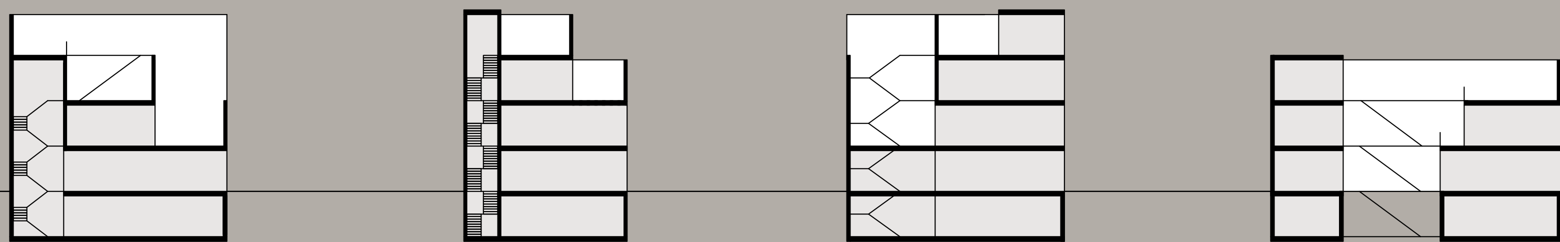
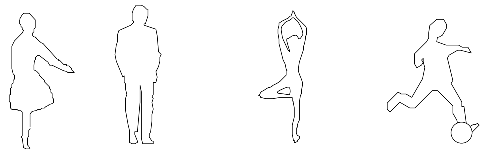
Jan Cremers Peter Bonfig David Offtermatt

Compact Courtyard Housing

A Guide to an Urban Building Type

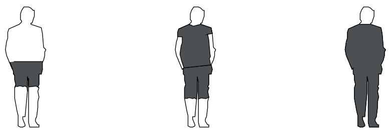


Triest



Leaning: 0.8 met
Standing light activity: 1.6 met
Standing medium activity: 2.0 met
Walking (2 km/h to 5 km/h): 1.9–3.4 met

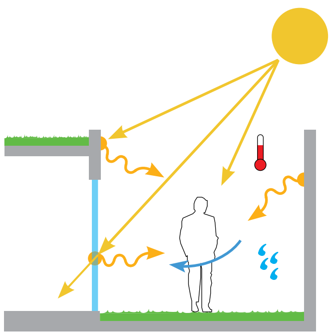
Fig. 126: Energy expenditure of different physical activities according to DIN EN 7730: 2005.



0.1 0.3 1.5

Insulation value of the clothing = clothing factor = clo
1 clo = 0.155 (m²K)/W [U-value: 6.45 W/(m²K)]

Fig. 127: Estimation of the insulation value of clothing combinations according to DIN EN 7730: 2005.



Interior Exterior / Courtyard

Fig. 128: Factors influencing the microclimate in a courtyard: short-wave and long-wave radiation, air movement, air humidity, air temperature as well as the person's motion and clothing.

Factors Influencing Thermal Outdoor Comfort

The extent to which people feel thermally comfortable indoors and outdoors depends on various influencing parameters, including air and radiation temperature, air humidity and air movement, but also on the type of clothing and degree of activity. While the conditions indoors are often easy to control and fluctuations are comparatively small, the seasons and the weather have a periodic effect outdoors. Conditions are only predictable and controllable to a limited extent.

The personal perception of temperature, which depends essentially on the thermal equilibrium of the body, can be described technically by the universal thermal climate index (UTCI) – basically a mathematically approximated equivalent value for the expected temperature perceived by a person under the respective conditions. The more stable the body's heat balance, the less effort the body has to expend on cooling or warming, for example, by sweating or shivering.
A major influencing factor is a person's metabolic rate (met) which describes a person's activity: the greater the physical strain, the higher the rate. The factor of individual clothing fluctuates seasonally and is therefore rather difficult to influence. The clothing factor (clo) describes the clothing insulation value. In winter it is rather high and in summer it is rather low, as it makes heat transport between the environment more difficult or easier.

The air humidity, temperature and movement as well as the sky temperature, solar radiation and also the average long-wave radiation temperature of enclosing surfaces are further environmental conditions with a significant influence on comfort. An increase in air movement, i.e. flow velocity, is expected to increase convective heat transport between the person and the environment. Overall, however, solar radiation with its diffuse and direct component has the greatest influence on a person's perception of heat.

Solar radiation also has a significant influence on the surface temperature of individual enclosing surfaces, which in turn are in a long-wave radiation exchange with a person. Since incoming radiation is reflected, transmitted and absorbed by components, the enclosing surfaces must be divided into opaque and transparent, i.e. surfaces transmitting radiation. Opaque components present no transmission but reflect and absorb incoming radiation. Absorption causes the surface temperature and possibly also the air temperature to rise in the layer adjoining the component. Through transparent components, solar radiation largely reaches the interior as a heat source, where it is absorbed and reflected. However, the actual surface temperature of a component is also influenced by its heat storage capacity. In the case of thermal insulation composites, for example, this is very low due to the low thermal storage capacity of the plaster layer. An increase in the externally effective storage capacity of the wall structure up to the heat-insulating layer can attenuate the surface temperature's volatile daily fluctuation.

Microclimate in the Courtyard

Solar radiation as well as the envelope's surface temperature have a significant influence on thermal comfort. In order to quantify this, two variants with different heat storage capacity (variant 1: 7 kJ/(m²K), variant 2: 307 kJ/(m²K)), but equal thermal resistance of 7.2 (m²K)/W were investigated. One wall in the courtyard was depicted as a solid wall, facing different directions. This ensures that it is exposed to varying solar radiation. The courtyard under consideration has a dimension of 3.6 × 3.6 × 3 metres. An average of 750 direct hours of sunshine per year (h/a) is assumed.

Courtyard Orientation

One of the courtyards' tasks is to provide sufficient lighting for the interior spaces. It can be stated that if the interior is naturally lit sufficiently this also applies to the exterior. Whether or not sufficient direct lighting of the interior is provided depends largely on the courtyard's orientation.

Depending on the shadow cast by the courtyard's enclosing areas, the hours of direct sunlight in the courtyard will increase or decrease. The amount of shade is determined by the height of the enclosing walls and the sun elevation angle. As the sun elevation angle increases, the shadow cast is reduced. As the location's latitude decreases, the influence of the wall height on the amount of shadow cast is reduced.

By rotating the courtyard in the sun chart, it quickly becomes clear that the length of the courtyard's stretch parallel to the course of the sun must be as long as possible in order to increase the hours of sunshine in the courtyard.

However, this only applies to courtyards with enclosing surfaces of up to three metres in height and a ratio D/H ≥ 1.2. If the height of the enclosing surfaces is the same and the ratio D/H is less than 1.2, the diagonal of the courtyard should be parallel to the course of the sun.

If the areas surrounding the courtyard are up to six metres high, a D/H ratio of at least 0.9 should be the goal. North-south or east-west orientations should be avoided. In comparison, the hours of sunshine in the courtyard can be increased if the orientations deviate by 30 ° to 60 °.

A north-south orientation combined with the longest possible courtyards is only advantageous in the case of enclosing walls higher than six metres. For these courtyard geometries, a D/H ratio greater than 1 should be aimed for. By staggering the courtyard towards the south, an increase in sunshine hours in the courtyard can be achieved. This creates a kind of funnel, improving the natural lighting of the interior spaces.

The constraints described here for an optimal orientation of courtyards apply to European regions and can be applied in a mirrored orientation to the southern hemisphere.

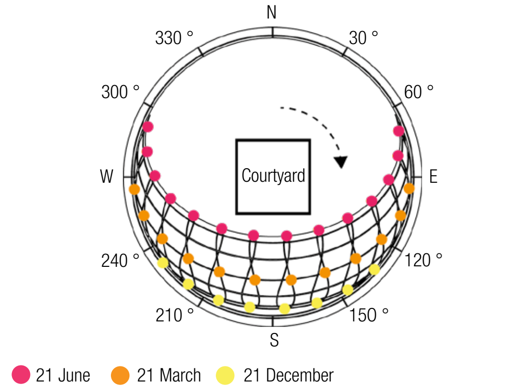


Fig. 138: The sun chart for the location Stuttgart shows the hourly course of the sun on 21 June, 21 March and 21 December as well as the rotation of the courtyards to determine the direct sun hours in the courtyard.

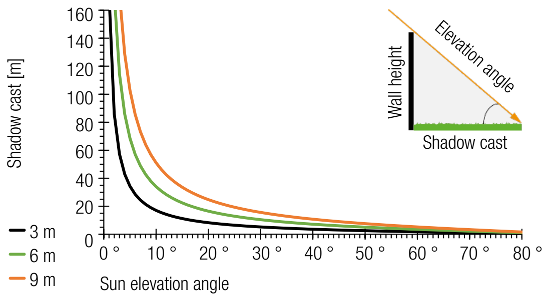


Fig. 137: Shadow cast by a wall of 3 m, 6 m and 9 m as a function of the sun elevation angle and with ideal solar exposure.

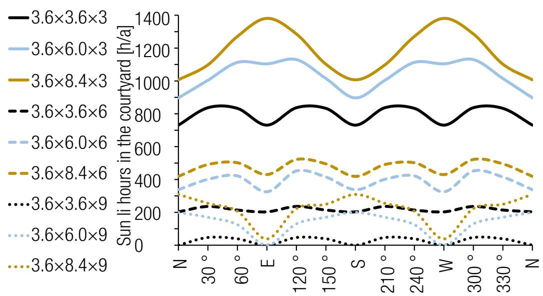


Fig. 139: Direct sun lit hours on the courtyard floor area with different orientation and different proportions of the courtyard.

Acoustics

There are various requirements for the acoustic design in courtyards. Conversing parties need to be able to understand each other clearly, while at the same time there must be discretion and privacy between neighbouring parties. In addition, the courtyard should be protected from outside noise – from neighbours or streets.

This being said, sound from outside can also support the desire for discretion and privacy by impairing intelligibility and masking conversation. Natural sounds such as birdsong or splashing of water are particularly suitable for this purpose and can also be used deliberately. Especially in very quiet neighbourhoods, pleasant masking sounds can significantly improve the acoustic conditions.

As the distance to a sound source increases, sound which propagates spherically (Fig. 145), usually decreases in intensity and intelligibility, but it can be amplified and sustained in the courtyard itself and from courtyard to courtyard or street to courtyard by reflections. In addition, the sound waves are diffracted and scattered in different directions at the upper edges of the courtyard.

In order to prevent the danger of unwanted extraneous noise in the courtyards, the distances between courtyards of the same and different buildings should therefore be designed to be as large as possible when forming neighbourhoods and the structural separation should have good sound insulation.

List of Measures for Acoustics

The schematic section of the neighbourhood shows various possibilities for improving the acoustic conditions as well as for reducing noise in the courtyards. Measures for targeted reflection and absorption reduce the leakage and penetration of sound waves into the inner courtyards.

The propagation of airborne and structure-borne noise within the building should always be counteracted in accordance with the building regulations for terraced houses. Double-layer partitioning walls with a separating layer extending all the way down to the foundations should be used, which can be further improved with siding.
In order to reduce the penetration or leakage of sound waves into or out of the courtyard, sun protection measures with sound insulation effect or projections on the courtyard walls or at the courtyard end are also possible. The courtyard end wall can also act as an absorber or reflector.

The acoustics and sound insulation in the courtyards can be further improved by cladding the courtyard facades with alternating surface roughness, for example using acoustic plasters. Perforated or micro-perforated elements on different levels of the courtyard are also conceivable, such as perforated sheeting, wood wool panels or translucent elements. Vegetation on the courtyard facades, for example in front of cavities, with integrated absorber elements has a similar effect.

In addition, the sound propagation between the courtyards is attenuated by green roofs. The vegetation reduces the sound energy through absorption and ground effects and at the same time is an important urban climate measure. Any vegetation should have a high leaf content.

As in the courtyards, noise sources can also be used for masking in selected open spaces. Water fountains have a synergetic effect on acoustics and local microclimate. All measures to reduce traffic in the neighbourhood are also welcome.

[24] Energieagentur NRW (eds.), Doris Haas-Arndt, Fred Ranft, *Tageslichttechnik in Gebäuden*, Heidelberg 2007, p. 82.

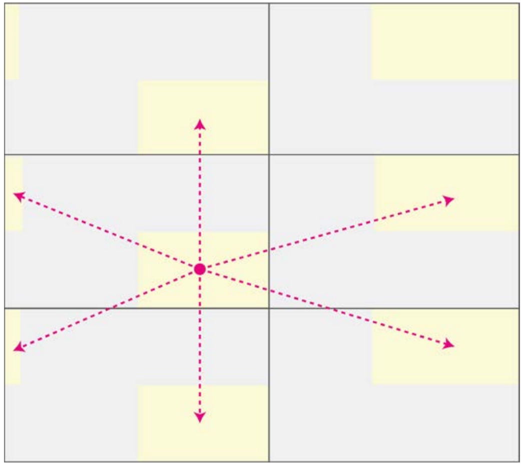


Fig. 144: Staggered arrangement of the courtyards to generate the longest possible paths for sound transmission.

Resource Efficiency

Resource efficiency describes the relationship between benefit (product, function, functional unit) and cost (resource input).[25] Applied to the construction industry, this refers to factors such as material, soil sealing, energy saving, used energy and embodied energy. Taking into account that about 90 percent of the mineral raw materials used in Germany are deployed in the production of building materials and that about 54 percent of the total waste volume in Germany originates from the construction sector, the development of a future-oriented building type is only possible by considering resource efficiency.[26]

In the following chapter, aspects of sustainability and resource efficiency will be applied to the compact courtyard house. In terms of content, this section focuses on:

– area efficiency / area type,
– enveloping surface,
– D/V ratio,
– energy requirements,
– energy supply,
– building material ecology
(see the section Building Construction).

Subsequent compaction and special situations offer further possibilities.[27]

The study *Energieeffizienzsteigerung Gebäude – Wege zu einem nahezu klimaneutralen Gebäudebestand* (Energy Efficiency Strategy for Buildings – Methods for achieving a virtually climate-neutral building stock) by the Federal Ministry for Economic Affairs and Energy for 2015 forecasts an average primary energy requirement for residential buildings of approximately 40 kWh/(m²a).[28] This is currently equivalent to the value of a KfW Energy-Efficient House 55 and shall be defined as a target value. The results obtained show ways to achieve resource efficiency, but do not claim to be exhaustive; they are intended as a guide.

[25] Verein Deutscher Ingenieure, Gesellschaft Energie und Umwelt (ed.), *VDI-Richtlinie 4800: Ressourceneffizienz – Methodische Grundlagen, Prinzipien und Strategien*, sheet 1, version 11/2016.

[26] Verein Deutscher Ingenieure, Zentrum Ressourceneffizienz, online unter: https://www.ressource-deutschland.de/ themen/bauwesen/ (last access: 3/4/2020).

[27] See chapter VIII “Potential for Today and Tomorrow”.

[28] Federal Ministry of Economics and Energy (ed.), *Energieeffizienzstrategie Gebäude – Wege zu einem nahezu klimaneutralen Gebäudebestand*, version 18/11/2015, p. 48, online at: https://www.bmwi.de/Redaktion/EN/Publikationen/energy-efficiency-strategy-buildings.pdf (last access: 3/4/2020).

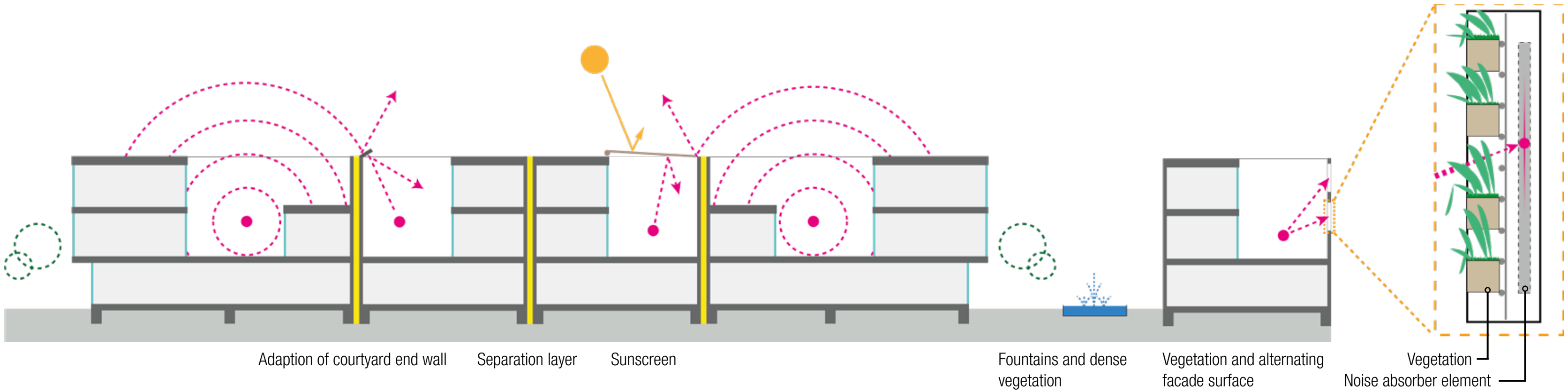
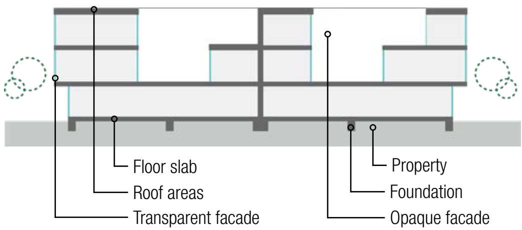


Fig. 145: Measures to improve intelligibility and reduce sound transmission from courtyard to courtyard. In public spaces, fountains can have a masking effect.

Fig. 154: Potential energy surfaces of a compact courtyard house and their evaluation. The available space, the expected yield, the technical feasibility and the suitability for a KfW Energy Efficiency House 55 are evaluated.



Potential energy surfaces	Space available	Yield	Feasability	KfW 55
Transparent facade	0	-	0	+
Opaque facade	0	-	+	+
Roof area	-	0	+	+
Floor slab	+	+	-	0
Foundation	0	+	-	+
Property	-	+	-	+

Individual Solution
Depending on the concept, different surfaces on the building are suitable for energy generation. Their potential differs depending on the available space, the expected yield and the technical implementation.

For example, photovoltaic cells can be integrated into transparent facade glazing or a separate system for energy generation can be added – albeit with disadvantages in terms of lighting and transparency.
For opaque facade areas receiving sufficient sunlight, there are many possibilities for system integration of solar active technology.

Various types of solar collectors are suitable for the roof surface, but additional shading of the courtyards should be avoided. This supports almost horizontal orientation, even if yield and economic efficiency of the active technology is reduced. Due to wind force, the usable roof area is very small and is only 39 percent across all concepts. If the collectors are mounted, on average only 14 percent of the roof area can be activated. This significant reduction is due to the required distance between the collectors to avoid mutual shading.

Usable vs. non-usable roof area

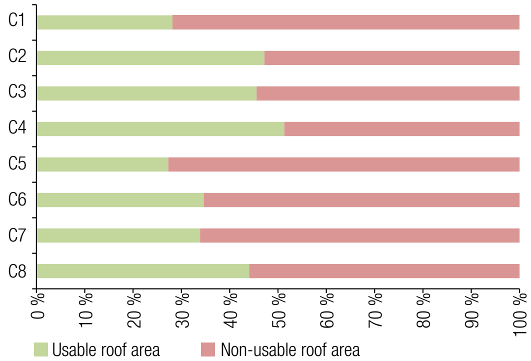


Fig. 155: The mean values of the concepts› usable roof areas with collectors in horizontal orientation compared to the non-usable roof area. The mean value of all concepts is 39 % usable roof area.

For the operation of heat pumps, the base slab, the foundation or the property's soil serves as an energy source. However, there is little free space available on the property, which is also difficult to regenerate over the summer when using a surface collector.

Due to the low proportion of usable roof area, the poor regeneration possibilities of soil or the foundation area, the high space requirement of plant technology and the desired clarity of the ownership structure, the implementation of an individual solution is generally not expedient.

Neighbourhood Solution
A neighbourhood solution offers the advantage that system technology within the individual buildings can be limited to a transfer station, hot water storage tank, pump technology and heat exchanger. These system components are either located in the individual units or centrally in the building.

Waste heat, biomass, geothermal energy and solar radiation can be used as a source of energy depending on the location. Biomass should be acquired regionally. Heat pumps, solar collectors and combined heat and power (CHP) convert the energy into heat or electricity. The respective type of energy is thus supplied to the building or stored. A holistic approach to a neighbourhood solution not only includes the provision of space heating, domestic hot water (DHW), electricity and possibly also cooling, storage capacity and water retention, but should also address the issue of mobility. For this purpose, for example, the surplus energy is stored in batteries or converted into a synthetic energy carrier via the power-to-x process (e.g. power-to-gas or power-to-liquid). The stored energy can then be fed into the mobility sector or back into the building via energy supply stations.

Building Material Ecology
The demand for sustainability must be reflected in the choice of materials used for implementation by promoting optimisation. This also applies to sensible component thickness, which is discussed controversially and questioned in public, especially in the case of thermal insulation.
The course of the thermal transmittance (U-value), plotted in Fig. 162 over the insulation material thickness, shows that by determining the latter, an economic and ecological optimum can be achieved. While more insulation reduces the heat transfer, more material and space are required. The relationship between transmission heat losses, embodied energy and space requirements must therefore be considered over the life cycle.

Life cycle assessments provide an overall view of material and energy flows and the associated environmental impacts over a variety of life cycles. Fig. 163 shows the key stages of a life cycle assessment, for example for a building material. DIN EN 15804 divides the life cycle into four life cycle modules (A-D):

- production A1-A3: raw material supply, transport, manufacturing;
- use B1-B7: use / application, maintenance, repair, replacement, renewal, energy consumption for building operation, water consumption for building operation;
- disposal C1-C4: dismantling / demolition, transport, waste treatment, landfill;
- credits and debits outside the system boundaries D: reuse, recovery or recycling potential.

After demolition or dismantling and clean separation of the building materials, however, they can generally only be re-used to a limited extent. Often, only downcycling is possible, and the quality of the original product cannot be restored. In addition, the various processes again require considerable energy inputs, and these are included in the balance sheet along with the corresponding environmental impacts.
For these reasons, the focus should ideally be on the most complete possible recycling of raw materials after use and demolition and with this as a clear target starting from the earliest planning phase; the goal is to avoid waste from the very start.
Generally speaking, this means: maximum use of recyclable and renewable materials, if possible no composite materials or structures that are difficult to separate, no glued joints, no coatings that limit the recycling potential and a selection of materials and design methods that consider life cycle assessment data, etc.

Building Separation Walls / Exterior Walls or Facades
In keeping with the logic of the compact courtyard house, adjacent buildings do not share an exterior wall, each building rather has its own separately founded exterior walls with dividing joints on the property boundaries. This results in synergy effects for fire and noise protection. The noise insulation issue between neighbouring courtyards is comparable to situations involving public space: it is more intensive, but there are more options for coping with it.

From building classes 1 to 3, type-tested flammable exterior walls are permissible instead of fire walls: highly fire-retardant or fire-retardant and fire-resistant from the outside to the inside, if no additional mechanical demand is present.

Building class 4 permits the use of type-tested highly fire-retardant walls that withstand defined mechanical stress.
If the core is combustible, they require a non-combustible cladding and insulation.

Conclusion: The previous typology of compact courtyard houses basically allows exterior walls with partially or completely flammable materials.

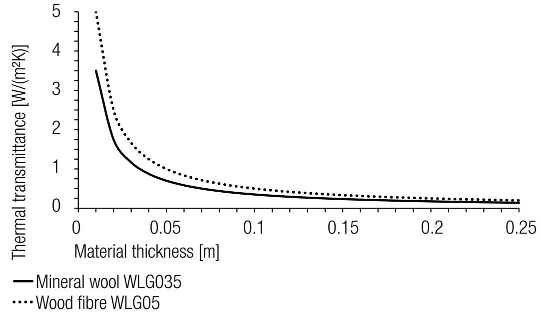


Fig. 162: Performance of thermal transmittance with increasing material thickness.

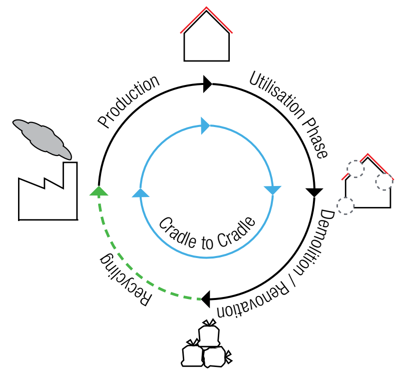


Fig. 163: Life cycle of a building material for the construction of a building. In some cases, transport must also be taken into account in the individual stages of the cycle.

Construction Process – Construction Site Organisation

It is an obvious fact that small-scale plots of land offer little space for storage, work preparation and the usual construction site facilities with a crane.
Furthermore, accessibility is usually only possible from one (narrow) side. Therefore, public space with official permission to deliver, store and set up a crane during the construction period must be included.
In addition or alternatively, an inner courtyard can be used as a storage area or, if necessary, also for crane placement.

Construction is implemented as usual on a floor-by-floor basis. The higher the component prefabrication level, the faster the construction process and the easier the building site can be organised. Up to five buildings are expected to be managed with one crane as a construction segment.
Basements are to be organised in the construction process and through construction segments in such a way that expensive underpinning is avoided.

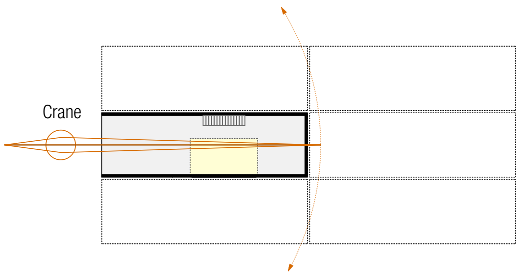
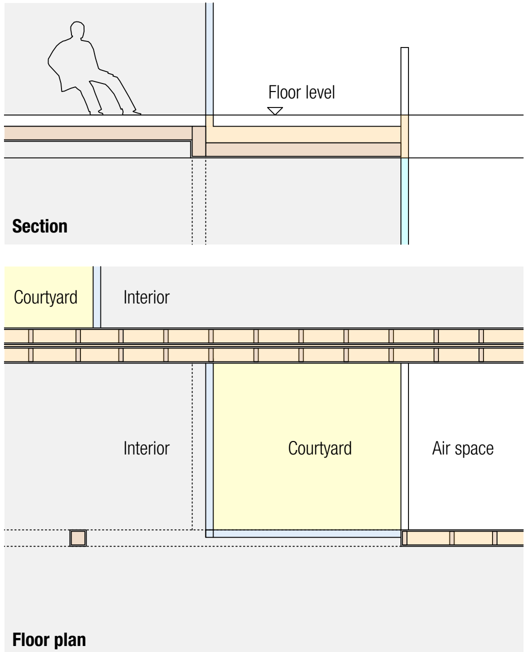


Fig. 181: Typical construction site situation of a compact courtyard house in schematic representation.



Timber frame construction with glued laminated timber ceilings, up to building class 4

e.g. inverted roof, water-bearing level 15 cm below floor level

Glued laminated timber ceiling

e.g. element facade, metal frame with infills (thermally separated), triple insulating glazing (transparent, translucent), insulation panels

Building end walls:
timber frame wall, non-combustible cladding, highly fire-retardant, type-tested

Load-bearing walls and columns: highly fire-retardant, non-combustible cladding

Fig. 182: Construction example in timber frame construction.

Heavy and bulky objects can be brought deep into the building at a later date using cranes and via the exterior spaces or courtyards, provided generously opening glass facades to the courtyard and/or public space are available.

Conclusion: With well-considered construction site organisation and logistics, an advantageously high level of prefabrication and just-in-time deliveries, no serious or exceptional problems are to be expected, comparable to construction sites in cramped inner-city locations, for example in infills.

Fig. 196, right page: Street space of an urban quarter with compact courtyard housing according to concept C1.

Fig. 195: Perspective to type 121-C1-3-1-2.8.

Degree of Prefabrication and Cost

The strategy on which the case study is based – timber frame construction method and modular system – allows a high prefabrication level plus a short construction time on site.

If ensembles or neighbourhoods can be realised by multiplied addition of the same or related types, an economical serial production is possible with individual adaptations similar to a construction set. By dispensing with a costly basement, the foundation can be reduced to a frost-free base slab and components necessary for the building services (not shown in the drawings). A dry assembly method, also for floor structures, saves desiccation time. Prefabricated installation walls are a further option for the bathrooms.

All of these measures and factors are suitable for bringing the construction costs down to a level in line with the market, despite the widely vegetated flat roof constructions.

Natural Illumination

With the exception of the bathroom on the first floor, all interior rooms receive daylight via the street facade, courtyard facades or additional skylights.

Previous considerations on the courtyard orientation are embraced. By rotating the building type to a position where the diagonal of the courtyard is parallel to the course of the sun, the amount of insufficient illumination is reduced. During the occupancy period, the area below 100 lux is reduced by an average of five percent. The improvement is particularly noticeable in the bedroom next to the bathroom on the first floor. The second floor is sufficiently supplied with daylight and a rotation here has a tendency of leading to an oversupply.

To avoid overheating in summer, the top floor needs appropriate sun protection, as does the street facade if the orientation is between southeast and southwest.

Fig. 215: Perspective view of a street space with variants according to concepts C2 (left side of street) and C6 (right side of street).

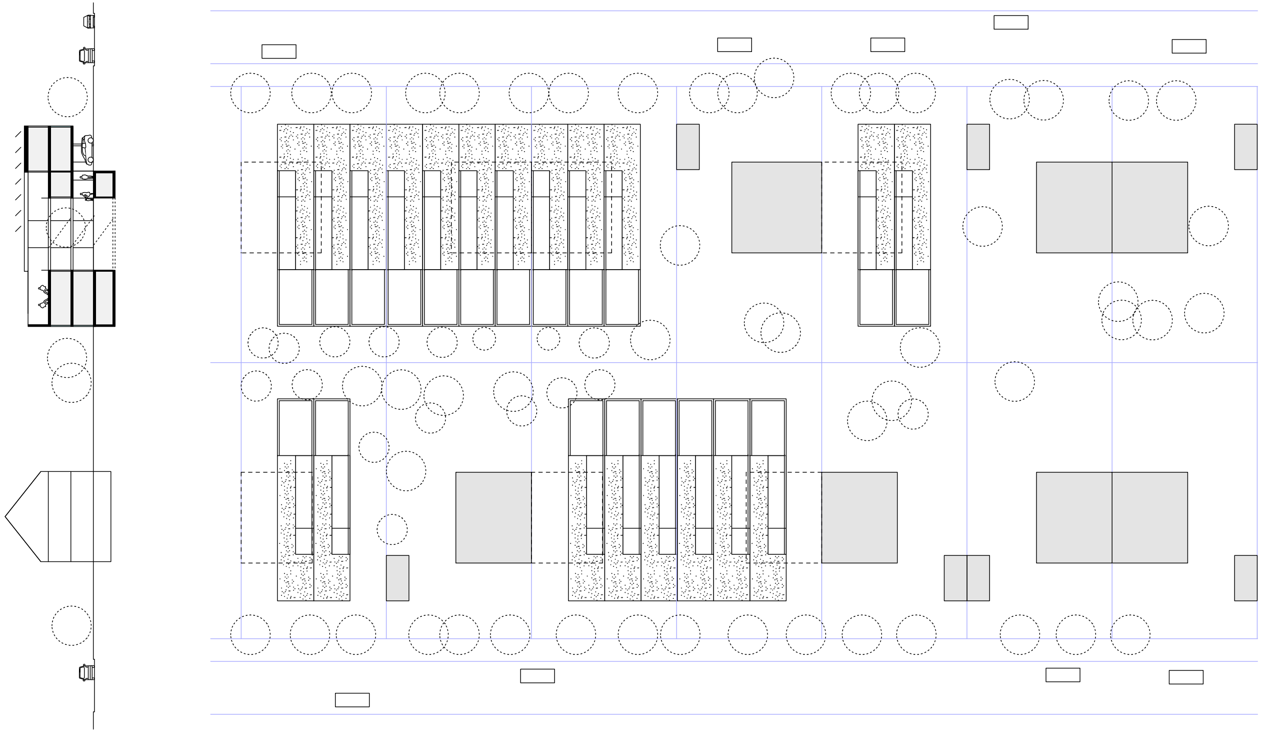


Fig. 238: Case study for the conversion of a typical low-density settlement from the 1960s into a much more sustainable urban structure in the long term. Schematic representation of a temporary intermediate state, site plan and schematic section, scale 1:1000.

Duplex houses with garages as boundary buildings on plots of about 700 m² form the existing buildings. The two-storey buildings (ground floor + first floor + extended roof) have a gross floor area of 200 to 220 m², which corresponds to a utilisation of the building land or a floor area ratio (FAR) of 0.3.
With narrow and deep compact courtyard buildings (e.g. according to concept C1), the utilisation or floor area ratio can be increased to 1.4 while maintaining the distance (1/2 × H) to the existing conventional buildings and property boundaries. The 50 to 60-year-old existing buildings (usually still unrenovated) will be replaced in stages by compact courtyard houses. This can be accompanied at the same time by a division of the plots into four narrow plots of 175 m² each, which can be sold individually if required.
With land prices in metropolitan regions ranging from 1,000 to 5,000 Euros per square metre, a landowner can earn approximately 500,000 to 2.5 million Euros in this way. As a rule, the increase in building rights will, according to the laws of the market economy, cause land prices to rise even further. This creates a strong economic incentive to demolish, sell and rebuild, which few are likely to be able to escape. This will not only save the costs of renovating the existing conventional buildings (approx. 150,000 to 300,000 Euros), but also completely finance the new building and possibly create funds for other areas of life and investments. Even the interest of retired owners and users could be aroused in this way, for example, if necessary home care and accessibility are made possible or if building land is generated for children and grandchildren.

In this way, valuable building land is created in good locations for those willing to build, prospective buyers and investors (internal development). The living quality of such a compact courtyard house (with a central courtyard, roof terrace that cannot be seen, integrated parking space, generous storage areas, etc.) will at the same time far exceed that of the existing conventional building. The range of services in the neighbourhood is also improved with the higher density.