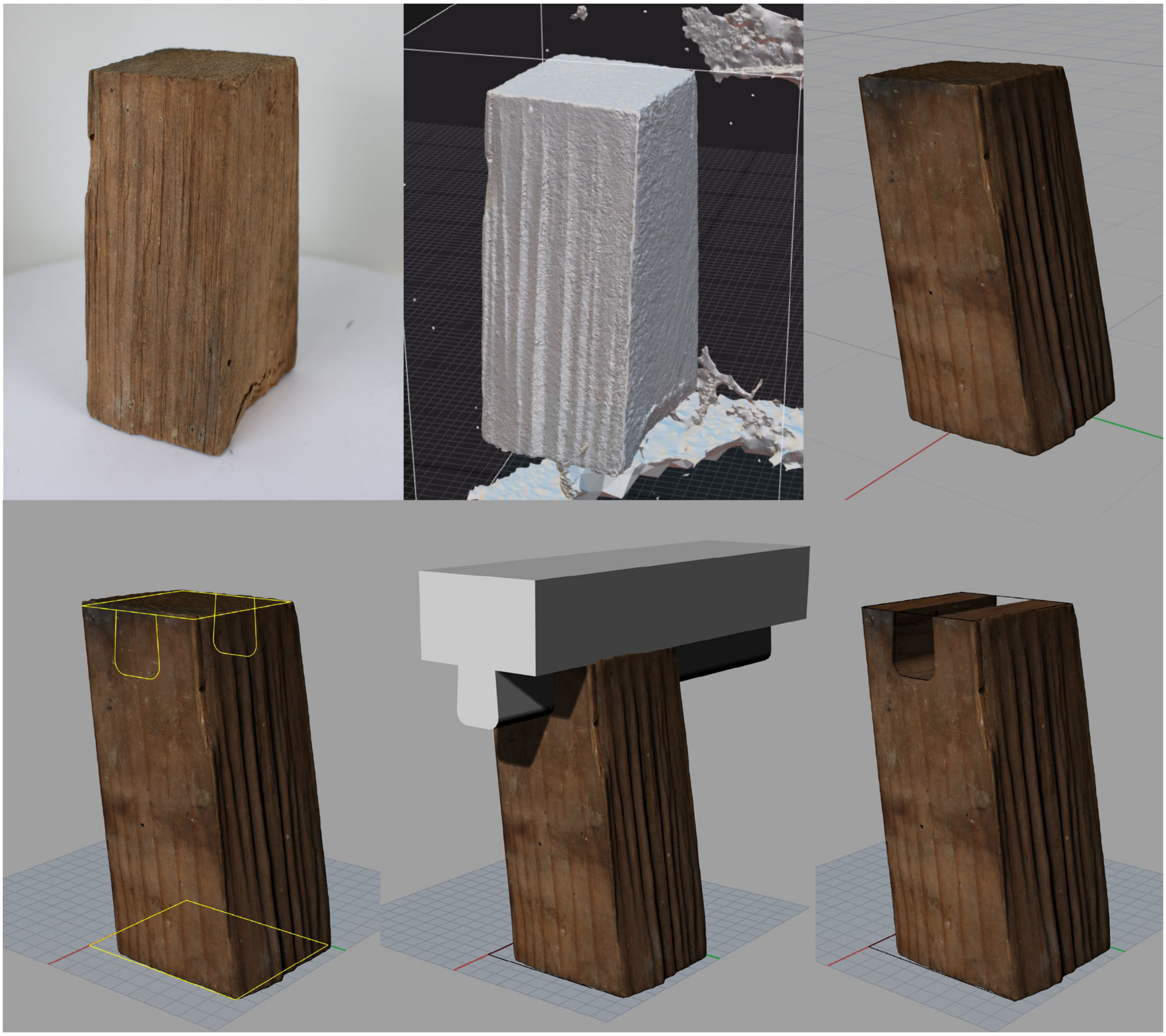


Fig. 7 | Images showing an old sofa leg, photographed using a turntable and digitally modelled in RealityCapture and imported with texture mapping into Rhino 3D for joinery experiments with potential for CAM.

scaffolding boards, with this data subsequently used to inform toolpathing for a CNC sandblaster[70].

Despite the entropic complexities it presents for CAM and robotic fabrication, wood is, however, highly suitable for practice-based research into design-led and transformative reuse because it can be manipulated through digital processes that mimic real world carpentry processes. Using an extrusion or Boolean operation to slice a solid in a 3D CAD modeller, for example, simulates the processes of a mill, drill or saw in the timber workshop. Such processes, if they are captured in a digital workflow, can be used to generate tool pathing for CADCAM processes, for example via CNC milling, as illustrated in this joinery experiment (Fig. 7) conducted on a photogrammetry scan of a sofa leg found inside the aforementioned Anyoji temple.

Wood is suitable for 3D scanning practices of design-led reuse because wood is typically non-reflective, except when it has been lacquered. Reflectivity is problematic for texture mapping and can lead to less-than-optimal visual appearance of the scanned objects. It is important for a digital designer to understand the appearance and structure of a material when they cannot access the material directly to examine it with their hands. Grain direction for timber, for example, is useful for understanding the best orientation to resist lateral forces in tension. A frustrating issue is that once a texture mapped digital object is manipulated digitally the texture map is lost as it no longer aligns with the objects' geometry as scanned. One solution proposed by research associate Josh Harle during the Anyoji Temple case study was to programme dynamic texture maps that respond to changes in geometry, (re)simulating grain texture, as shown in the illustration (Fig. 8).

Technologies: AI

The increasing digitalisation of waste, in any state of and between the uses of BIM and 3D scanning described above, leads to the consideration of artificial intelligence technologies as a means to manage the complexity of waste and simplify its design-led reuse by humans. While there is no single definition of AI, the term AI here is used generally to refer to technologies that mimic the human capacity for learning and problem solving in ways that are considered 'narrow' applications concerned with optimising a single but complex task traditionally only possible by human operators or designers.

The same alignment of BIM, CADCAM and 3D scanning to linear, waste-based design paradigms applies to the emerging use of AI in design for construction; a systematic review of 165 articles discussing AI tools for the construction industry has no mention of waste, reuse or sustainability[71]. Research approaching from a different tangent, a review of 227 articles for

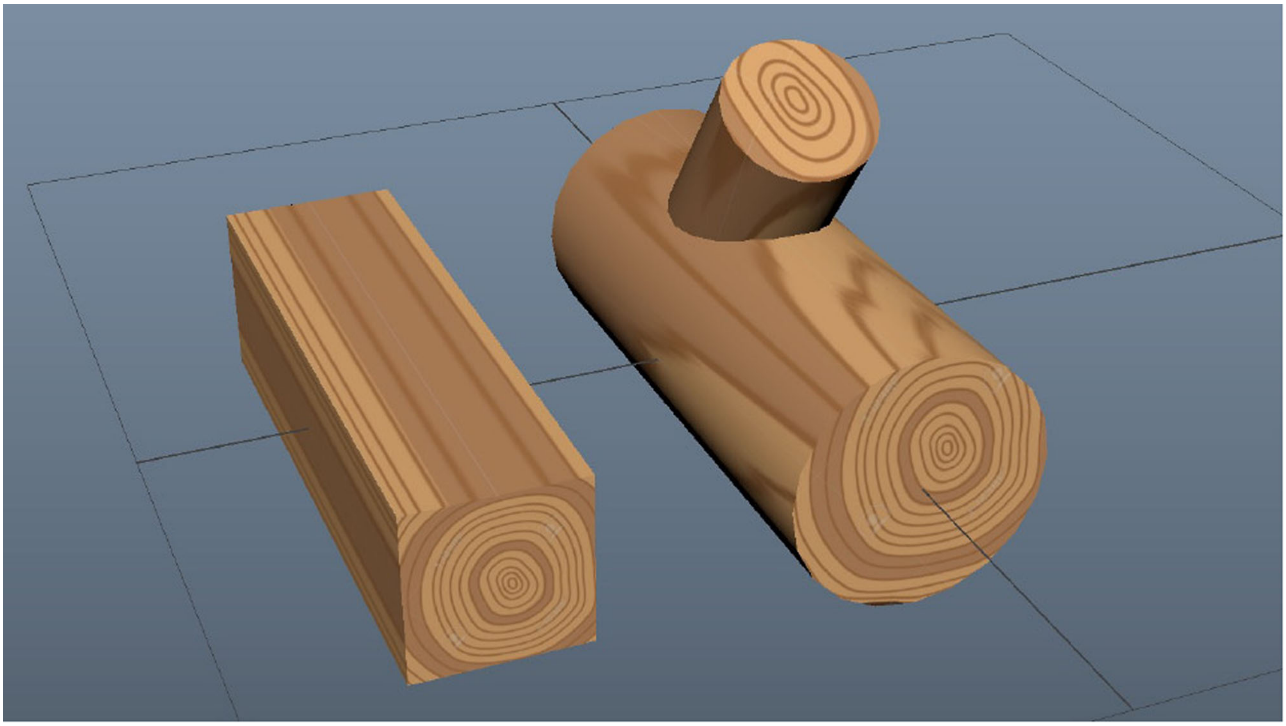


Fig. 8 | Wood-grain texture dynamic remapping experiment proposed by Josh Harle for the Anyoji Temple project.

emerging trends in adaptive reuse of buildings did not identify use of AI tools as a trend[72].

Conversely, a 2022 systematic review found 472 papers relevant to the use of AI tools in solid waste management, noting the use of AI powered computer vision programmes, deep learning algorithms, intelligent waste bins etc. for sorting different kinds of waste[73]. One example proposes machine learning and graph theory for the problem of sorting waste within a geo-spatial framework at a municipal level[61]. The flourishing of AI in waste management, while clearly beneficial, appears to reiterate the industry-government emphasis on recycling in CE, though it is also true that these concepts have potential to divert waste towards reuse rather than recycling, for example through resale in digital markets as an outcome of AI powered sorting. AI tools for estimating building waste, aligned to the material passport and urban mining concepts, can potentially foster reuse practices, as well as repair and maintenance, in addition to recycling[74].

More promisingly, a collection of 311 papers found using keywords including reuse design and circular economy were reviewed for algorithmic and AI applications, finding 68 relevant papers, but only a handful were able to inform a literature review of the nascent field[75]. These included use of greedy algorithms[76] mixed integer problems[76] and graph representations[77]. These papers were then used to inform the design of a matching algorithm that can substitute reused materials in place of new stock for an existing design, and then calculate the reduced carbon emissions of this substitution[75]. An urban mining proposal from Parry and Guy uses genetic solving algorithms in Grasshopper to map digital twins of irregular timber for a virtual curved wall design that could be adjusted to minimise or theoretically eliminate waste[78]. The digital twins were not created from 3D scanning or manual measuring but by a minimum viable method of placing QR codes at each end of the timber and calculating length with the marker tracking tool Fologram for Grasshopper in Rhino.

While we have yet to complete our own AI practice-based experiments at the time of writing, we believe there are many under-explored possibilities for AI integration into design-led reuse that are additional to those described above. These include use of image recognition tools and machine learning to expediate discovery of physical damage in 3D scans (as opposed to knots in photos of timber as described earlier[70], and use of the full range of established generative design techniques with capacity to work with existing geometry captured from waste materials. In addition to the use of genetic algorithms described above, these include shape grammar (geometric outcomes based on provision of initial shapes) and swarm intelligence (capacity to interact with and change initial design elements or shapes)[79]. These possibilities inform our future research activities.

Discussion

The premise of this article is that wastes within any repository, be it an obsolete building, a scrapyard or even landfill, potentialise any number of reuses should designers have flexible, systematic approaches. Discrete, granular inventory of waste materials and products, perhaps captured by scanning technologies, can inform designers of their capacity to transform and provide useful information for collaboration and stakeholder consultation. The decision making around the use of second-hand and waste materials in new builds can be integrated into BIM from the beginning of the design process, improving communication with clients, builders and stakeholders, encouraging flexible approaches to design-led reuse. Digital visualisations of waste adapted from 3D scans can be augmented with metadata in BIM, such as historical, ecological or material quality information, for sharing over digital networks. Generative AI tools have promise for improving the efficiency of designing with digitized waste materials and facilitating creative uses of mixed, granular resources.

On reflection, these technologies exert influence good and bad on our design practices. They open up the design process. 3D laser scanning enables digitally driven intervention into waste that expands the possibilities of design. Having a digital double of a component or waste material allows great precision in reuse design, in ways that can conserve waste and reduce the creation of by-product. This has led us to consider how such material conservation can apply more broadly to all sorts of non-standard resources, such as gnarly timber, of importance for bioregional design practices. However, such capacities also create complexities that must be resolved through technical labour. The mesh imprecision and subsequent mesh clean-up required inhibits smooth integration into existing design processes. The fast changing technical requirements of 3D scanners likewise creates complications for ease of use. The time or expense of digital postprocessing has been noted in literature as a reason to use simpler geometry capture methods for simpler objects[80].

In regard to generative AI, it can be difficult to communicate the strategic goals of generative AI for design-led reuse to specialist, computational designers, for whom the waste problem may be rarely experienced. Waste does not emerge in digital media in the same way, conceptually, as it does in the material world, and while computational designers, like all humans, encounter problems of waste in their general lives, they may not experience it as an ugly by-product of their professional practice as other designers do. There are additional issues for AI techniques related to 3D scanning, as described above; imprecision and overly complex geometry. Even with cleanup, the mesh may be too complex for algorithmic manipulation.

In respect of BIM, its use is increasingly standard for interior architecture, so it must be integrated into any design-led reuse that hopes to transfer to mainstream industry. The frustration with using BIM currently is that the default template materials are for virgin and raw resources, i.e. conventional materials that are easily sourced through construction industries. The darkest aspect of this situation is that the digital textures of rare and exotic materials, such as endangered hardwoods, can end up in software material libraries, such as the 3D rendering library Keyshot, potentially leading to unwittingly harmful specifications[81]. The broader circumstance is inherently paradigm-asserting, inhibiting designers from working with the diversity of second-hand materials though lack of integration within their digital workflow. For second-hand materials to become easier to use, BIM software architectures must interface with the dynamically changing supplies of second-hand materials available from salvage yards, and for reuse designers, such as ourselves, this prospect motivates the research of this paper.

Used materials, with unique and often desirable details, are not readily available on online platforms, and so need to be created by the designer themselves by scanning, modelling or 2D representation. Digital doubles should be created, but barriers exist. Designers may not have ready physical access to an object or material to scan it, or model it manually. We have discovered this BIM workflow step for design-led reuse takes time, though less time in practice than commonly imagined. It is nonetheless necessary to explore how used objects and materials can be digitally inventoried and made accessible for dynamic integration into BIM. This is a question for not only designers but for those industries with ready access to used objects and materials, such as salvage yards.

Strategically, diverse and disparate stakeholders must support the deployment of used materials from early on in any project. Early communication allows concerns and needs to be heard at a time when they can best be accommodated. Practically, early consideration of diverse second-hand materials will increase likelihood of supply. While the interior layers of a building are structural and thus more codified by building regulations, as one travels to the outer layers of a building there are diminishing structural expectations, expanding possibilities of form and aesthetics provided by second-hand materials. Design-led reuse reveals a way to think deeply about how the material needs to perform, and what the material needs to be, rather than what it is. Such thinking can reveal that non-traditional materials suffice for conventional ones, e.g. the use of pressed tin instead of tiles, or in how an old table can be trimmed for new use as a benchtop.

The digital workflow for a designer is heavily impacted by such decisions. For example, cladding specification will impact the depth required for a window reveal. As windows need to be fabricated ahead of time, this detail needs to be confirmed. For this detail to be confirmed, cladding supply needs to be assured. For cladding supply to be assured, storage of the material prior to use is likely to be required, placing logistical pressure on suppliers. If storage cannot be assured, then the cladding specification may change, impacting the design process from its start. Such perplexities may only be solved with fast, dynamic, computational design approaches capable of resolving multiple design, specification and resourcing processes together.

Yet, in the process of renovating a building or installing second-hand fixtures and furnishings, there are many practices of assembly, joinery and installation that benefit from the flexibility of hands-on traditional labour and craftsmanship. In such cases, there may be little need for rich digital methods, and rather, thin or lightly applied digital methods can be used to inventory, select, specify and visualise second-hand components by a designer or architect. Designers should consider the minimum viable capture of second-hand components may only need the outside dimensions for an architect to communicate size and placement to a builder or client. A simple 2D photograph of a component object can be collaged into a 3D CAD render or drawing for visual context. Such alternatives to 3D scanning are further examples of ‘flexibility’ needed in the design stage, additional to the flexibility required to manage the unpredictable supply chains of second-hand materials[29]. Nonetheless, the promise of the emerging technologies discussed in this paper is in their capacity for computational automation that reduces the labour of such manual approaches.

Advocating for design-led reuse has its own developmental trajectory; it requires a professional design culture that does not recoil from waste and takes responsibility to divert the trajectory of enabling “the affluent to dump their trash on the poor”[82]. It requires belief in the design integrity of design-led reuse, negotiating or seeking to improve regulations, having confidence in one’s design-led reuse skills, and having the communication skills to advocate these approaches to clients.

This article establishes the need for designers to practice design-led reuse, and some of the strategic directions required to make this more feasible, easier and widely adopted. Further research is required to address other practices indicated in the background of this article, including how designers collaborate and communicate with the waste industry, how they understand the regulation and insurance boundaries that design-led reuse operates within, and how they develop relationships with tradespeople and makers who can materialise design-led reuse through expert construction.

The fragmentation and granularisation of materials is a key concern for both recycling and reuse: as materials break or obsolesce, they tend to become discretely smaller and more assorted within waste repositories, increasing complexity and difficulty of management. While we contend that granularisation of materials and products should be avoided, and hence, maintenance, repair and reuse privileged in that order before remanufacturing and recycling, we propose and have attempted to show in this article that there are also many new possibilities emerging for the management of granulised materials though the use of digital methods of BIM, 3D scanning and AI technologies.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Computer-aided design files created during the practice-based research described in this article can be requested from the first author.

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Author contributions

G.K. is responsible for conceptual development, writing and the practice-based research, excluding the BIM experiments. R.A. conducted the practice-based research on BIM and contributed to the writing of the BIM, CE, recycling and Discussion sections, as well as contributing suggestions and assistance to the remainder of the article.

Competing interests

The authors declare no competing interests.

Additional information

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