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Citation for the original published paper (version of record):
Josefsson, T., Thuvander, L. (2020). Form follows availability: The reuse revolution. IOP Conference Series: Earth and Environmental Science, 588(4). http://dx.doi.org/10.1088/1755-1315/588/4/042037

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To cite this article: Taleen Astrid Josefsson and Liane Thuvander 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 042037

IOP Conf. Series: Earth and Environmental Science **588** (2020) 042037 doi:10.1088/1755-1315/588/4/042037

Form follows availability: The reuse revolution

Taleen Astrid Josefsson and Liane Thuvander

Chalmers University of Technology, Sven Hultins gata 6, 412 96 Göteborg, Sweden

tjosefsson@gmail.com

Abstract. This study links construction-related overuse of resources to design strategies that enable architects to reuse building and waste materials. The strategies are applied in a design proposal in a local Swedish context. Stakeholders and material systems have been mapped applying a systems approach; sixteen interviews with different experts have been conducted; and a methodology for finding and evaluating materials suitable for reuse has been created. Based on that, a building design proposal employing circular design transformed into the concept "Form follows availability" has been developed, taking into account locally available materials, the lifetime of the building and specified materials, and resilience against changing functions, cultural perceptions, and climatic conditions. Results show that it is difficult to design a building solely with reused materials when confined to the existing system. Still, it generates realistic design strategies demonstrating that material reuse is both possible and desirable. To facilitate material reuse at scale, transformation of architectural education, improved material testing and documentation, and supporting logistics are required. The benefits - reduced waste, increased cultural value, attractive aesthetics - argue for architects, clients, and contractors alike to employ material reuse as an effective means to reduce the building industry's negative impact on the environment.

1. Introduction

Architects are highly influential in determining the built environment and its overall footprint through design, material selection, and construction methods, therefore playing a key role in changing the course of the construction industry. Even if architects can disrupt the current cycle of wasteful material usage by, for example, specifying reused materials found in the existing building stock, there are still few built examples. There is currently a lack of supporting structures for building material reuse, and architects are traditionally unfamiliar with circular design practices.

Globally, the construction industry is responsible for over 30 percent of resource use [1], buildings account for 32 percent of energy use and 30 percent of energy-based greenhouse gas emissions [2], and in 2016, the Swedish building sector produced 9.8 million tons of waste, of which 55 percent was recovered [3]. A massive amount of energy and resources have been used to shelter the world's population up until now, currently estimated at 7.5 billion; however, by 2050, the global population is expected to increase to nearly 10 billion people. Rather than extract new materials and waste those already in circulation, materials in the existing building stock should be reclaimed and reused in new construction and renovation.

Far from a new practice, as evidenced by Roman empire spolia, building material reuse is returning to the narrative today. Advancements in digitalization and internet connectivity, as well as a clearer need for resource efficiency due to the existing or predicted overshooting of the nine planetary boundaries on the current resource use trajectory [4], have set the stage for material reuse on a large scale. In the context of architectural design, building material reuse touches on seven main drivers of current construction demand and practices: waste [5], resource management [6], cultural perceptions [7], consumption patterns (linear economy) [5], economy[8], building lifetime [9], and energy [10].

The purpose of this study is to empirically link architectural design strategies that enable the reuse of building and waste materials to construction-related global climate issues and the overuse of resources and discusses necessary transformation both in the construction sector and beyond. The outcome is two-fold: first, an architect's method of working to identify, quantify, qualify, and apply used materials in a building. Second, a sample application utilizing the proposed method, which shows that reused material can be applied to the majority of a building, greatly reducing a building's carbon footprint and adding cultural value. The proposed work methods and material applications can be replicated in any location supporting the wide adoption of material reuse practice.

In the paper reuse is defined as: to reapply or reinstall a material (post-consumer, by-product, waste) in the same manner as originally intended or for a useful new application.

The paper is based on the master thesis work by Josefsson [11].

2. Methodology

As an overarching approach, systems thinking and systems analysis were adapted as part of the architect's toolbox to understand and communicate the complexity of the construction industry, its impact on society and the environment, and the countless variables contributing to its current state. Design strategies for reuse have been developed and applied in a site-specific design proposal of an office building in a local Swedish context, the city of Mariestad.

To get an overview of the local conditions, relevant stakeholders and material systems have been mapped. Sixteen both semi-structured and informal interviews with experts have been conducted, including architects, deconstruction firms, and researchers. The interviews ranged from ten minutes to an hour and took place in person, except for one video call. The informal interviews were open discussions on the topic of material reuse, occasionally supplemented by email exchanges. They gave insight into the current state of affairs in regard to the concepts of material reuse and upcycling, including ambitions, feasibility, perceived hurdles and difficulties, supply and demand, and material flows.

The material contents of the local building stock have been tracked through demolition permits provided by the city planning offices of Mariestad and Göteborg and field observations of four buildings. The observations and permits informed the quantitative and qualitative make-up of the building cadaster.

In order to prepare a design proposal based on available material, a methodology for a material inventory has been created for finding and evaluating materials suitable for reuse sourced from secondhand markets and buildings to be demolished, including material inventories of existing buildings, see Figure 1.

In the building design proposal, theory and technical solutions were combined, and the feasibility of low environmental impact construction with reused and upcycled materials tested. The building design proposal is based on the material locally available employing the concept of circular design transformed into the concept "Form follows availability." The design proposal takes into account the lifetime of specified materials and the building itself as well as flexibility over time to maintain resilience against changing functions, cultural perceptions, and climatic conditions. The building proposal's material content and embodied energy quantities were obtained using 3D modeling and a simplified student version of the Passive House Planning Package tool [12]. The embodied energy was calculated with an Excel-based simple early design phase life cycle analysis of the global warming potential of modules A1-A4 (raw material supply, transport, manufacturing, transport) [13] relying on standard industry values. Given the scope and time restraints of the study, evaluation of the building's material content and embodied energy focused on the most energy-intensive layers, the skin and the structure. In addition to the quantitative design evaluation, the challenges and opportunities of designing with and for reuse were brought to light by the interviews and during the different design phases.

The success or failure of specific design strategies can in some part be attributed to the study's time constraints of one semester, limiting the depth of reuse theory testing through design application. On the other hand, attempting to design with solely reused materials illuminated barriers in the existing system to circular building design processes.

Reuse of Building Materials			
*Materials marked with * should be prioritized*			
Building	Barn B		
Year of Construction	Early 1900s, Renovated 1987 & 2000s		
Location	Vara, Sweden		
Material	**Amount**	**Reuse Potential**	**Handling (dismantling process req'd)**
Wood structure (main) 	34 vertical truss components @ 4.78m W x 6.42m H w/ ±.2m x .24m timber crossections 2 Purlins @ 25m L each 2 Purlins @ 26m L each 4 Purlins @ 31m L each w/ connections & ±.2m x .24m timber crossections	Structure Good condition	Unbolt from connected wooden elements

Figure 1. Inventory guide for evaluating materials suitable for reuse

3. The case study – conditions and design proposal

Mariestad, a small city (16300 inhabitants) located inland on Sweden's biggest lake in the western part of the country, was the site of the case study. In this former industrial city, globalization has caused local job market losses, and many younger residents have moved to larger cities for greater work and education opportunities. However, Mariestad's municipal authorities are hoping to reinvigorate the region, including attracting new businesses, investing in local crafts and production, and generally building sustainable resilience. To support increased density and the attraction of new business, an office building was designed on a brownfield lot downtown with the intention of future adaptability.

3.1. Design guide for building design proposal

Based on the stakeholder mapping and identified drivers from literature, a set of strategies embodying the project objectives of providing healthy built environments, reducing construction's negative environmental impact, and reducing waste was established to guide the design. These included: design for future transformation and adaptation (sub-strategies: design in layers for maintenance and changing needs, simple structural grid, tall floor to ceiling heights), design with and for material reuse (sub-strategies: design in standard dimensions, detail for disassembly, specify high quality materials), healthy interior environment (sub-strategies: daylight, healthy materials with little or no dangerous chemical content, ventilation), and low environmental impact (sub-strategies: on-site energy production, minimize building's embodied energy, design for beauty).

Designing a building with low embodied energy was of great importance in this instance, and it was therefore determined that all material should be sourced locally from within a 200-kilometer radius to reduce transport energy and emissions.

3.2. Locally available material

Aggregated data from approved municipal demolition records, along with academic and government-funded studies showed that concrete, stone and aggregates, ceramics and brick, steel, and glass were among the most widely available materials in the Västra Götaland region's urban building cadaster [11,14]. Lumber, specifically from increasingly unused barns and farmhouse structures, dominated the cadaster in non-urban areas [15]. While steel has a high reuse potential and is readily abundant in the Swedish building stock, it requires off-site processing, high energy consumption in transformation, and heavy machinery. Wood is also widely available and is more easily transformed on site using less energy [11]. As a result, salvaged lumber was chosen as the primary material for the structure and space planning layers, while hung terracotta tiles and rehabilitated glazing components formed the skin.

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Lumber quantities per barn structure were calculated based on the measurement and inventory of two timber barns, both typical in size, construction and detailing to the region.

Two material processes were developed to transform the available materials to meet the needs of their re-application. First, the salvaged wooden timbers needed to carry heavier loads than their original applications and were transformed into glued solid timber members to maximize material efficiency in a process modeled after typical glulam production. Secondly, a set of window component reuse and rehabilitation alternatives was proposed to meet current environmental performance and regulation standards, with the additional aim of providing an element of interest to the façade with a random collection of small windows collaged into large glazing components.

4. Results and discussion

Figure 2 identifies the reused materials and Figure 3 illustrates an interior view of the final design proposal for the office building.

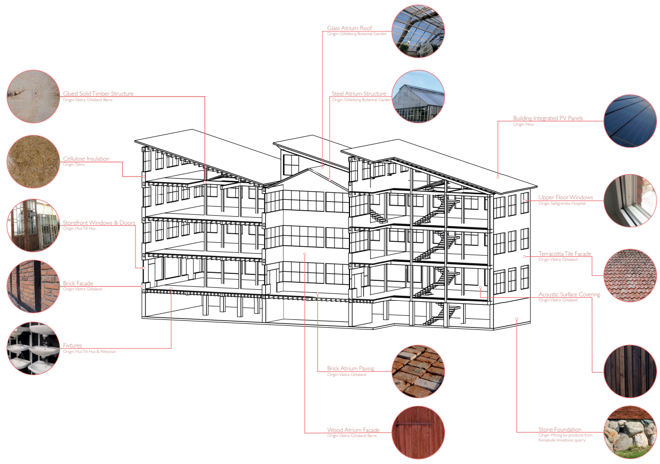

Figure 2. Section with local reused materials

Figure 3. Interior atrium

4.1. Reuse Evaluation

The proposed four floor office building was designed with a total floor area of 3717m^2, a volume of 15607m^3, and 420m^3 of structural timber required. The structure itself is formed from ten wooden barns (of the inventoried type) by employing the proposed glued timber element process from salvaged wood. Metal structural connections are largely eliminated by using traditional timber construction joinery techniques, reducing the need for new, energy intensive metals.

Exclusively salvaged materials were specified for the skin and structure, and a majority of used materials can be reapplied to other building layers. Calculations (details can be found in [11]) show that about 80 percent of the total building can be constructed from reused material. However, sourcing only reused materials for building services proved difficult given technological advancements in internet wiring, for example. Only the embodied energy of the structure was calculated. The salvaged glued solid timber structure was compared to a new glulam structure of the same size, considering the extraction, processing, and transportation energy needed for each. The structure with reused components did not receive a value for extraction energy but did require some processing energy during the timber transformation, as well as 100 kilometers of travel between the barn collection points, factory, and construction site, estimated at -29368 kgCO_2/ 50 years. The new GL30c glulam required about 18 kilometers of travel from the factory to the site, with a total footprint of 34976 kgCO_2/ 50 years. Despite the processing and transport energy required, reclaimed wood results in a negative carbon footprint.

The benefit of material reuse can theoretically be exhibited by comparing the embodied energy of a building design specifying new, first-use materials to a design of the same size and material quantities with reused materials. However, life cycle value standards for reused materials are widely disputed, as

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each item in the building cadaster is unique and its origins largely untraceable. A true comparison between the embodied energy calculations of new and reused materials is impossible.

4.2. *Workflow for reuse*
In a loose order of events, the steps carried out are as follows: local context analysis; program and project goals development; site choice and analysis; identification of locally available materials (buildings to be demolished, secondhand stores, post-consumer, surplus, pre-consumer, by-products); measuring and evaluating available materials; design concept development; adaptation of drawings, design, and details to reflect available material; purchase of used materials by contractor; and on-site collaboration with contractors through completion. The building's form, aesthetics, and details are directly influenced by the materials available at the time. Thus, the architect must freely move between the steps for continuous refinement and adaptation, especially during the construction process. This requires the architect to remain involved in the construction administration phase, finalizing details based on materials available and unexpected problems that may arise, given the inherent imperfections of used materials. The adopted workflow can easily be repeated in other projects.

4.3. *Design strategies*
Designing for future transformation and adaptation can partially be fulfilled by the sub-category of detailing for disassembly. The specification of high-quality materials, which is necessary to withstand disassembly and continued reuse, can be inferred but the actual testing of such materials, when lacking documentation, is a costly and time-consuming process, often outside of the scope of typical building auditors, deconstructors, or material specifiers. The same is valid for low hazardous chemical content of materials to meet the goal of providing a healthy interior environment; without lab testing, it may be impossible to know the chemical content of a salvaged material, especially those with high VOCs.

Other strategies under the category of low environmental impact were easily met. Maintaining a low embodied energy is implicit when designing with reused materials. A 200-kilometer transport boundary aided in reducing the embodied energy but designing with local used materials comes with additional considerations in that buildings from urban and rural areas differ in material palette and detailing.

On-site energy production was achieved by estimating built-in photovoltaic panel production of 311194 kWh/year on a 1310m^2 roof. The final sub-strategy of designing for beauty is subjective, but it is true that the salvaged materials are imbued with unique histories, seen by their weathered textures and potentially adding to their beauty. Materials mined from pre-globalization constructions often exhibit the vernacular, strengthening the ties to local history of the new building in which they are re-applied.

4.4. *System Intervention*
A systems thinking approach links many smaller, related topics to large questions, such as building demands and emissions. This study's system design brings forth the Swedish construction industry. The system boundaries include main drivers of current stakeholders, practice, and material and construction demand. In understanding the contributing variables and the relationships of their subsystems, the root causes of issues were determined, informing impactful solutions. Possible interventions at leverage points target social, logistical, and legal barriers to material reuse at scale, increasing the possibility for reuse as a common practice. In summary (see Figure 4), the following interventions must occur: provide education on working circularly to architects, contractors, and lawmakers; standardize pre-demolition audits with material inventories to contribute to the larger catalogue of material in the building cadastre; increase transparency and availability of information to support informed decision-making; plan ahead for a circular future using the data and tools provided.

While both a top down and bottom up approach are needed for the greatest effect, government support can initiate systemic changes. European, national, and local authorities hold the power to require the selective deconstruction of buildings, a minimum of reused or recycled materials in new construction, and to provide tax penalties for waste disposal or incentives for circular initiatives. More details can be found in [11].

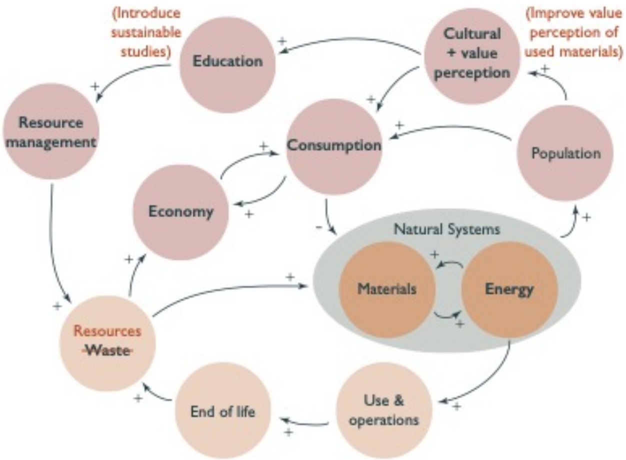

Figure 4. Modified system (including seven main drivers) with interventions. (+) Indicates reinforcing relationships, (-) indicates balancing relationships between variables.

4.5. Challenges and possibilities for reuse

With the prevalence of large-scale, machine-constructed buildings filled with highly processed materials of sometimes questionable chemical content, implementing building material reuse in the construction industry is not so simple, presenting a number of challenges and possibilities. There is a lack of practical experience and standards for building material reuse. Additionally, unreliable salvaged resource availability and quality complicate the questions of building and material guarantees. It is currently neither physically nor economically feasible to test material strength or chemical content on site during building disassembly. This creates a barrier towards informed reuse of materials, especially in the case of structural components. At present, in Sweden's existing reuse sector, no structural components may be reapplied in structural bearing capacities, and Swedish regulation prevents any material designated as waste from being reused [16]. However, with the growing implementation of material passports, material will be imprinted with this information, barring defects occurring over time, reducing the need for expensive, time-consuming materials testing prior to re-application.

When considering the possibilities for transitioning to widespread reuse, there are a few successful built projects to reference for technical solutions but, more importantly, prove that building with reused materials sacrifices neither aesthetics nor quality [17], which this project has also shown.

Beyond the construction industry, advancements are being made in cross-sector collaborations, such as between data science and construction, where digital platforms can match available materials to buyers, even predicting material needs and availability in advance based on data aggregation [18].

Another possibility for invoking change is that people are open to environmentally friendly solutions as long as they remain convenient. A study performed by Boverket [7] determined a generally positive view towards recycling and reuse, but the cost of building a house from such material is perceived as being high. While salvaged materials can be acquired cheaply due to imperfections causing value loss, if reuse becomes standard practice, labor costs will also reduce. Circular economy implementation would provide many opportunities for job creation and new roles in construction-related sectors.

4.6. Education

Changing the way professionals affiliated with the construction industry approach the design, construction, life, and end of life of buildings begins with education. An architect's (or contractor's) education and training informs their values and approach.

This study was performed during a master's degree program in an architecture school. While the teachings of the program greatly influenced the author [11], the author was also encouraged to pursue research related to personal interests and found that many important concepts required to prepare young architects for sustainable practices in their professional work were lacking in architects' basic training.

Given the widespread acknowledgement of the environmental crisis, it is the architectural curriculum's role to incorporate mandatory environmentally and socially sustainable practices in all courses, from introductory to advanced levels. Without their own efforts, the author [11] would not be equipped with the tools necessary to make fully informed decisions in the design and planning of the built environment, especially in regard to the positive influence of circular design and material reuse.

One example of enacting changes in the architectural curriculum in line with the recognition of the many social and environmental difficulties currently faced can be found at Pratt Institute of Technology (https://www.pratt.edu). A committee was appointed to 'de-colonize' the curriculum, including teaching responses to climate change, social movements, power imbalances, exploitation, and accumulation of wealth, among others. The aim is to democratize, diversify, and liberate architecture as a profession.

With education as a central variable in the system (Figure 4), the content and values of the architectural curriculum should reflect the systemic change required to support a circular economy.

4.7. *Upscaling of reuse – some reflections and guidance*

The inventory, cataloguing, and analysis of materials is a critical step in the reuse process. Materials available for reuse can be mined from the existing building cadaster at buildings' end of life, secondhand building material retailers, and post-consumer recycled products available on the market. In the first two cases, availability is likely in limited supply and must be quantified. The material should then be evaluated and given an impact rating according to its: resource management ranking, hazardous chemical content, potential for future uses, value retention, and energy intensity required in transformation for reuse. Especially in the case of structural reuse, materials should also be tested for strength.

In specifying salvaged materials based on the resources available, the architect must choose the best possible materials according to origin and established rating. In order of least transformation and transportation energy required, materials were sourced from: buildings to be demolished, secondhand retailers, and products with high recycled content. By specifying according to the rating established in the evaluation stage, material will maintain its highest possible value in its re-application, considers human health impact (chemical content), and evaluates its future reuse potential. However, the specification of a new product may provide greater benefits in performance efficiency and capacity for future re-application after disassembly than a salvaged component from the existing building stock.

Should the beauty and cultural value of reused materials become widely accepted in addition to a greater interest in environmental sustainability, the social barriers will be broken, increasing the demand for building material reuse from both clients and designers. From the architect's perspective, reused materials and designing for future reuse can be achieved at present, but as demand grows and the market reacts over time, reuse can be implemented with considerably less difficulty.

There are many individuals and groups interested in, studying, or already engaging with material reuse throughout Europe, often without connection to or knowledge of similar efforts being made, as is evidenced by the interviewees. An open network of collaboration consisting of both practitioners and academics could bolster knowledge exchange and education amongst the groups.

Building material reuse and the systemic changes required to support its large-scale implementation can be tied to three UN SDGs. Preventing used materials from being designated as waste and instead reused supports SDG 12 (responsible consumption and production). Altering architects' design processes to focus on circularity and adaptability will affect the construction industry and material flow logistics, connecting to SDG 9 (industry, innovation, and infrastructure). Finally, the responsibility of teaching sustainable practices at all levels of education is tied to SDG 4 (quality education).

5. Conclusions

A building design proposal employing the concept of circular design and transformed into the concept "Form follows availability" has been developed, taking into account the material locally available, the lifetime of specified materials and the building itself, and resilience against changing functions, cultural perceptions, and climatic conditions. The study shows that it is difficult to design a building solely with

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reused materials when confined to the existing system, but to employ circularity and material reuse is an effective means to reduce the building industry's negative impact on the environment. The salvaging and reuse of materials currently stored in existing buildings is necessary to meet the need for providing shelter for future growing populations. Building material reuse in a circular economy can only be made possible by reframing the design and construction processes, which relies in part on education, including re-training practitioners and reforming architectural education.

Opportunities for change and the effects of change can be identified using systems thinking to provide a framework for efficient material reuse for all actors related to the construction industry. Using systems thinking and design together as a tool to illustrate the contributing factors helps individuals and groups visualize the challenges and possibilities, as well as paths towards a common goal of a circular economy. Shifting practices towards a circular economy generates new jobs and businesses as linear economy-based jobs are phased out. In general, implementing reuse will require large-scale systemic change, but the environmental and aesthetic benefits outweigh the drawbacks of the economic and status quo factors. To facilitate material reuse at scale, transformation of architectural education, improved material testing and documentation, and supporting logistics are required. The benefits - reduced waste, increased cultural value, attractive aesthetics - argue for architects, clients, and contractors alike to employ material reuse as an effective means to reduce the building industry's negative impact on the environment.

Acknowledgements
The authors would like to thank the interviewees who contributed valuable insight to both the Master Thesis report [11] and this article.

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