

Breaking the Renovation Cycle: Learning from Architectures of the Past for Low-Metabolism Building Design Today

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ABSTRACT: The paper develops new knowledge of patterns of building material consumption in renovation and adaptation cycles, to design new buildings to have a lower future material use in their use-stage. By comparing component lifespans and environmental impacts of material uses in the life of three cases in Copenhagen, Denmark, certain architectural characteristics were found to influence the levels of material use and sequences of change. The cases were: a preindustrial case (*1755) with multiple transformations of use, an industrialised case (*1972) and a control case (*1958) from right before industrialised building practices intensified in Denmark. Change patterns, material uses, and environmental impacts differed significantly across the three cases from preindustrial to industrialised building cultures. In the qualitative interpretation of the quantified material changes, the paper challenged Duffy and Brand's models of "Shearing Layers of Change" and Design-for-Disassembly frameworks with a design principle focused on the relationships of component types and their "*hierarchy of alterability*". This principle could be used in the design of new buildings and in transformation projects to meet shifting user needs while lowering the use-stage consumption of materials over a period of 200+years of use and adaptation.

KEYWORDS: Hierarchy of alterability, LCA use-stage, material flow, lifespans, adaptability, lasting architecture.

INTRODUCTION

In Denmark, reuse covers 6,5% of current needs for building materials, and up to 18-25% if every demolished square meter and gram of demolition debris was reused despite toxins (R. Andersen 2023). This highlights that Circular Economy strategies of reuse need complementary strategies to tackle the construction industry's material consumption and environmental impacts. Renovations of buildings and their components occur many times in their relatively long use-stages. In Denmark, the renovation industry is about 65% larger than the new construction-industry (measured by production value) primarily due to use-stage refurbishments and replacements of the building envelopes, HVAC/plumbing, and interior fittings (Rasmussen and Birgisdottir 2015). Considering the size of the renovation sector, the consumption of building materials is not only costly but also with large environmental impacts (Rasmussen and Birgisdottir 2015; Duffy 1990). Nonetheless, Danish Building Code currently excludes the module "B5: Refurbishment" from Life Cycle Assessment requirements (LCA) and uses a building lifespan of just 50 years whereas buildings in Denmark are predicted to last an average of 200 years (Aagaard et al. 2013). Further, were the LCA's 50 years calculation period extended to 80 years, the environmental impact from replacements of building components would triple (Zimmermann et al. 2020). While overlooked in policy, practice, and research, the material use in the use-stage of buildings clearly holds a potential as a field of study to lower the industry's environmental impacts (Pomponi and Moncaster 2016; Bowyer et al. 2022). To explore this potential, historiographies of change in buildings from different building cultures could yield new insights. Existing studies have shown:

- How load-bearing structures can be designed to adapt to future uses, yet without a focus on the most frequently added/removed building components in renovations. (Till and Schneider 2005; Wilkinson 2018; Geraedts 2016)
- Technical lifespan properties of building components to withstand deterioration, yet not with a focus on reduced material use in renovation/adaptation in new-builds. (Ejstrup 2019; Loonen et al. 2013; Aagaard et al. 2013)
- Economics of marginal utility (Stigler 1972) and the Rent-Gap Theory (Smith 1987) to theorise when a product/component/existing building meets demands or cannot fully capitalise on current market potentials.
- Aesthetic/architectural qualities, mainly in low-rise preindustrial buildings, yet not systematic studies of characteristics that impact practices of material use in multistorey, urban buildings (Hassler 2020; Ventzel Riis et al. 2021; Eybye 2016; Bak-Andersen 2020, Andersen 2015).

There is a research gap on the relationship between architectural characteristics and material consumption patterns in buildings' use-stage, and on studies that combine quantitative material flow analyses with qualitative assessments of architectural characteristics. Further, material flows and component lifespans have, to our knowledge, not been studied in the comparison of multistorey, urban preindustrial and fully industrialised buildings. The paper focuses on both of these aspects. To limit the scope, the study foregrounds the increasing scarcity of natural resources from building material consumption in the use-stage (Seifi 2021) and does not assess operational energy, comfort standards, or user expectations which have been studied widely (Azari and Abbasabadi 2018).

1.0 RESEARCH QUESTION

How do patterns of change, material uses, and environmental impacts of use-stages in preindustrial and industrialised buildings compare, and how may this comparison inform design decisions to lower the consumption of building materials in future use-stages in new-builds and transformation projects?

2.0 THEORY

The environmental impacts from building material uses in renovation and adaptation cycles are commonly quantified via LCAs. Here, both operational energy and embodied energy (EE) are calculated with the metric of kg CO₂-eq/m² in a 50-year calculation period, using pre-tabulated component lifespans (Rasmussen and Birgisdottir 2015). Since this study assesses EE of materials only with the use of actual component lifespans from the cases instead of generic data, the term “metabolism” is used, adapted from the theory of “Metabolism of the Anthropocene” (Brunner and Rechberger 2017). The metric remains kg CO₂-eq. of material use per m² per year from renovations and adaptations, documented in the period of archival material availability in the use-stage of each case.

Patterns of change are qualitatively compared among the cases with two theoretical models of the sequences and categories of change: Francis Duffy grouped building components with similar lifespans into four “layers”: “Shell”, 50 years (foundations, walls, roofs, structure), “Services”, 15 years (HVAC, plumbing), “Scenery”, 5-7 years (partitions, interior fittings, furnishings, surfaces), and “Sets”, a day (moveable furniture) (Duffy 1990). Stewart Brand named this theory “The Shearing Layers of Change”, added a permanent “Site”, and split Duffy’s Shell in two: “Skin”, 20+ years (building envelope), and “Structure”, 30-300 years. Finally, Brand renamed Scenery into “Space Plan” and Sets into “Stuff” (Brand 1995). When referring to any of these layers, the first letter is capitalised, e.g. Shell. To represent the received, silent knowledge of practicing architects, renowned architect and writer Rafael Moneo’s hypothesis of what makes buildings last is used as an additional qualitative analytical lens. Moneo’s theory springs from a case study analysis of the 800 year adaptive reuse history of the Mosque of Cordoba in his essay, “Life of Buildings: The Mosque of Cordoba” (Moneo 2017). Moneo used the mosque as a paradigmatic case (Flyvbjerg 2006) of *robustness* which was achieved by *its formal structure, and in the principles upon which this structure depends* (Moneo 2017, 2). The architecture could withstand alteration because it was *defined with enough clarity (...) to be always present* and used *already-used elements* from various traditions to make architectural principles easy to recognise, see value in, and keep across time (Moneo 2017, 5). In this theory, robustness or longevity is achieved when (architectural) principle and structural logic fully overlap and are visibly present in every building element, communicated to users over time through the use of well-known building elements, syntaxes, and materials, echoing Alberti’s and Vitruvius’ writings (Alberti 1991; Vitruvius 1960). While not explicitly used for the analysis in this paper, the article also builds on a lifespan model from engineering by BUILD (Department of the Built Environment, Aalborg University, Denmark) to categorise different qualities that impact a component’s lifespan: technical (physical durability), functional (meeting programmatic needs), economic (operations viability), and aesthetic (meeting owner/users “aesthetic standard”) (Aagaard et al. 2013).

3.0 METHODS AND SELECTION OF CASES

The paper uses mixed-mode research methods (Aksamilja 2021). In summary, three case studies are chosen, data is gathered through archival research, material changes are mapped, and the metabolism of renovations and adaptations of each case is quantified. Patterns and frequencies of change, component lifespans, and material uses are comparatively analysed across cases with Duffy and Brand’s models of change and Moneo’s example of the received knowledge of practicing architects on the dependency of a structural logic on architectural principles.

For the case selection, the paper uses an “information-oriented” strategy to choose three cases based on the expectation that they are rich in information content (Flyvbjerg 2006). One case is selected to represent a preindustrial, premodern building culture, another case to represent an industrialised building culture, and a preindustrial control case is added for a sensitivity analysis. All three cases are chosen to come as close to “critical cases” as possible for deductions of the type *“If this is (not) valid for this case, then it applies to all (no) cases”* (Flyvbjerg 2006, 230). To minimise selection bias, cases are selected on their independent rather than dependent variable (King, Keohane, and Verba 2021), as the main criterion of the three cases – building age – is independent from the dependent variables of metabolism and component lifespans (to the best of authors’ knowledge). To select the preindustrial case, 2000+ buildings in Denmark are screened from the office portfolio of preservation and adaptive reuse projects of RØNNOW LETH & GORI, host company of the industrial Ph.D.-project. The inventories of physical and digital case folders enabled a screening with the following selection criteria: 1) *200+ year old (to gather knowledge to design new-builds in a 200+ year perspective)*, 2) *Unclassified status for public disclosure*, 3) *Multistorey, premodern, preindustrial (research gap for multistorey, premodern, preindustrial buildings)*, 4) *Urban, in Copenhagen Municipality (urban buildings have a longer use-stage and thus greater material use in renovation/adaptation (R. Andersen 2023))*, 5) *Rich transformation history (with the assumption that transformations entail significant spatial reorganisation and material use. If the preindustrial case’s material use is low compared to the industrialised case with no transformations, the more robust will findings of a lower preindustrial metabolism be)*, 6) *Period of data availability*. 13 cases matched all criteria, had 2+ adaptive reuses, and were at least 250+ years old. Søkvæsthuset by J.C. Conradi, 1755, is chosen, due to long data availability (1755-2006) and six whole-building transformations of use. To overcome the difficulty of comparing two primary cases of different locations, weathering conditions, design quality levels, maintenance/repair cycles, and programmes, the following criteria were used to choose both the industrialised primary case and the preindustrial control case: 1) *Built right before/after the Montage Circular (1960) which rapidly industrialised Danish building culture*, 2) *Built by the same architect with a comparable level of design quality*, 3) *Built in direct proximity to have similar weather conditions and other localised impacts*, 4) *Administered by the same housing association to have similar operations management*, 5) *Comparable programme*, 6) *Built by a renowned architect to ensure high design quality*. The industrialised case Tingbjerg Dormitory, designed by renowned architect Steen Eiler Rasmussen and constructed in 1972 (with data availability from 1972-2012), was selected as the industrialised primary case. This case matched all the criteria and faced a building constructed right before 1960 in the same street, by the same architect, same housing administrator, and with a comparable programme, namely the Tingbjerg Family Housing constructed in 1958 (with data availability from 1958-2023) which was chosen as the control case of a pre-industrialised construction practice.

To limit the scope of the paper, Yin's *embedded unit* analysis of multiple cases is used (Yin 2018). Yin proposes a cross-disciplinary case study research method to analyse single or multiple cases in one or more units of analysis *embedded* within one or multiple cases, as a representative part of the whole. Representative sections of regular floor plans of each case (all 2nd floors) are chosen: Søkvesthuset's embedded unit includes >25% of each of the four room sizes on the regular floor plan, >25% of the long façade, a primary and secondary heating source, one of two main stairwells, and the three forms of vertical loadbearing structure: outer walls, inner walls, and columns – a total of 191 m². Tingbjerg Family Housing's embedded unit includes one standard apartment and a stairway shared between two apartments, a total of 99 m². Tingbjerg Dormitory's embedded unit includes a shared kitchen and four of the ubiquitously sized and fitted dorm-rooms, a total of 157 m². (See Figure 1 in 4.0) Archival Research (Aksamilja 2021) is performed to assemble, organise, and analyse each case's drawings and text documents from the project archives of RØNNOW LETH & GORI, the Danish National Archives, and the Municipality of Copenhagen Building Case Records. All material relevant to the renovation/adaptation history of each case is arranged into chronological folders and drawn in a series of plan and elevation drawings in AutoCAD.

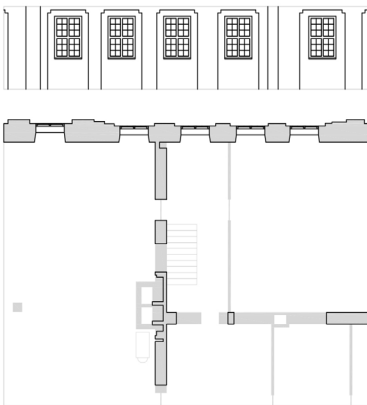
An LCA of each case's metabolism is calculated for the LCA A1-A3-phases only, since actual building component lifespans and refurbishments in the B-phases modules are documented through the archival work, and C- and D-phases are omitted because of the significant differences in reuse practices before and after 1960 (Bak-Andersen 2020) and since construction waste from demolitions accounts for just 3% of the environmental impact in contemporary practice (Rasmussen and Birgisdottir 2015). The calculated volumes (m³) of each material added in the renovation/adaptation history of each case is converted into kg CO₂-eq. with the digital tool "The Construction Material Pyramid" (CINARK 2019), a database of EPDs, analogous to other LCA-tools. For materials not included in the database, building components with EPDs are used as substitutes. The kg CO₂-eq.-results are divided by the embedded unit-size (m²) and by the studied time-period (years) of each case respectively.

Subsequently, patterns of change, component lifespans, and metabolisms across the three cases are compared and discussed with the theories of Brand, Duffy, and Moneo. This discussion aims to develop qualitative, empirically rigorous design knowledge and, in turn, to discuss the models of Duffy, Brand, and Moneo against the findings.

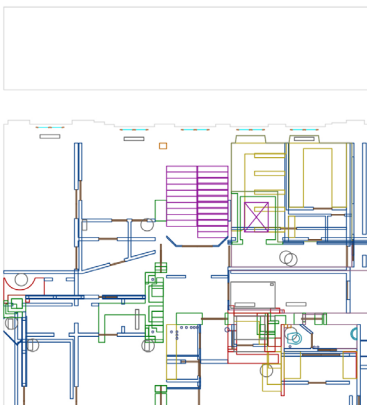
4.0 RESULTS

SØKVÆSTHUSET (1755-2006)

Grey: original. Black outline: 2006-remains



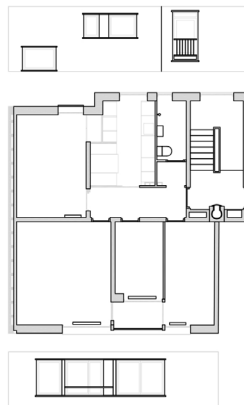
Added materials over 251 years of renovation:



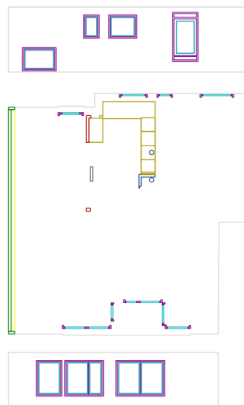
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TINGBJERG HOUSING (1958-2023)

Grey: original. Black outline: 2023-remains

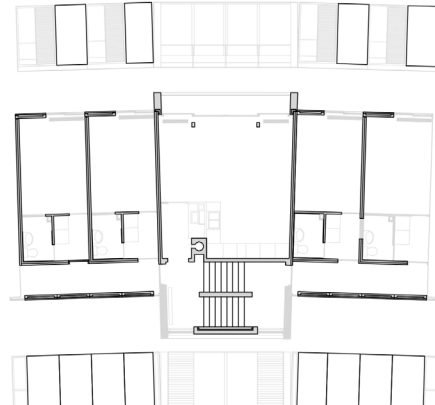


Added materials over 65 years of renov.:



TINGBJERG DORMITORY (1972-2012)

Grey: original. Black outline: 2012-remains



Added materials over 40 years of renovation:



Figure 1: Metabolisms of the embedded units of the three cases, redrawn from archives. Source: (1st author 2024)

4.1. Søkvæsthuset’s metabolism (1755-2006)

Søkvæsthuset’s Shell was the longest lasting layer, followed by Services, and lastly Scenery, as predicted in Duffy’s categorisation. This order slightly deviates from Brand’s theory: Søkvæsthuset’s Skin is structural and was the longest lasting layer, followed by Structure in terms of inner structural walls, Services and lastly Space Plan (/Scenery). Half of Søkvæsthuset’s metabolism was concentrated around just three datapoints in the first 110 years (see Figure 2). These spikes occurred with the first two changes of use – to hospital and to barracks. The other half of the metabolism was spread out more evenly over the following 141 years and 13 datapoints. However, the partial change of function to apartment units (1870), and the introduction of bathrooms (1888), radiators (1933), and an elevator (2003), were main contributors to the overall metabolism of Søkvæsthuset.

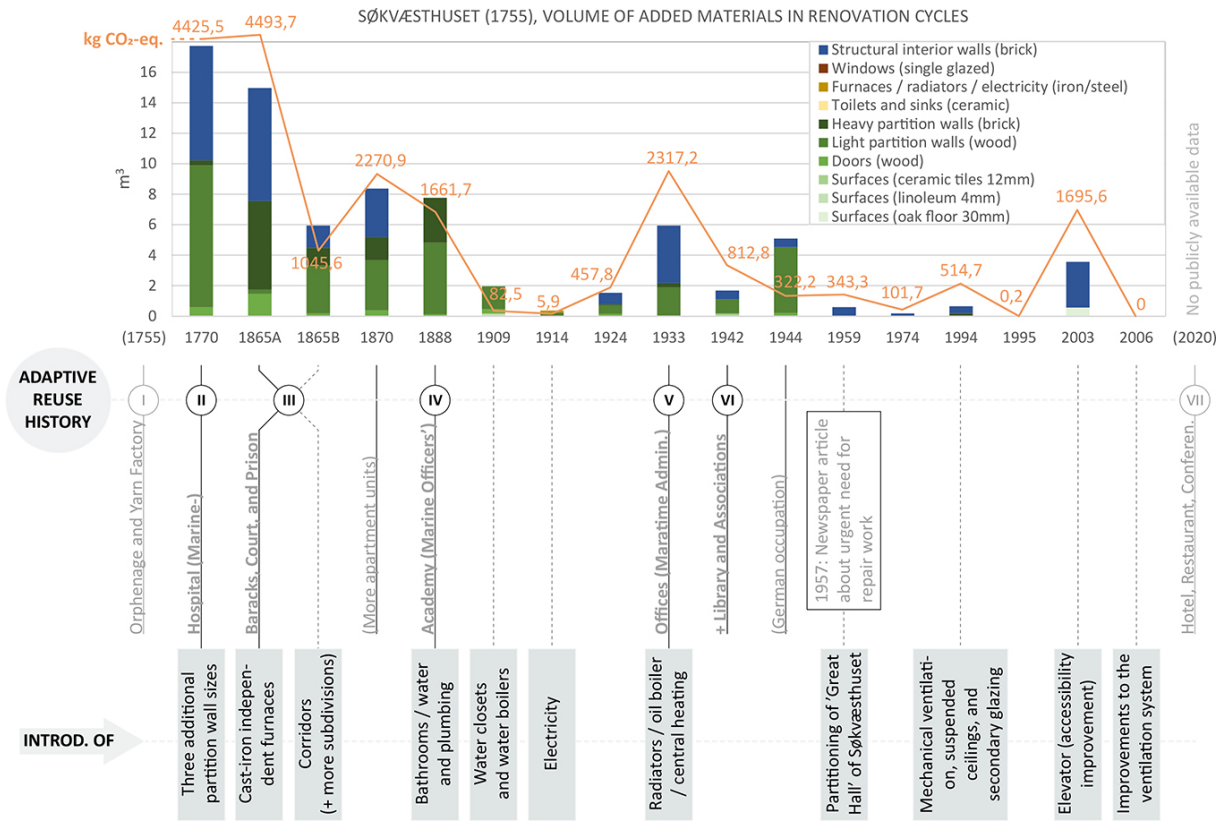


Figure 2: Søkvæsthuset: The transformation history, material uses in m³, and metabolism. Source: (1st author 2024)

4.2. Tingbjerg Family Housing’s metabolism (1958-2023)

Services was the longest lasting layer in Tingbjerg Family Housing, followed by Scenery / Space Plan, and Shell / Skin+Structure. Since changes were happening most rapidly in the Shell / Skin+Structure, and then Scenery / Space Plan, the case deviates from both Duffy’s and Brand’s models. The replacement of the Shell’s windows and wood frames to double glazed windows in PVC-frames was the biggest CO₂-emitter, closely followed by the structural changes to the façade. Had the outer part of the cavity wall not been rebuilt with reused bricks, its impact would have nearly doubled. Services had the second lowest metabolism with the addition of new radiators, mechanical ventilation, and bathroom fittings. The Scenery’s addition of light partition walls contributed the least to the metabolism. Yet, had the furnishings been included in the study (see 4.5), the Scenery would likely have had a larger metabolism than Services, with the addition of new kitchens (see Figure 3).

4.3. Tingbjerg Dormitory’s metabolism (1972-2012)

In Tingbjerg Dormitory, the Scenery/Space Plan and the Services were, surprisingly, the most lasting layers. Relative to the other cases, however, their lifespans were low: thoroughly reconfigured in 2012, just 40 years after their construction. These layers were followed by the Structure (in-situ cast concrete) which was lightly improved on in the first renovation of 1992 and again partially in 2012, while the Skin was replaced and altered thoroughly two times in the studied period (1992 and 2012). Neither Duffy’s nor Brand’s theoretical models were predictive of the sequence of change, yet Tingbjerg Dormitory followed Brand’s separation of the Shell into Skin and Structure-layers with notably diverging lifespans. The metabolisms of layers in Tingbjerg Dormitory followed the lifespan order (see Figure 3): The Skin accounted for 2/3 of the total metabolism, with the exchange of windows as the main event, followed by fibre cement cladding, galvanised steel rails, and a balcony staircase (also galvanised steel). The Structure accounted for 1/5 of the metabolism, where the biggest contributor to the metabolism was the extension of the concrete deck beyond the existing balcony for the extension of the kitchens, and secondarily the structural steel balcony deck in front of the common kitchens. While Services was the second lowest contributor to the metabolism of Tingbjerg Dormitory, its metabolism was still six times higher than in Tingbjerg Family Housing per m²/year. The Space Plan contributed the least to the metabolism. However, had the new kitchen cupboards in the common kitchens and the kitchenettes in the dorm rooms been included in the study (see 4.5), the environmental impact of the Space Plan layer would have been greater.

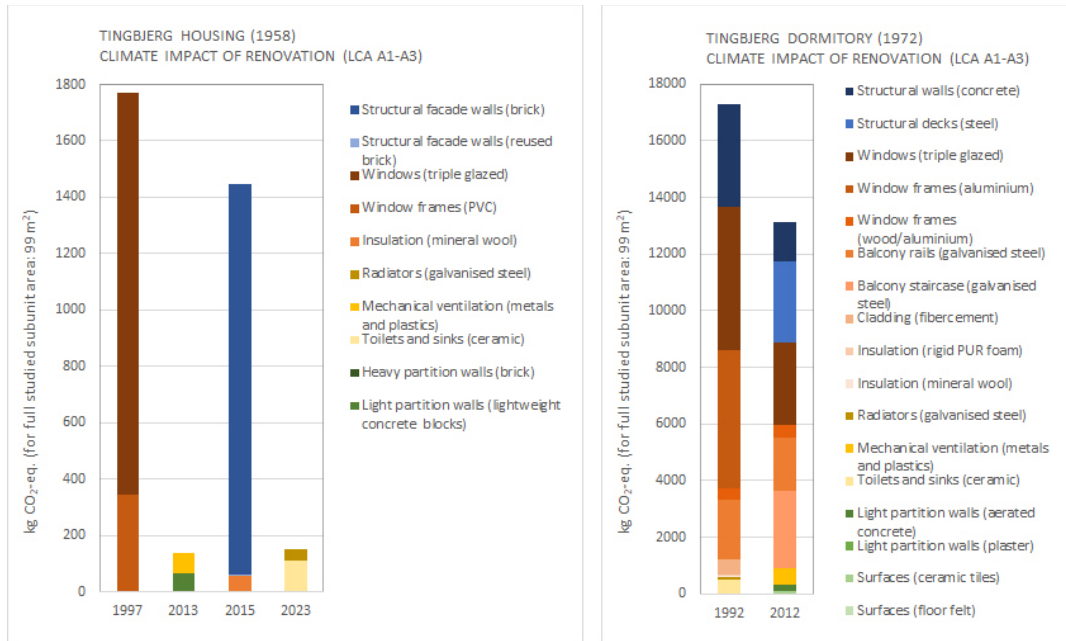


Figure 3: Tingbjerg Family Housing and Tingbjerg Dormitory: Metabolisms (in kg CO₂-eq). Source: (1st author 2024)

4.4. CO₂ and lifespans across cases

The assessment of the case metabolisms (kg CO₂-eq./m²/year) had the following results: Søkvæsthuset’s metabolism (0,43 kg) was 11 times lower than the Dormitory’s (4,83 kg), whereas only 1,25 times lower than the Family Housing (0,54 kg) (see Figure 1 in 4.0). If viewed by m³ material per m²/year, the order comes out differently: the Family Housing (0,0013 m³), Søkvæsthuset (0,0017 m³), and the Dormitory (0,0019 m³). This shows that the materials used in the metabolism of Søkvæsthuset are generally low-CO₂ compared to materials used in Tingbjerg Dormitory that used high-CO₂-materials like metals and glass (Figure 4, left side). With the marginal metabolic difference between the control case and Søkvæsthuset, the differences in locations, weathering conditions, design quality levels, maintenance/repair cycles, and programmes did therefore not challenge the robustness of the results.

The sequence of change of building layers differed from both Duffy and Brand’s models in the three cases. Brand’s change categories did not correlate with any of the cases but came closest to that of Tingbjerg Dormitory, while Duffy’s model matched Søkvæsthuset’s (Figure 4, right side). An overall trend from the oldest to the newest case was the increasing metabolism and shortening of lifespans of the Skin/Shell (Figure 4, right side). In Søkvæsthuset, the façade was not renovated/adapted except for the addition of secondary glazing where openable single glazed windows in wood frames were added on the inside in 1985 (12 % of façade area). Windows were replaced in the Tingbjerg Family Housing in 1997 to higher energy-performance windows (24% of the long façade areas), and most of the façade including walls/windows was replaced in the Tingbjerg Dormitory in 1992 (64% of the façade area) and in 2012 (38% of the façade area), both as energy-upgrades and for outwards expansions (see Figure 1 under 4.0). From almost no changes and the longest lifespan in Søkvæsthuset, the Skin had the shortest lifespan and highest metabolism in the two other cases. In Søkvæsthuset, the Structure had the second longest lifespan while the second shortest in the Dormitory. The Space Plan changed most frequently in Søkvæsthuset.

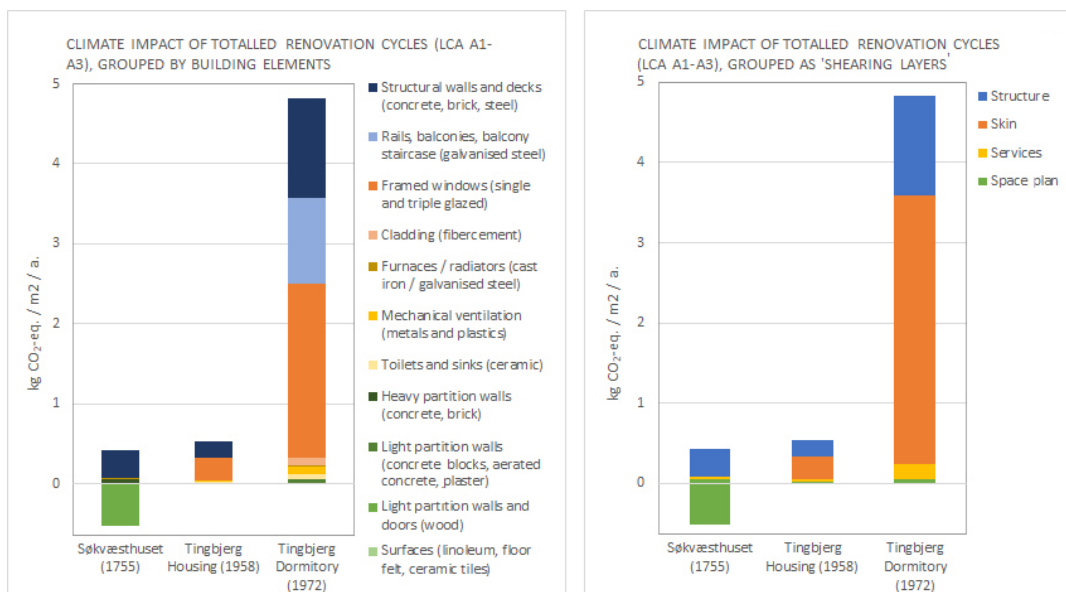


Figure 4: Metabolisms of all cases by components and by layers (in kg CO₂-eq/m²/year). Source: (1st author 2024)

4.5. Limitations and uncertainties

- Furnishing with drawers, cupboards, tables, and shelves were not included in the calculation because of varying data quality on materials, material thicknesses, and dimensions.
- All wood (e.g. in Fig. 4) was left out of the calculation for all cases since the lifespans of wood and traditions of reuse diverge greatly between preindustrial and industrialised building cultures (Bak-Andersen 2020).
- The addition of an elevator in Søkvæsthuset in 2003 improved the accessibility of the building compared to the other two cases, which did not have elevators. Because of the different levels of accessibility between the cases, the elevator itself is not included in the calculations, only its changes to the structure and surfaces.
- Embedded units are samples and thus not 100% representative of each case which could impact the results.

5.0 ANALYSIS AND DISCUSSION

Brand's and Duffy's models of lifespan categories differ in what is a crucial point for this study. In Tingbjerg Dormitory, the separate Skin- and Structure-layers gave rise to a high metabolism, whereas Søkvæsthuset's singular Shell-layer – a solid fired brick wall – had a remarkably long lifespan and a low metabolism over 250+ years. Tingbjerg Family Housing's Shell is somewhat in-between the two paradigms: There are no multi-layered light façade-panels, but the layering of its brick cavity wall enabled post-insulation of the gable facades with mineral wool in the cavity. The differences between the three cases indicate an overall shift in the building culture's view of the façade – from a singular Shell to Skin+Structure-layers. While not a surprising finding in itself, the different wall types' frequencies of change showed that lifespans relate less to fixed groupings of building components as in Duffy and Brand's models, but rather to the architectural character of building components, their respective capacity for alteration, and the architectural/structural relationship between components. In the following, this is explored further in a comparison of wall types across the cases using Moneo's relationship of structural logic and architectural principle as an analytical lens.

In Søkvæsthuset's nearly 1-meter-thick symmetrically and rhythmically ordered façade walls, the architectural principle of *lesenes* that divide the façade into segments, each with a row of windows, reveals the structural logic of walls that thicken to carry more loads. The half meter thick inner structural walls, also in brick, are from both architectural and structural perspectives secondary to the façade walls. Less expressive of an architectural order and structural logic, door openings have been moved, and the built-in shafts resized over time. However, the inner structural walls organise the overall spatial layout, such as room depths, circulation, and distribution of shafts (which originally constrained room sizes in relation to heating sources). The architecturally and structurally tertiary original wood plank partition walls of 12 cm in thickness spanned between the principal and secondary walls and required the least amount of effort to change and move over time, which also made them the most frequently changing wall type. The significant architectural differences between the three wall types – from heavy mineral to light biogenic materials and with wall thickness ratios approximating 1:2:8 – coincide with their respective levels of change. The lightest and most easily changeable wall type was physically altered the most, where the heavier walls resisted physical alteration in meeting shifting needs. For example, the incredibly “stubborn” façade wall – which would probably seem like a nightmare in the view of most Circular Economy design frameworks like Design for Disassembly (Guldager and Sommer 2018) – has accommodated an orphanage, a hospital, military barracks, an academy, offices, a hotel and more, with next to no physical changes. From the perspective of adaptability and design-for-disassembly, this shows that all three wall types do not need to be physically altered to the same extents to meet shifting user needs, to adjust to evolving indoor climate comfort standards, and to adapt to new uses. There is a “*hierarchy of alterability*” where the structural logic and architectural principle intercept and facilitate different frequencies of change for each building component type over time. This hierarchy of alterability is in Søkvæsthuset experientially emphasised through form (thick walls and niches vs. thin, less sculptural partition walls), structure (thicker walls carry more loads), and materials (heavy mineral materials which feel cold to touch vs. light and alterable biogenic materials which feel warmer).

Tingbjerg Family Housing's walls have a similar hierarchy of alterability which coincides with the frequencies of change for each component type. The structure is a traditional brick cavity wall, in which Skin and Structure are one and the same. The 36 cm thick structural cavity walls have a monolithic and massive appearance, with windows and door openings as punctuations on the otherwise flush surface of the body of the building. The 18 cm thick inner structural walls are of bricks and have remained largely unaltered with the exception of door holes and openings around built-in wardrobes, whereas the 8 cm thick aerated concrete walls and wood cabinet walls were of lighter materials and altered the most with the expansion of kitchens into the corridor/entry. The ratio between the three wall types approximates 1:2:4, which is roughly also the ratio of change and of structural/architectural importance.

In the hierarchy among wall types in Tingbjerg Dormitory, the relationship between architectural principle and structural logic is not as legible as in the other two cases. The Structure's 15 cm thick walls of reinforced concrete are perpendicular to the façade and slightly *thinner* than the non-structural façade walls. At the same time, the structural in-situ walls are spatially unarticulated; hidden from the outside and plastered over from the inside. They were altered where dorm rooms were fused as well as around staircases and common kitchens where decks were expanded. The 19 cm thick non-structural façade walls are composed of four different façade wall build-ups, each with their own intricate layering of materials. While parts of the structural façade look structural, and were only partially re-clad, the parts looking decidedly non-structural were replaced two times in just 40 years. The 8 cm thick partition walls in aerated concrete bricks are only slightly thinner than the structural walls and were altered to about the same degree as the structural walls. The difference between the depth of the structural walls (experienced through door openings), the non-structural façade walls (seen through windows), and the light partition walls (experienced through door openings) is minimal – the ratio of the three wall types approximates 5:3:8 (structure : façade : partition). The order of the most frequently changing component types are the opposite of the order in the

two other cases: the building envelope changed the most, then structural inner walls, and least the partition walls. Thus, in the absence of a hierarchy of alterability, the Dormitory continually met user needs through physical alterations of some of the more laborious, costly, and environmentally taxing elements, which drove up its overall material use and metabolism.

The paper proposes a “*hierarchy of alterability*” to differentiate the level of change among building components and parts, and, at the same time, meet future uses and needs. The hierarchy of alterability is present in both of the preindustrial cases, Søkvæsthuset and Tingbjerg Family Housing: The least architecturally and structurally significant building component types have changed the most and vice versa. The presence of this hierarchy lowered the overall material consumption and the environmental impacts compared to Tingbjerg Dormitory where a hierarchy of alterability was lacking and obscured. Where Duffy/Brand’s models define frequencies of change by families of building parts e.g. Skin, Space Plan or Structure that act independently from each other, this paper suggests a different explanation of change, which appeared as a more consistent pattern across the cases. Degrees of change depend on the relationship between components and their respective degree of alterability. In other words, the alterability of the individual component is contextually dependent on the alterability of other components, cutting across Duffy/Brand’s building layers. The degree of alterability is, in part, defined by how present the relationship between architectural principle and structural logic is – from structural and architectural significant to non-structural and architecturally subservient. And in part by how well components are architecturally differentiated to express and experientially emphasise their respective margins for alteration so that generations of users and building owners can recognise, feel, and value this hierarchy of alterability across building cultures.

Beyond Duffy and Brand’s widely used models of change (e.g. in Le Den et al. 2020; Danish Government’s Climate Partnerships 2021), the hierarchy of alterability challenges influential design frameworks of the Circular Economy paradigm on how to understand and facilitate change in buildings to lower their environmental impact and evolve with changing needs. One such example is Design-for-Disassembly where all components should be designed for non-wasteful/non-destructive/easy disassembly to give future users a maximum of freedom to physically change buildings to meet their needs (Lysgaard Vind 2024; Guldager & Summer 2018; Crowther 2005). However, this paper found that the levels of adaption to new uses did not require all building components and parts to be physically alterable to the same extents. Rather, the case studies showed that when a building did not clearly differentiate the alterability of components, the consumption of building materials and the environmental impacts were significantly higher. When the margins of freedom of physical alteration were differentiated across components and building parts in a clear hierarchy of alterability, adaptation to new uses and needs was possible with a lowered consumption of materials. Within the hierarchy of alterability, frameworks like Design for Disassembly could be applied selectively to those building parts which are intended to have the most frequent physical alterations. Thus, the paper proposes the hierarchy of alterability as a novel design framework for the design of new buildings, or for the transformation of existing ones, to break with an excessive consumption of building materials in renovations and adaptations cycles and thereby lower the metabolism in a 200+years perspective.

CONCLUSION

The paper quantitatively analysed the environmental impacts from the material use – the “metabolism” – in the use-stage of three public multistorey housing buildings in Copenhagen from different building cultures. The three cases were the premodern, preindustrial Søkvæsthuset (1755), the fully industrialised Tingbjerg Dormitory (1972), and the preindustrial Tingbjerg Family Housing (1958) as a control case right before industrialised construction methods became prevalent. Environmental impacts were calculated of all added building materials’ LCA A1-A3 phases with today’s CO₂-eq factors, using each component’s actual, observed lifespan. It found that the preindustrial, premodern case Søkvæsthuset, despite its many adaptive reuses, had a metabolism that was 11 times lower than that of the fully industrially constructed Tingbjerg Dormitory, and slightly lower than that of the control case. With this data and through drawn mappings of spatial changes across all cases, the relationships between architectural characteristics and patterns of change were qualitatively interpreted with several theoretical models of building change: Duffy and Brand’s models of layers of change in buildings and Moneo’s theoretical proposition of an alliance between structural logic and architectural principle. The paper found that differences in architectural characteristics from different building cultures greatly influenced the frequencies of change and the metabolism results. Neither Duffy’s nor Brand’s models of change predicted the frequencies of change in the three cases, while Moneo’s hierarchy of structural/architectural significance of building components emerged as a better explanation of how the cases changed. A particular design principle of low metabolism was identified: to differentiate the dependency of structural logic on architectural principles in a “*hierarchy of alterability*” that is experientially emphasised through form, structure and materials. By design, some components adapt to new uses and needs through ease of physical alteration and others adapt while actively resisting physical alteration.

More broadly, these results show the potential value of empirically grounded architectural design knowledge in the context of reducing the environmental impact and material consumption. Specifically, the paper challenged Brand’s model of change in buildings where separable building layers act and change independently and proposed instead that change follows the relationship and hierarchy of alterability between building components. This hierarchy also challenged Design-for-Disassembly as a blanket sustainability design strategy and rather proposed a more selective use of it. The hierarchy could be used for different purposes: To lower the operations costs or environmental impacts by distributing costly or reuseable/low-carbon materials according to where changes are most frequent. Or, for architects to prioritise time, budgets, and design efforts by focusing on the hierarchy of alterability itself and the longest lasting building parts where architectural quality matters most in the long run. There is a need for further research into the relationships between hierarchies of alterability and changing user needs over time, as well as to study more factors influencing patterns of change. There is also a need to study patterns of change and hierarchies of alterability among more cases and more building parts e.g. installations and interiors.

ACKNOWLEDGEMENTS

The article is a part of the 1st author's industrial Ph.D.-project, supervised by the co-authors and the company supervisors at Rønnow Leth & Gori A/S which together with Innovation Fund Denmark funds the project (≈50/50).

REFERENCES

- Aagaard, Niels-Jørgen, Erik Brandt, Søren Aggerholm, and Kim Haugbølle. 2013. *Lifespans of Building Parts for LCA and LCC*. (Freely translated from Danish). SBI forlag.
- Aksamija, Ajla. 2021. *Research Methods for the Architectural Profession*. New York: Routledge.
- Alberti, Leon Battista. 1991. *On the Art of Building in Ten Books*. MIT Press.
- Andersen, Nicolai Bo. 2015. 'Sustainable Transformation: Building Heritage, Transformation and Sustainability in a Holistic Perspective.' Thesis presented at the PHN Conference. Copenhagen, Denmark. <http://passivhus.dk/7phn/>. n.d.
- Andersen, Rune. 2023. *Informing Architectural Design Processes in a Circular Economy - the Quantification of Circular Construction*. Technical University of Denmark.
- Azari, Rahman, and Narjes Abbasabadi. 2018. 'Embodied Energy of Buildings: A Review of Data, Methods, Challenges, and Research Trends'. *Energy and Buildings* 168 (June): 225–235.
- Bak-Andersen, Søren. 2020. *Old Knowledge for New-Builds: Traditional Building Materials and Crafts in Contemporary Building*. (Freely translated from Danish). Copenhagen: KADK.
- Bowyer, E, V Stephenson, W Hawkins, and I Tim. 2022. 'New Angles for Adaptive Building Reuse Research'. *IOP Conference Series: Earth and Environmental Science* 1078 (September)
- Brand, Stewart. 1995. *How Buildings Learn : What Happens after They're Built*. New York: Penguin.
- Brunner, Paul H., and Helmut Rechberger. 2017. *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*. CRC Press, Taylor & Francis Group.
- CINARK. 2019. *The Material Pyramid for Constructions*. (Freely translated from Danish). Copenhagen: KADK.
- Crowther, Philip. 2005. 'Design for Disassembly - Themes and Principles'. *Environment Design Guide*, 1–7.
- Duffy, Francis. 1990. 'Measuring Building Performance'. *Facilities (Bradford, W. Yorkshire, England)* 8 (5): 17–20.
- Ejstrup, Henriette. 2019. *Tectonic of Insulation: What's in the Past for Future Construction* (Freely translated from Danish). Copenhagen: KADK.
- Eybye, Birgitte Tanderup. 2016. *Sustainability in Danish Preindustrial Building Practice and Its Current Relevance: Assessed Through Six Case Study Dwellings* (Freely translated from Danish). Aarhus: Arkitektkolens Forlag.
- Flyvbjerg, Bent. 2006. 'Five Misunderstandings about Case-Study Research'. *Qual. Inc.* 2006 12 (2): 219–245.
- Geraedts, Rob. 2016. 'FLEX 4.0, A Practical Instrument to Assess the Adaptive Capacity of Buildings'. *Energy Procedia* 96 (November):568–579.
- Guldager, Kasper, and John Sommer. 2018. *Building a Circular Future*. 3rd ed. Vol. 248. Denmark: GXN.
- Hassler, Uta. 2020. *Building and Preserving: An Introduction* (Freely translated from German). München: Hirmer.
- King, Gary, Robert O. Keohane, and Sidney Verba. 2021. *Designing Social Inquiry : Scientific Inference in Qualitative Research*. New ed. Princeton: Princeton University Press.
- Le Den, Xavier, Samy Porteron, Andrea Herbst, Matthias Rehfeldt, Christine Collin, Matthias Pfaff, Lise Sorensen, and Martin Garbers. 2020. *The Decarbonisation Benefits of Sectoral Circular Economy Actions*. Rambøll
- Loonen, R. C. G. M., M. Trčka, D. Cóstola, and J. L. M. Hensen. 2013. 'Climate Adaptive Building Shells: State-of-the-Art and Future Challenges'. *Renewable and Sustainable Energy Reviews* 25 (C): 483–493.
- Lysgaard Vind, Ditte, ed. 2024. *Building A Circular Future- Insights from Interdisciplinary Reseach*. Realdania.
- Moneo, Rafael. 2017. *La vida de los edificios: La mezquita de Córdoba, la lonja de Sevilla y un carmen en Granada*. 1st ed. Barcelona: Acanalado.
- Pomponi, Francesco, and Alice Moncaster. 2016. 'Embodied Carbon Mitigation and Reduction in the Built Environment - What Does the Evidence Say?' *Journal of Environmental Management* 181 (October): 687–700.
- Rasmussen, Freja Nygaard, and Harpa Birgisdottir. 2015. *LCA of Major Building Renovations: Environmental Impacts Assessed via Case Studies*. (Freely translated from Danish). Copenhagen: SBI forlag.
- Regeringens Klimapartnerskaber. 2021. 'Advice to the Government from the Climate Partnership of the Construction Sector' (freely translated from Danish). <https://kefm.dk/klima/regeringens-klimapartnerskaber-og-groent-erhvervsforum>. n.d.
- Seifi, Shahla. 2021. 'Introducing Resource Depletion'. In *The World's Future Crisis: Extractive Resources Depletion*, edited by Shahla Seifi. *Approaches to Global Sustainability, Markets, and Governance*. SGP: Springer Nature.
- Smith, Neil. 1987. 'Gentrification and the Rent Gap'. *Annals of the Association. of American Geographers* 77 (3): 462–465.
- Stigler, George. 1972. 'The Adoption of the Marginal Utility Theory'. *New England Journal of Economics and Business* 11 (4)
- Till, Jeremy, and Tatjana Schneider. 2005. 'Flexible Housing: The Means to the End'. *Architectural Research Quarterly* 9 (September): 287–296.
- Vitruvius. 1960. *Vitruvius: The Ten Books on Architecture*. Translated by Morris Morgan. NY: Dover Publications.
- Wilkinson, Sara. 2018. 'Rating Tools, Resilience And Sustainable Change Of Use Adaptations.' In *Building Resilience In Urban Settlements Through Sustainable Change Of Use*, edited by Hilde Remøy and Sara Wilkinson. Wiley-Blackwell.
- Yin, Robert K. 2018. *Case Study Research and Applications: Design and Methods*. 6th edition. Thousand Oaks, California: SAGE Publications, Inc.
- Zimmermann, Regitze Kjær, Camilla Marlene Ernst Andersen, Kai Kanafani, and Harpa Birgisdottir. 2020. *Environmental Impact from 60 Buildings: Possible Reference Values for Building LCA (Freely translated from Danish)*. Report. Kgs. Lyngby: Polyteknisk Boghandel og Forlag.