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A DESIGN FRAMEWORK FOR TIMBER BUILDING SYSTEMS

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ABSTRACT: The paper proposes a design framework as a means to invigorate considerations of ecological, social and economic sustainability in the development of industrialized timber building. The framework describes principles, participants, processes and tools. Central requirements are (1) open innovation, (2) user / inhabitant participation and influence, (3) simplified quality control and production of code compliant design documentation, (4) adaptability, (5) integration of self-build, (6) preparedness for material hybridity, and finally (7) circularity of materials, components and buildings. To test the relevance and design implications of these imperatives, a diagrammatic study of a four storey block of flats was carried out. The example shows that a high degree of adaptability can be achieved while maintaining openness for integration of a wide variety of light-weight timber structures. In turn, this provides options for the size and weight of elements and components. They can be adapted to different strategies for off-site production and on-site assembly. The design framework will impact the patterns of information and influence in design and construction processes. Sharing of solutions and experience will speed up the innovation needed to meet the sustainability goals of the building industry.

KEYWORDS: Timber, building systems, circular building, industrialized building

1 BACKGROUND

A holistic understanding of future building systems is vital to meet the UN sustainability goals. Unfortunately, architect-designed building systems tend to be beautiful but with limited spread. [1], [2]. One reason is that they focus on detailed design of key components instead of defining the boundaries and rules of the building system itself.

Modern building systems face a series of new challenges. For instance (A) the sorting, evaluation, and reuse of parts from used (demolished) structures must be facilitated in the system. (B) The components and subsystems or "layers" [3] of future buildings must be designed for variable cycles of construction, maintenance, exchange, disassembly and reassembly. And (C) user participation and self-build options should be integregrated, as they may affect the durability, costs and availability of housing.

N. John Habraken´s work on inhabitant participation in the early 1960s, and Norwegian examples of studies of building systems in the 1970s [4] have gained new relevance reflected in recent open building initiatives [5].

Against this backdrop we propose a design framework for timber building systems supporting open innovation. We define key requirements common to all building systems, and test their impact through a diagrammatic exploration of a system for lightweight, wooden buildings.

As example we have chosen a four storey timber block of flats. The advantages of low production emissions and sustained carbon storage in timber buildings are well documented [6]. Low-rise buildings in high-density urban patterns represent the biggest potential for increased use of timber. Lenient codes, especially up to 4 stories, make this building category a low-hanging fruit for innovators. Challenges regarding the future availability and cost of sustainably harvested timber also favour the efficient, light-frame structures suited for low-rise buildings.

2 A DESIGN FRAMEWORK FOR TIMBER BUILDING SYSTEMS

A design framework for building systems is the overarching structure that definine the key properties of the subsystems and components constituting a finished building. This comprise of the cyclic processes of design, production, use, disassembly, reuse, and the organizational structure of maintaining the system itself through open innovation. We propose the following key properties as useful for defining an effective design framework for building systems.

2.1 OPEN INNOVATION

To make the design framework expand and evolve according to the needs of users and industries we propose applying an open innovation process. Ollila & Yström (2016) [7] outline how a focus on engaging the participants of a community is central in open innovation projects. Because of this we suggest a focus on development of open-source design resources shared

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under open licences such as creative commons [8] Open-source development is an ongoing process dependent on a system that is both used and expanded through the contributions of a community. In the case of a building design framework, we will emphasize the need to simplify use through making the design resources available as easy too use tools, such as integrations in common CAD applications or in emerging web based systems. The latter is crucial since online systems can better enable participants to access, discuss and add contributions to the system.

2.2 USER / INHABITANT CENTERED

Recent research (Groba 2021) [9] shows that user involvement may clarify architectural strategies that increase the understanding and appreciation and thus the durability of timber buildings. This also applies to the programming of private and common areas. The building design framework must define roles, interaction and output for the design process. It also needs to provide design resources such as tools and guidelines that are adapted to the requirements both of the future inhabitants and the participating architects, engineers and builders. All aspects can be supported by applying human centered desing processes such as ISO 9241-210:2019 [10]. The upper part of Figure 1, shows the outline of the design framework and its development through user-centered and interdisciplinary design processes.

2.3 SIMPLIFIED QUALITY CONTROL AND CLASSIFICATION

The design framework must give immediate access to qualified competence and certified products and solutions. Environmental, planning and building legislation, together with building codes, standards, and certifications constitute a regulatory control and information system for the building industry. It aims to secure democratic processes and reduce risk of damage to people, property or environment. However, its complexity has grown into an obstacle for overview and participation by users of buildings. In Figure 1, the control and information system is visualized as a table of information that has to be filled in to initiate and finalize each step in a building process. At the end of a building´s lifecycle, the system should enable tracing of all subsystem and component properties that are relevant for reuse. This is presently far from being implemented.

The design framework must contribute to information systems that support cicularity. It will harvest information from each production step for relevant materials, products and buildings, and integrate it in user / inhabitant -centered design processes. The overview in Figure 1 both of the regulatory system and the production of materials and construction of buildings must inform the processes and tools of the design framework.

In Norway, SINTEF / Byggforsk´s Building Research Design Guides [11] provide comprehensive and updated input to a design framwork for timber building systems. They are supplemented by SINTEF Technical Approval (TG) of building systems, modules and components, which is coordinated with European standards, marks and certification systems. Other product databases together with Environmental Product Declarations (EPDs) and building classification systems (e.g. BREEAM-NOR) offer important additional information. For Technical Approvals, not all data are open source, and several databases require subscription and payment for access. A systematic overview is required to optimize data access and exchange between the design framework and other sources. Sharing of information is essential. Open catalogues of design solutions may be an integrated part of the design framework, or maintained by the associated architects, consultants and builders. Combinations may also be developed.

Norwegian and EU codes and directives for qualification of architects and other design and construction professionals must be integrated in the recruitment of participants in the design framework.

2.4 ADAPTABILITY

The building system must be adaptable to local conditions. In Norway, this means a variety of climate zones and prospects of a warmer, wetter and wilder future. Topography and biodiversity, together with building heritage and urban patterns, also demand adaptabilty of building systems. A potential for density is necessary to limit land use and emissons related to transport. Many of these properties are embedded in timber building traditions, but they must be rediscovered and reinterpreted.

User needs will change according to the inhabitants´ life situation and with changes of residents. Adaptability of the dwellings is therefore essential. The spaces should be general, and the internal walls easily movable to facilitate refurbishment. During a buildings´s lifecycle, integration and separation of dwellings may vary, and this must be part of the system design. Expandability of dwellings is associated with detached, semidetached and terraced housing, but should also be considered in low-rise, multistory buildings.

Adaptability impacts the choice of structural systems, their span widths and the solutions for noise and fire protection. Moving or exchanging parts requires easy access to structurally and functionally independent subsystems and components. This affects the design of joints and details. In turn, these choices have implications for the readability of the building system and its architectural character and qualities. Clarification of these implications must be integrated in the design framework.

2.5 INTEGRATION OF SELF-BUILD

A user-centered design process based on open innovation will strengthen the inhabitants´ knowledge about the

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buildings. It will prepare active participation in changes and maintenance. It will counteract the present loss of contact with construction, and also of mastering and appreciation of practical skills. Low-cost laser-based and magnetic instruments for measurement and detection improve precision in traditional do-it-yourself work. Better screws and multifunctional, loadable electric tools also push the limits for self-build. By integrating builders and craftsmen in the design processs, new divisions of labour and responsibility may be developed without sacrificing quality.

The adaption described above is not only dependent on access to and exchangeability of parts, but also on the size and weight of the components. When it comes to prefabrication of light-weight, multistory timber buildings in Norway, there is presently (spring 2023) a trend towards larger floor and façade elements (8 meters long and 3 storeys high), which means speedier montage [12]. At the same time, robots are being developed for operations within the heights and spatial constraints typical of multistory timber housing (Tekna 2018) [13]. This may represent an area of innovation where manual construction assisted by lifting tables and hoists gradually may include robots (Figure.1). It will also be a robust production environment which may backtrack to traditional methods if scarcity of money or high-tech components should occur. Small structural members and building elements expand the possibilities of self-build also of multistory buildings. They may be supplied by a large number of diverse producers. Small components reduce the dependency on transport by ship, train or heavy trucks, and montage by tower cranes. This also contributes to economic and logistic robustness. Division into small (demountable) components does not exclude larger assemblies to rationalize the initial on-site construction.

2.6 PREPARED FOR MATERIAL HYBRIDITY

We have recently experienced that pandemics, wars and blocking of shipping routes may disrupt supply chains. Wood-based building systems must therefore be prepared to include other materials. For timber, beetle attacks and climate-induced droughts, storms and wildfires may be more acute threats. They remind us that optimal use of timber in many buildings should be the aim, rather than maximized use of the same resources in fewer projects.

The distribution of emissions among the different building subsystems is important when combinations of materials are considered. Column and beam structures account for a small part of material-related emissions compared to floors and external walls. Thus converting to a steel skeleton will have minor effects. The slimmer steel columns and beams are easier to integrate in wall and floor constructions. Steel joints and details may be better suited for future disassembly and reuse than screws or wood-only connections (Vandkunsten Open source 2021) [14]. To limit the emissions from weight-increasing tiles in the large floor areas, using clay instead of concrete may be beneficial.

2.7 DESIGNED FOR CIRCULARITY

The adaption of dwellings to the inhabitants should be facilitated by reusable components and materials. Circularity starts inside a dwelling and continues at the end of the building´s service life. For each component, the size, geometry, robustness and integrity of form and function must be balanced against adaptability to new needs and preferences, both of the existing habitants and and future constructors and users of the next building. The next building should be designed to utilize a variety of materials inherited from donors in good shape.

In an environmental perspective, the slowing down of material cycles in buildings contribute to increased carbon storage. At the same time, climate change may impose threats to the long-term safety of building sites. Design for circularity also means preparedness for moving buildings instead of deserting or demolishing them.

3 EXPLORATION OF A SYSTEM EXAMPLE

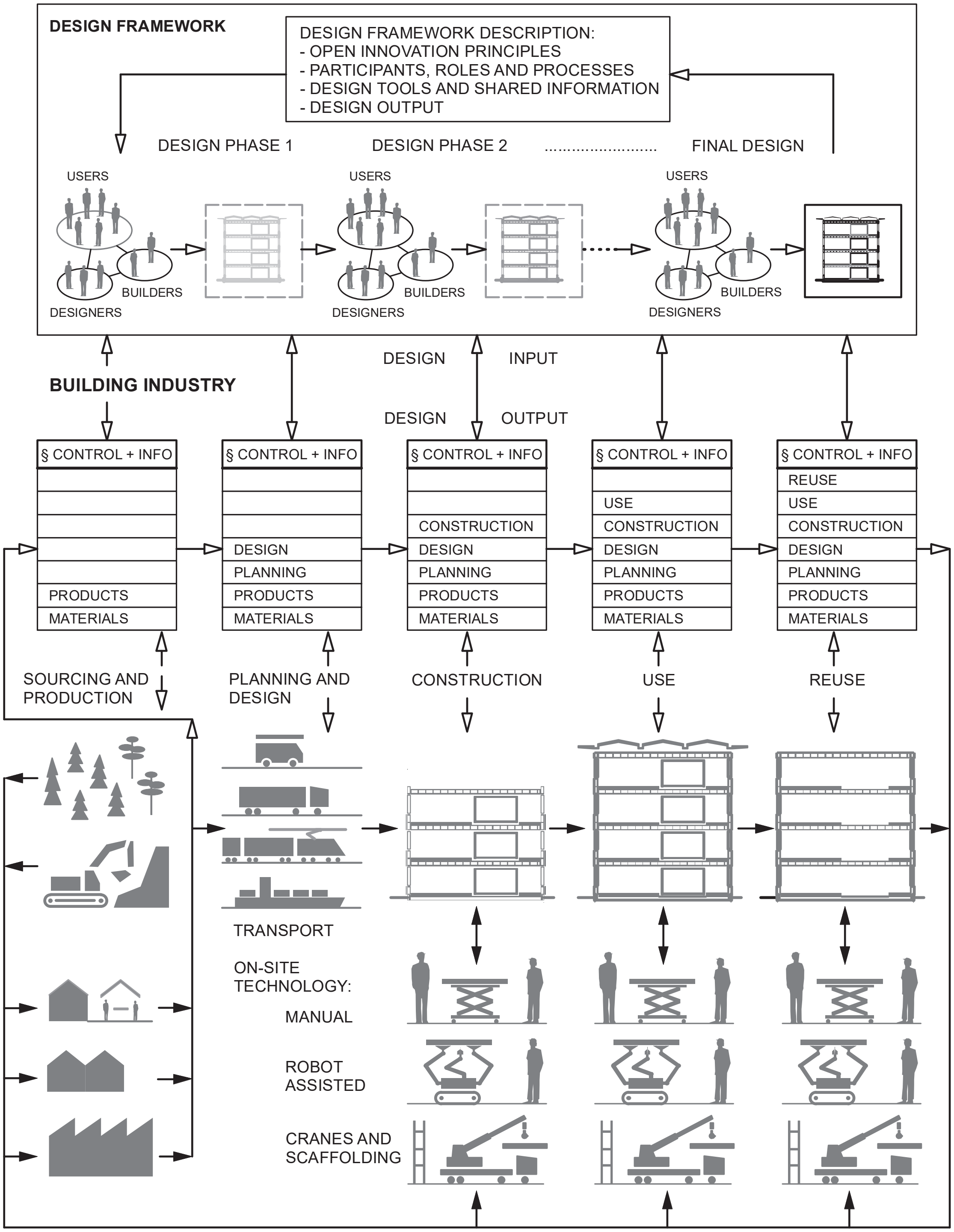
To test the relevance and design implications of the design framework, we have applied it on a project example. A four storey block of flats was chosen as a case. As emphasized above, this is a large building category where timber is well suited. Low emissions related to production of sustainably harvested timber materials is a framework condition for the study. Figure 2 and 3 give an overview of the system example explored below.

3.1 PROCESS AND PARTICIPATION

The purpose of a diagrammatic study is to facilitate an immediate and active user or inhabitant participation in the design of buildings. In Figure 1 it would be carried out in the first phase of design within the design framework. It focuses on the main functional and architectural properties while maintaining openness for a variety of choices regarding materials, structures and details. Simplified quality control and classification should be embedded in the components that are introduced and then repositioned and transformed during this initial design phase. As emphasized above, qualified architectural and technical advice must be defined as a part of the design framework.

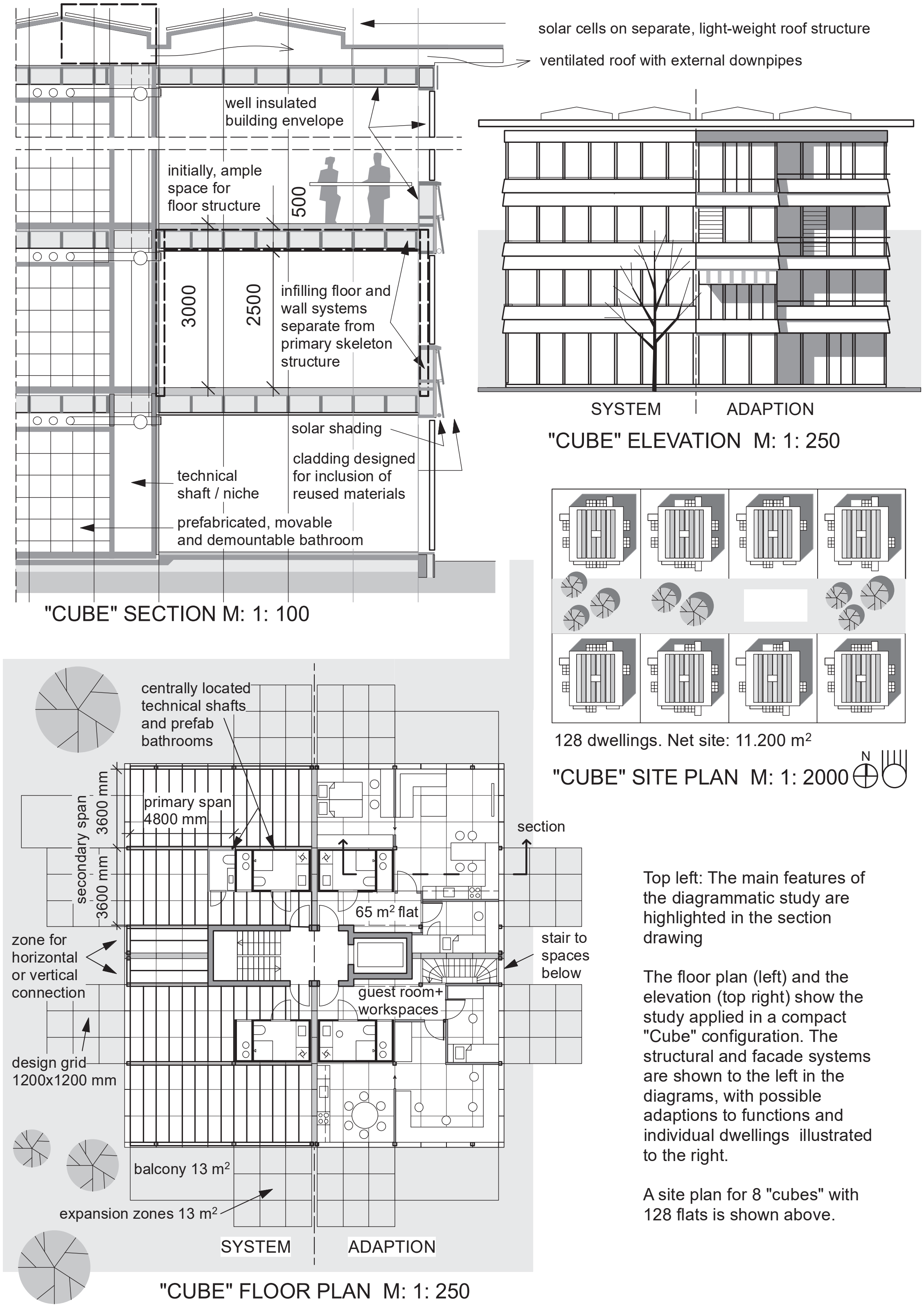
3.2 ADAPTABILITY TO CLIMATE, SITE AND URBAN PATTERNS

To ease the overview of the example, The authors have chosen to focus on a limited number of environmentally significant features that are shown in the upper diagrams in Figure 2.



TOP: The design framework and the processes it defines
MIDDLE: The regulatory control and information system
BOTTOM: The cycles of materials and components, and the associated transport systems and construction technologies.
Black arrowheads mark material and mechanical flows, systems and interactions.
White arrows mark interaction and influence based on flows of information.

Figure 1: *Overview of design framework and building industry.*


"CUBE" SECTION M: 1: 100

"CUBE" ELEVATION M: 1: 250

"CUBE" SITE PLAN M: 1: 2000

"CUBE" FLOOR PLAN M: 1: 250

Top left: The main features of the diagrammatic study are highlighted in the section drawing

The floor plan (left) and the elevation (top right) show the study applied in a compact "Cube" configuration. The structural and facade systems are shown to the left in the diagrams, with possible adaptions to functions and individual dwellings illustrated to the right.

A site plan for 8 "cubes" with 128 flats is shown above.

Figure 2: *Main features of the diagrammatic study, and their integration in the "Cube" example*

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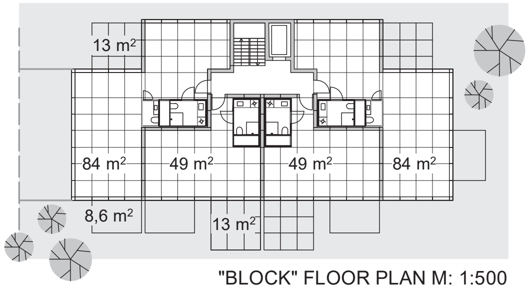
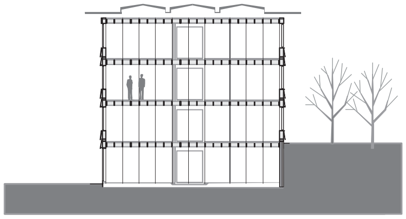
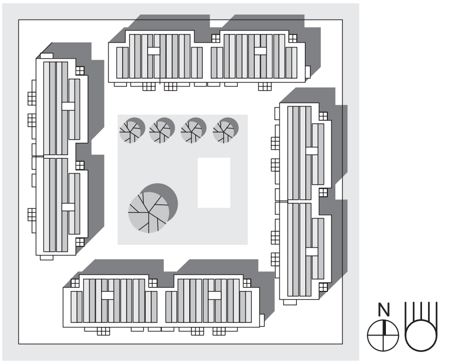


"BLOCK" FLOOR PLAN M: 1:500



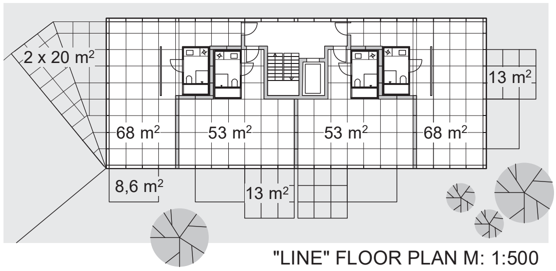
slope: ca.12° "BLOCK" SECTION M: 1:500



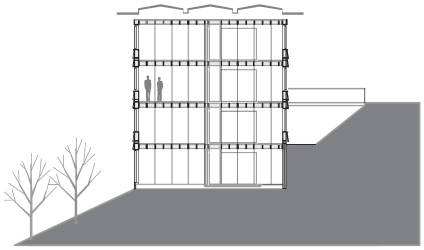
128 dwellings
Net site: 8.800 m^2 "BLOCK" SITE PLAN M: 1.2000

"BLOCK" : ADAPTABILITY TO LANDSCAPE AND URBAN PATTERN

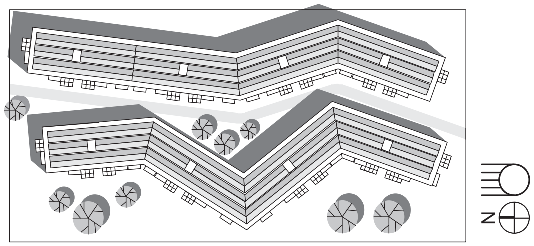
The solutions from the diagrammatic study applied in a slimmer volume (13.1 m), adaptable to moderate slopes and a typical urban block pattern.
The flexibility and expandability of the dwellings is maintained.



"LINE" FLOOR PLAN M: 1:500



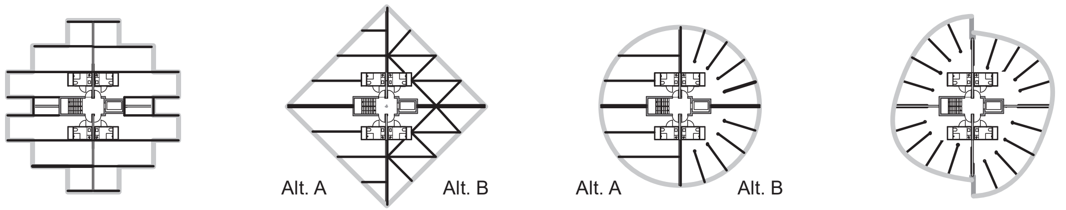
Slope: ca.20° "LINE" SECTION M: 1:500



128 dwellings
Net site: 8.900 m^2 "LINE" SITE PLAN M: 1.2000

"LINE" : ADAPTABILITY TO LANDSCAPE AND URBAN PATTERN

A still slimmer volume (11,0 m) for steeper sites and linear urban patterns.
Linking volumes with flexible geometries facilitate adaption to curved topographies.



GEOMETRIC ADAPTABILITY OF MAIN STRUCTURAL GRID (SAME FOOTPRINT AREA)

Figure 3: *Solutions developed in the diagrammatic study applied in the "Block" and "Line" examples.*
Bottom: Geometric adaptions of the "Cube" example

- A well insulated envelope that encloses a compact building volume. This limits heat loss to the exterior.

- A flat, ventilated (cold) roof with easily accessible gutters leading to external downpipes.

Ventilated roofs reduce melting and icing in near-zero temperatures, and also heating of the interior during summer. In a four storey building, a flat roof may serve as platform for solar cells with a signifcant area per apartment. It will be an important step towards lower energy demands. In Norway, 10 degree slope towards East and West is optimal on flat roofs. An elevated, lightweight roof structure will facilitate future maintenance or exchange of the photovoltaic panels. Significant roof overhangs will allow variation in the direction of the "solar waves" without affecting the overall character of the building. The overhangs will accentuate the separate roof. The folded geometry will improve ventilation and drainage. External downpipes eases local use of rainwater in landscaping, combined with measures for delayed stormwater runoff. There are also caveats linked to flat, ventilated roofs in arctic climate, but this is an opportunity for rethinking.

- The basic components can be applied in buildings with varying depth and orientation, adaptable to different topographies and urban patterns.

Figure 2 shows the starting point of the diagrammatic system study - called "Cube". As higher user involvement and lower costs are intended, the initial floor plan is dimensioned for four two-bedroom flats. They are adequate entry-level dwellings of 65 m2, served by a compact, central stair and elevator core. The total building however, is about 17,5 x 17,5 m, which demands a relatively level site. The four-sided orientation, which is optimal for views and daylight, puts limits to the arrangement of groups of such buildings. The "Cube" siteplan in Fig. 2 shows rows of separate, low-rise apartment buildings sharing a common, inner green belt.

In Figure 3, the upper diagrams show the "Block" alternative where the four combined apartments are rearranged within a slimmer (13,1 m) and two-sided building. This can be adapted to slightly steeper slopes (12%), and to a traditional urban block pattern, which is shown in the "Block" section and siteplan.

The middle diagrams of Fig.3 show the "Line" alternative, which is a still slimmer solution (11,0 m), adaptable to slopes of 20% or more. Such topographies demand a linear urban pattern, which should also be able to follow varying contours of hillsides. This is accommodated by introducing linking volumes with a flexible geometry.

A common requirement for all building types and urban patterns should be a capacity for high density. The site plans of "Cube", "Block and "Line" vary between 11,4 and 14,5 dwellings per 1000 m2 of the rectangular net sites shown in Figures 2 and 3. These are urban levels in a Norwegian context. The similarities in density indicate that the tree building alternatives can be combined in a diverse urban "vocabulary" without losing density.

3.3 ADAPTABILITY TO INHABITANTS´ FUTURE NEEDS

The primary structural system of the diagrammatic study is a regular and modular skeleton system, which allows for large spaces free of columns and loadbearing walls. The stair and elevator shafts, together with the floors provide lateral stiffness. The free spans are limited to 4,8 m, which is sufficient for housing (Drexler 2020) [15]. It opens for use of a variety of materials and timber technologies. The small and light structural members will be managable in manual building, and transportable by small vehicles. They may also be supplied by a large number of producers.

The sizes and weights of the infilling floor and external wall elements are also limited to be adaptable to different assembly procedures. As shown in Figure 2, the typical wall elements are 1.2 m wide, and typically ca. 2.5 m tall, which allows inclusion of doors and windows with free openings demanded for universal access and secure escape routes. The floor elements have a maximum free span of 3,6 m, A spatial zone of 50 cm height is assigned to the floor construction. This is a conservative starting point, may be controversially so. It allows for a variety of sound-insulating layers above and ceilings below beams, that also may vary in design, size and stiffness. (Required airborne sound insulation between dwellings in Norway is $R'_w \geq 55$ dB, and impact sound insulation $L'_{n,w} \leq 53$ dB.) The gross storey height is initially set to 3.0 m, which represents an incentive for slimmer floors that will increase spaciousness and daylight in the dwellings. The secondary, infilling systems are placed between, and not on top of, or overlapping the structural members of the primary, loadbearing skeleton. This limits construction heights and depths. The components are easily accessible and demountable to facilitate maintenance, modification and reuse. The section and façade diagram in Figure 2 show horizontal and overlapping bands of façade cladding which create depth and shadows, while opening for use and reuse of many types of materials. They also ease inclusion of different kinds of solar shading. The horizontal cladding and protruding eaves contrast the vertical modules of the external walls, forming a basis for further architectural development.

The possibility of expanding the size of spaces or dwellings is referred to as elasticity in buildings systems. In the plan drawing in Figure 2, bordering zones of adjacent flats are prepared for connections horisontally or vertically. The idea of allowing expansion, also outside the initial envelope of multistory buildings, is more radical. It is however, a natural next step in building adaptable, first dwellings. The plan diagram in Figure 1 shows a series of expansion zones of 3,6 x 3,6 m, offering substantial, functional additions to the dwellings. They are based on the same structure and materials as the main volume, and will maintain views and daylight in the original spaces. Similar additions are prepared in the diagrams of "Block" and "Line" in Figure 3. Agreeing on the time and sequence of additions to different floors is a complex, but solvable issue. The initial building volumes of all alternatives are regular, which means that they will grow into complexity and hopefully, richness of expression. If such variety is carefully balanced in the intitial situation, expansions may be regarded as unwanted, or they may fill in gaps, resulting in bland regularity.

Rectangular structural grids are advantageous in accomodating varied floor plans and furnishing. They also ease alternative reuse of the infilling, secondary components. The design framework should however, not have inherent, geometric constraints, which have proven to be damaging to many building systems. Adaptability to different geometries is exemplified in the bottom diagram in Figure 3.

3.4 BATHROOM MODULES AS TECH CENTRALS IN APARTMENTS

The bathrooms contain the dwellings´most complex subsystems and components. Their design and production are subject to detailed, interdisciplinary coordination, regulation and control. Water damage is very expensive, and may induce health risks in the form of fungi. It is natural to expand the "technical core" to include ventilation and power supply. Service systems stand for a growing part of the emissions related to production of materials and components. Simplification and concentration may reduce emissions and at the same time free larger parts of the buildings of interference with the technical systems. Incorporating partially natural ventilation may play a role here.

The sound insulating layers that are required on top of timber floors (normally 100 mm or more) solve the problem of step-free access to bathrooms. The bathroom floors may substitute sound and fire insulation functions of the layers on top of timber floors. Bathrooms are typically produced as whole "plug-in" modules. This means that they are difficult to move, exchange or modify. An element-based design, both of bathrooms, technical niches and ventilation systems would ease the adaptability to changes in flat layout and available technology.

The bathroom unit shown in the "Cube" floor plan in Figure 2 is also used in the "Block" and "Line" alternatives. In the large, two-sided apartments in the "Block" solution, a separate toilet is added, linked to the technical core (also shown in Figure 2).

4 DISCUSSION AND CONCLUSION

Some architects regard building codes, standards, design guides and pre-accepted solutions as the place where innovative architecture goes to die. For the authors, this made it a good place to start. The search for a safe acoustic point of entry resulted in 50 cm thick floors, including a continous, double layered ceiling of gypsum boards. Fire concerns pointet towards columns and beams integrated in walls and floors, again hidden behind two layers of gypsum (fire resistance rating REI 60 in walls and floors between dwellings). Standard tables for structural capacity confirmed that with spans of 4,8 and 3,6 meters, timber could do the job alone, but slimmer steel profiles would ease the integration and protection of a skeleton structure in walls and floors.

Hiding the timber was not a wanted or final solution, but a choice of postponing its return to visibility until the implications for a detailed design (succeding the diagrammatic study) could be mapped. When structural timber enters interior spaces, it is usually upscaled to allow burning and charring while maintaining its loadbearing capacity until sprinkler systems or firefighters interfere. It may also need vibration damping in the form of elastomer pads or strips to prevent sound transfer between dwellings. Unlike concrete, appreciation of exposed timber does not get smaller when the the dimensions get bigger. Visible structures communicate how the building is constructed and how it can be used. They also frame the spaces and add interplay of materialities to the atmosphere of the interiors [9].

The principle of adding high quality timber to be sacrificed in the case of fire, could be substituted by a slimmer, hybrid solution that still conveyed the position and character of the structural system. For many inhabitants wood everywhere may be too much. Visibility is not the only way. A complete documentation will include 3D models of the different subsystems. They will enable Lidar-scanning smartphones to visualize the exact positions of columns and beams in a room.

With timber, sound and fire out of sight (until further notice), focus could be put on processes and principal solutions.

The systems overview (Figure.1) made clear some features and constraints that would support use of local resources and expertise and facilitate user involvement in adaption, and potentially in construction. Together with environmental parameters they were included in the design framework for the diagrammatic study.

The diagrammatic study was an exercise in modular stringency and extraction of a small number of standard parts. Having completed the initial "Cube" solution (Figure 1), developing the "Block" and "Line" variants proved to be surprisingly simple. Interestingly, the limited kit of parts forced compromises that (to the

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authors) appreared new and appealing. The "too big" but multifunctional and generously daylit corridor in the flanking aparments in the "Line" alternative (Figure 3) may not have appeared in a more fine grained system.

The diagrammatic study may form the basis for a pilot system that can be easily visualized in open source and web-based 3D software. The digital model will then be integrated in quick cycles of user-centered design development. As a process example this may respond to the call for speeding up the adaption of the building industry to environmental demands. Cheaper and better housing is a central aspect of the UN goal for sustainable cities and communities. By maintaining compliance with industry standards, the process may also ease the production of documentation required for agreements and construction.

This combination of new design organization and new digital tools may affect several industrial patterns. First and foremost, the presence and influence of the user / inhabitant will be stronger. It will affect when and how the architect communicate with the users and other members of the design team. The dependency on dominating CAD systems may be reduced. Instead, they will be expected to communicate with high frequency output from open innovation processes. Open source publication of architectural details may demand more and speedier technical approvals, which will also be expected to be competitively priced and openly documented. Complete and tracable building data is vital for circular flows of materials and products. The vision of open and accellerated innovation challenges the knowledge gaps that are part of the economic foundation of many businesses within the building industry. Their skill and strength are vital to take on the inherent responsibilities and risks of large projects. On the other hand, tendencies of dominance by acquisitions rather than competitive innovation may postpone vital transitions beyond critical points. This paper argues that processes of real participation in designing buildings with real adaptability and real reuse, are necessary to limit the environmental risks embedded in present industrial trends.

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