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Adaptation for Sustainability – Adaptability and Reusability through Modularity and Digitalization in Building Technology

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Abstract. While reusability and Design for Disassembly are increasingly present in sustainability discussions within the building industry, topics such as adaptability and modularity remain only marginally explored. Yet these approaches could provide solutions not only for climate change and resource scarcity (including space, materials, energy and human labor) but also for rapidly changing living and usage patterns. This paper therefore examines, through a transdisciplinary approach, the extent to which adaptability, circularity and modularity are linked and explores the hypothesis of whether adaptable construction can increase the reuse of building components, especially in building technology. Twelve interviews with stakeholders from different fields within the Swiss building industry serve as the primary methodological element of this study. The research concludes that Design for Disassembly becomes more attractive for users and investors when it results not only in end-of-life reusability but also enables individual adjustments during the use phase and reduces resource consumption. Furthermore, adaptability holds a high priority in real estate valuation, though an integration into common life cycle cost analysis is necessary to make it quantifiable. Modular units demonstrate greater potential for adaptability and reuse than individual parts, while standardized components have greater potential than non-standardized components. Additionally, prefabrication contributes to the digitalization and consistency of information throughout the entire life cycle. Together with Digital Twins of buildings, digitalization is ultimately identified as a crucial aspect for leveraging adaptability.

1. Introduction

Reusability and Design for Disassembly (DfD) are not new concepts in the building industry and can be found, for example, in the traditional timber houses of central Switzerland since the thirteenth century (1). With DfD, a building can function as a component repository where components can be added or removed as required. In modern times, DfD has been increasingly discussed since the 1970s, with early studies around 2000 addressing repairable construction techniques or DfD's potential impact on sustainability (2).

Adaptability and modularity were prominent topics in architecture from the 1950s to the 1970s among planners, contractors, and clients (3). This interest stemmed partly from the uncertainty of the era, driven by growth and lifestyle changes, as well as a strong desire for

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progress; modular buildings, often offered as complete packages, enabled rationalization, speed, and flexibility (3). Although modular buildings have existed for centuries, the area of modular, adaptable, and reusable building technology has received little research and application (4). Digital tools that map both static and dynamic information of built structures in real time could make the associated logistics and partially automated reconnection of building technology feasible. Digital applications could ensure user-friendliness – a critical factor since studies show that adaptability entails additional costs in planning and implementation and is only used during operation if it is perceived as both profitable and practical (5).

2. Methods

For a differentiated analysis, this research integrates the topics of adaptability, reusability, modularity and digitalization through a transdisciplinary approach. A literature review formed the basis of the research, while twelve expert interviews conducted in person by the authors between April and September 2023 served as the primary methodological element. The interview participants were Swiss specialists with expert knowledge in building technology, management, real estate development and valuation, system construction, digital construction, circular construction, and marketability (for details, see references). The experts came mainly from practice, bringing substantial application-related experience. The interviews followed a slightly adapted list of questions depending on the interviewee and were evaluated thematically for agreement or disagreement with the same theses and corresponding justifications. The main questions were: 1. To what extent is the topic adaptability/reusability/modularity/ digitalization applied in your company/institution? 2. What role do building types play? 3. What is or can be adapted from other sectors or from abroad? The sub-questions related to the role of the respective company/institution, products used, areas of application, limits and potential, demand and goals. Where necessary, the interview results were supplemented with findings from the literature review to provide a broader picture of the potential in the Swiss construction industry.

3. Results and discussion

3.1. Definition and prerequisites for adaptability and dismantlability in the building industry

A clear distinction between flexibility, adaptability, convertibility and dismantlability is important (see Table 1). For the German architect and researcher Loch, flexibility implies that a room or building can be adapted to changing needs without structural changes (6). Adaptability, however, allows a room or building to be converted with minor reversible structural adaptations (6). According to the Swiss Society of Engineers and Architects (SIA), a building is adaptable when it meets the requirements for needs-based subsequent adaptations to individual needs with little structural effort (7). Convertibility means a room or building can only be converted through

Table 1. Linguistic classification of adaptability. *Source*: Based on (6,7).

Term	Definition
Flexibility	A room or building can be used flexibly without structural adjustments; “people adapt”
Adaptability	A room or building can be converted with minor and reversible structural adjustments; “living space adapts”
Convertibility	A room or building can be converted with structural adjustments; “building adapts”
Dismantlability	A building or part of a building can be dismantled into modules or components for reuse without major losses

structural adaptation (6). Dismantlability indicates that a building or its parts can be dismantled without major losses, enabling entire modules, components, or building materials to be reused.

The interviewees identified visibility, comprehensibility, accessibility and detachable joining mechanisms as basic prerequisites for both adaptability and dismantlability (8,9). The selected joining mechanisms (10) depend on material properties, the technical possibilities of the element itself, and the frequency of planned changes (see Table 2). According to the interviewees, increased planning effort must be considered (11), while additional costs in planning and construction can be offset by lower operating costs and greater space efficiency (12).

Table 2. Joining mechanism. *Source*: Based on (10).

Main energy	Joining process	Joining mechanism	Consequences for adaptability
Physical	Contact	Magnetism	Adaptations are made frequently
Mechanical	Assembling [1] [a]	Laying, inserting, hanging, clicking, clamping	Adaptations are made often
	Filling [2]	Filling, impregnating	Adaptations are rarely made
	Pressing on and in [3]	Screwing, wedging	
	Joining by forming [5]	Folding, riveting	
	Textile joining [9]	Sewing, braiding	
Mechanical-thermal	Joining by welding [6]	Press joint welding	Adaptations are rarely planned
Thermal		Fusion joint welding	Adaptations are never planned
Chemical	Joining by soldering [7]	Soft soldering, hard soldering	
	Joining by primary forming [4]	Pouring, embedding	
	Bonding [8]	Bonding	

[a] The numbering [1–9] refers to the nine joining process groups according to DIN 8593.

Gratz, a Swiss researcher and editor, notes that few Swiss modular buildings from the 1950s to 1980s were adapted or converted over time to the extent originally planned and possible (3). There are several reasons for this: after a few years, the considerations behind this type of construction were often no longer clear; the growth forecasts of that period did not materialize as anticipated, eliminating the need for extensions; and ultimately, certain building components ceased to be manufactured (3). For adaptability, therefore, it makes a significant difference whether the elements used are universal or patented ones, which only specific companies are able to produce (3).

3.2. Adaptability in building technology

Heating, ventilation, cooling, plumbing and electrical pipes are typically manufactured in small sections comprising many prefabricated and universal parts. In principle, they can be easily separated and reconnected, for example by sawing and welding. Pipe clamps or sockets are also common mounting or connecting elements. Additionally, plug-in systems where building services cables are technically connected by simply plugging them together are increasingly being used according to the interviewees and offer interesting possibilities for adaptability (9,13,14). The implementation of findings from the automotive industry in the construction industry demonstrates, according to Blessing from Selmoni (a Swiss company for electrical planning and implementation), that pluggable electrical engineering improves quality, as performance loss due to connectors in electrical engineering is negligible (13). Moreover, Blessing and Peinsold, project leader at HHM (a Swiss building services planning office), have found that the assembly of pluggable systems in electrical engineering requires only one third of the assembly compared to conventional construction (13,15). Examples of pluggable systems in electrical engineering include entire routes and luminaires, such as the Purelite LED lights from Regent (15). Examples in the plumbing sector include the Push-fit system from Geberit. In the UNICON system, building technology connects via predefined interfaces when building components are assembled (16).

According to the interviewees, plug-in systems offer potential due to the following aspects: 1. elements can be prefabricated as larger modules; 2. prefabrication takes place in workshops under ideal working conditions; 3. a high degree of prefabrication leads to time and cost savings, fewer personnel, greater safety and higher quality on the construction site; and 4. cross-trade collaboration is simplified (13–16). When working with pluggable systems, the work is shifted from implementation to planning (13,15). Baumgartner, head of general planning at Renggli, sees obstacles for pluggable systems in building technology in the installation costs, the precision required and the susceptibility to errors (17). In addition, pluggable systems must be reduced to sizes that can be transported and assembled on site (15). In the plumbing sector, click connections have not been widely used for long due leakage risks (9,14), resulting in limited reference values for durability (11). Additionally, pipe joints commonly used today already offer possibilities not for adaptability but for convertibility and are significantly less expensive than click connections, as noted by Wehrle, CTO of the Swiss construction company ERNE (11). In contrast, a study by HHM concludes that in the overall calculation of a test object, a pluggable installation offering adaptability can actually be less expensive (18).

Building services installed openly or in hollow spaces increase their adaptability through their increased accessibility compared to those embedded in solid construction (12). The Interviewees highlighted several important considerations: First, space should allowed for future expansion of building technology without adding it prematurely, as this produces emissions during construction and could already be outdated by the time it is needed (11,12,14,15). Furthermore, FHNW facility manager Dömer suggests hollow floors are preferable to hollow ceilings due to their accessibility, as adjustments in hollow ceilings require impractical overhead work (12). Additionally, hollow floors should be fitted with reversible coverings – office construction often uses carpet tiles, which can be laid tightly enough to conceal joints (11). Direct connection options (e.g., for electricity) must also be provided, preferably on walls if not available, as water and dirt on the floor cause problems (11,12). Wehrle recommends inspection openings every four to five meters (11). Finally, it should be noted that continuous cavities can create problems with fire protection and sound insulation (12).

3.3. Reusability in building technology

Since a large part of building technology is already mechanically reversible, reuse is both interesting and practicable, according to Angst, a Swiss reuse expert from Zirkular (8). Obstacles also point to solutions (see Table 3). If building technology is accessible, it becomes not only easier to adapt and convert, but also to reuse (9,19). As noted by Schmuck and Stein, CEOs of the consulting company Mas Con, considering reuse from the outset would allow temporary technical building systems to serve as temporary storage for technical building components (14). However, the repetition of small, identical and inexpensively manufactured elements such as cable trays

Table 3. Obstacles and solution approaches for reuse in building technology. *Source*: Based on (8,9,12,13,17).

Obstacle	Solution approach
Non-detachable joints	Visible, accessible and detachable mechanical joining mechanisms (DfD)
Materialization, contamination	Incentive prices that consider origin, production and transportation; removal and cleaning must be more attractive than using new components
Regulations	Adaptability of components to exchange obsolete parts
Fast-moving nature	Differentiation of building technology components in terms of half-life
Fragility/small-scale	Modularity/connectivity
Logistics	Component catalogue, just-in-time availability, digital localization and matching

and pipes ensures that testing, measuring, dismantling and reassembling them is not financially worthwhile (8,14). Grünig, a developer at Halter, emphasizes that materialization (e.g., cable sheathing, steel routes) plays an important role in reusability (9). While inexpensive materials are imported from abroad, valuable metals (e.g., copper) are used in electrical engineering (13). Current regulations limit alternatives in material selection (13). Nevertheless, the increasingly noticeable shortage of raw materials could create financial incentive for the careful use of non-renewable resources in the future (14). Angst suggests that incentive pricing that considers origin, production and transportation could also serve as a driver of circularity (8). The situation differs for products that require more effort to shape, such as radiators (8).

Standardized elements like sprinklers, fresh and waste water pipes are generally easier to reuse than customized pieces (9). However, the interviewees note these are subject to strict regulations and constantly evolving standards, which can impede reuse (9,15). Fire dampers, for example, require approvals that expire (14). Fundamentally, building technology represents one of the most rapidly evolving building components (12); while aspects such as high voltage electricity change slowly, Information Technology (IT) changes rapidly (9,17). According to Peinsold the half-life in electrical engineering (e.g., lights, plugs) is 5 to 10 years, whereas steel water pipes made of steel last longer (15). Here, contamination and rusting can also hinder reuse, particularly with water-bearing pipes (9,14). This concern extends beyond actual soiling and rusting, but also about mistrust (14). Other mechanical components are too fragile for reuse (13).

Finally, the question of reuse is linked to the possibilities of storage and accessibility. Sorting, managing and storing incurs significant costs, currently making disposal in the building technology sector more economical (13,14). Reuse becomes worthwhile only when inventory is known and available at the right time for planning in order to minimize storage costs (9). Ideally, these inventories should be accessible not just for individual companies but to the entire industry (14). Blessing notes there is currently few suppliers of technical building elements for reuse, especially in large quantities (13). The authors' comparison of Swiss component markets reveals that they primarily offer individual parts such as fittings, radiators, lamps, light switches, washbasins, stoves, refrigerators, chimney pipes, and heat pumps from and for private consumers.

3.4. Modularity in building technology

Modularity is seen by the interviewees as a basic prerequisite for adaptability and reusability of building technology (14,20). It not only counteracts fragmentation and fragility but also reduces the work involved in adaptability and reusability. Modules are three-dimensional building elements based on a system that can be joined additively (21). They strongly reflect the concepts of industrialization and prefabrication (3). When buildings are planned modularly based on repetitive grids, building technology can follow this pattern (15). For Peinsold, a modular basic concept ensures flexibility and speed in planning, especially when changes are required (15). Closed systems require specific manufacturers, while open systems can be implemented with elements available on the market (21). The rapid evolution of technology creates problems when spare parts become unavailable (12). Selmoni addresses this challenge by using 3D printing for cost-effective production of individual connectors where components available on the market do not fit the specific application (13).

Baumgartner notes that modularity requires decisions in early project phases (17). For Wicki, member of the executive board of Zug Estates, a module's intended service life influences the choice of structural joints: In short use cycles it must be possible to assemble, rebuild, dismantle and reposition with as little effort as possible (20). In building technology, a distinction is made between primary, secondary and tertiary access (see Table 4). According to Peinsold, the potential for modularization increases from primary to tertiary access (15). Blessing reports that already 70% of electrical components are prefabricated, such as socket columns with compressed air connections (13). The Interviewees suggest climbing zones, technical centers and group superstructures are readily conceivable as larger modules, whereas horizontal distribution is more dependent on the structural concept (9,17). Modularized and prefabricated horizontal routes make sense if they are repeatable basic modules (8). According to the interviewees, modularity in building technology also depends on use and project size: large projects offer greater repetition effect, while healthcare buildings have a higher demand for building technology (9,13,14). Prefabricated wet rooms with a high density of building services installations are already widespread in hospital buildings (14,22).

Table 4. Modularity in building technology. *Source*: Based on (15).

Form of access	Localization	Modularization potential
Primary	Property connection, sub-distribution	Low
Secondary	Building distribution	Medium
Tertiary	Room distribution	High

3.5. Potential of digitalization for adaptability and reusability in building technology
Today's prefabricated components can leverage their already established closed process chains for future reuse. Their advantage lies in information already available digitally during planning and production that provides guidance on reassembly (11,20). Digital planning and production also ensure waste reduction, as to Blessing and Selberherr, partner at the real estate development company Wüest Partner, point out (19): material purchases are more considered, and factory production and storage offer better protection from damage (13). Planning and production are also more efficient, which generally increases customer satisfaction (13). Regarding potential reuse, Baumgartner notes that digital planning remains too new in the construction industry to to yield benefits today (17). Furthermore, for future use, it is important to understand that not all information required for production is relevant for subsequent life cycles such as operation, conversion, dismantling and reuse (17). Information relevant only for the production process

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need not remain permanently in a Material Passport (MP) or Digital Building Model (DBM) (17). Thus, complete consistency of information is not necessary, but defined interfaces and a common vocabulary are essential (15,17). Currently, no examples exist where component marking is coordinated across all trades; the complexity lies in the heterogeneity of the industry: Each trade requires different information, and suppliers often operate internationally in several languages (17). An EU-wide solution is forthcoming with regulations from 2024 requiring a Digital Product Passport (DPP) for all physical products within the EU by 2030 (23).

In the context of adaptability and reusability in building technology, the Digital Twin (DT) warrants special attention. A DT is defined by the following key elements: 1. it provides a digital image of a physical environment; 2. it possesses the intelligence to sense, understand and change its environment; and 3. there is a bi-directional information flow between the DT and its physical counterpart (24). According to Wicki, the use cases of a DT must be differentiated according to life cycles (planning, construction, operation, reuse), maintaining information consistency (20). Equipping a building with a DT could enable real-time visualization of installed components and their condition. In connection with Mixed Reality (MR) devices this is particularly interesting for building services pipes that are not visible from the outside. If a component with corresponding Track-and-Trace (T&T) technology is replaced, the DT would update accordingly. Determining which degree of automation makes sense at which point becomes a question of sufficiency (11).

Component matching presents particular challenges (8). This involves both temporal and physical alignment. Even when an element seems promising for reuse in a specific building (e.g., a building services core with appropriate size and equipment), the likelihood of having the available element is on site or nearby is low (8). Digital tools can support both aspects. Parametric design enables, for example, the installation of various components to be checked by comparing them with defined parameters. Proper information management (e.g., using a DT as a component inventory) can provide information about the availability of components in the surrounding area at an early stage. The goal is local reuse, as every additional transportation kilometer is a burden on the environment (8). However, data protection becomes relevant when specifying an element's location and condition (17).

The coordination of building technology trades simplified by Building Information Modeling (BIM) is now indispensable in large-scale projects to minimize costly errors in implementation, according to the interviewees (9,15). However, planning, production and operation generally remain too isolated, with insufficient interoperability (17). Clients and operators are often not able to use the data correctly (14). Thus, digitalization in construction is also a question of skills and education (15). Another way to counteract this problem is through collaboration models that involve contractors at an early stage, such as Integrated Project Delivery (IPD).

3.6. Market value and marketability

Assessing the potential of adaptability, modularity and digitalization for reusability requires addressing the issues of market value and marketability. According to Selberherr, the market value of a property is made up of income, costs and discounting (19). Possible future cost savings must be calculable in concrete terms, as market value estimates are regulated and standardized (19). The requirements for these are legal and technical feasibility and market plausibility (19). If factors cannot be priced in, investment is inhibited (19). Ultimately, supply and demand determine the price: New products should offer advantages over existing ones (25).

Currently, the market value is determined using the Discount to Cash Flow (DCF) method with a going concern valuation, assuming that the current use will continue indefinitely (19). In accordance with the applicable valuation standards and norms, the deconstruction and reuse of components are not considered (19). Today, dismantlability is only factored into projects with dismantling objects. In such cases, dismantlability and landfill costs are relevant in terms of value, but not the potential for individual dismantling of parts for reuse. Accounting for selective dismantling would create a positive effect (income from reuse). Conversely, it is difficult to consider future dismantling in a new building. As deconstruction approaches, it becomes more relevant in discount rate terms; however, planned deconstruction contradicts the desire for new buildings to be as durable as possible (19). If additional investments are currently being made for circularity, this is associated with a risk for investors. Buildings would have to be considered as if they would stand for 30 years instead of 100, which would be closer to today's reality, not because of lifespan but market factors – which would quickly shift incentives (19). Including deconstruction costs and revaluation income in calculations could strengthen advocacy for circular construction and potentially change regulations. France exemplifies this approach: every building application requires proof of predicted emissions during construction (19). The interviewees identify another driver for marketability value enhancement through certifications such as DGNB and SNBS (11,19).

For Wüest Partner, flexibility of use is an important criterion in property valuation with an influence on the market value and discount rate of a property (19). Prerequisites for flexibility of use in built environments include not only the construction, but also the neutrality of use, where high floor plan quality and appropriate technical equipment serve as criteria (19,20). Adaptability through movable elements can increase flexibility of use; however, a lack of durability and high maintenance requirements may negatively impact market value (19). For adaptability to enable circularity, it must be considered alongside DfD (20).

System separation represents another important aspect (8,11), as building components vary in lifespan, carbon footprint and value. Whether elements are plugged or screwed together involves cost-benefit considerations. If a building is to be adapted several times during its life cycle, pluggable connections become advantageous (19). Retail spaces illustrate this: After several years, Wicki observes many components are often discarded (20). New construction industry business models such as as-a-Service (aaS), renting, leasing or sale-buyback may drive circularity; for example, when investors focus on supporting structures and shells while interiors are leased by buyers or users (19). Currently, aaS and leasing models are most commonly be offered in building technology (14,19). The investor's role – whether merely ordering buildings or also operating them – makes a difference (17). Access to the latest technology can be particularly appealing in areas with rapid technological development. Additionally, sharing models are encouraged compared to traditional purchasing.

4. Conclusion

4.1. Summary

Without corresponding market incentives and synergies, the reuse of components is likely to remain a niche phenomenon, particularly for short-lived components such as those in building technology. This applies both to the reuse of components currently available in urban mines as well as the availability of future components in which dismantlability is already considered today and might become financially attractive. Valuation standards and corresponding calculation methods seem unlikely to change in the short term. It seems more likely that the priced-in costs will change. One aspect is the consideration of life cycle costs: Not only the construction costs, but also the costs of operation, conversion and dismantling. New models like aaS, leasing or sale-buyback offer promising contributions. Additionally, finite resources and greenhouse gas emissions require consideration. Discount rates already indicate that a valuable building is one that survives longer without conversion. Currently, the possibility of individual adjustments during the use phase can attract investors more than the potential reuse of a building at the end of its life cycle.

When digitalization is considered holistically, it can help balance costs and benefits across all levels – ecological, social and economic. User-friendly digital applications accessible via mobile devices could promote adaptability by demonstrating possibilities and methods; a shared network connected to DTs could help eliminate the need to search for components across differently structured catalogues on various web platforms, by functioning as a component catalogue itself, recognizing patterns and filtering information. Additionally, matching could be automated according to defined criteria. Finally, digitally supported prefabrication appears fundamental for circular building technology.

Building technology benefits during both production and reuse from modularization and planning on repetitive grids. When space is provided for appropriate installations, retrofitting proves more sustainable than prophylactic purchase of equipment, as space itself constitutes a valuable resource. Rather than occupying space prematurely in cavities or shafts, these can be constructed to be adaptable. Durability represents another key factor for circular building technology. As this research demonstrates, this is more likely to be achieved if, on the one hand, fragility is countered by modular structures and, on the other hand, individual elements are differentiated according to their service life.

In summary, a broader transdisciplinary and synergetic approach has the potential to lead to systemic change in the field of adaptability and reusability. IPD shows great potential for promoting customizable, circular and modular construction as a common language, basic knowledge, goal-oriented action, collective responsibility and value appear fundamental.

4.2. Outlook

The extent to which the installation of sensors can provide support for reuse requires deeper investigation, particularly regarding cost-benefit analysis in terms of sufficiency. The vision would be as follows: A component signals its location, arrives on the construction site just in time, is installed, automatically synchronizes with the DBM, and the DT follows in real time, even during a conversion. Specific case studies with different degrees of automation could form the basis for cost-benefit analyses. Synergies in terms of adaptability, modularization and digitalization in building technology and beyond already offer potential cost savings and added value in terms of deconstructability. In the future, practical examples accompanied by research will be able to provide information on the extent to which IPD supports reuse. In addition, it would be interesting to analyze what incentives are needed for DfD to become more firmly anchored in the construction industry. In this respect, it seems interesting to consider joining techniques that are less considered today. The question arises as to which industries can serve as a model for connection mechanisms and whether elements from building technology could be transferred to other areas of the construction industry (e.g., the principle of pipe clamps). Finally, it is important to analyze the extent to which what is adaptable is also easy to dismantle, and what roles adaptability and digitalization can play in marketability. The current and future value of data and its role in market value impact also merit further study.

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