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Daylight utilization in buildings:

Analysis of existing conditions and development of improved rules and metrics

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Energimyndighetens projektnummer: 41816–1

E2B2

Förord

E2B2 Forskning och innovation för energieffektivt byggande och boende är ett program där akademi och näringsliv samverkar för att utveckla ny kunskap, teknik, produkter och tjänster.

I Sverige står bebyggelsen för cirka 35 procent av energianvändningen och det är en samhällsutmaning att åstadkomma verklig energieffektivisering så att vi ska kunna nå våra nationella mål inom klimat och miljö. I E2B2 bidrar vi till energieffektivisering inom byggande och boende på flera sätt. Vi säkerställer långsiktig kompetensförsörjning i form av kunniga människor. Vi bygger ny kunskap i form av nyskapande forskningsprojekt. Vi utvecklar teknik, produkter och tjänster och vi visar att de fungerar i verkligheten.

I programmet samverkar över 200 byggentreprenörer, fastighetsbolag, materialleverantörer, installationsleverantörer, energiföretag, teknikkonsulter, arkitekter etcetera med akademi, institut och andra experter. Tillsammans skapar vi nytta av den kunskap som tas fram i programmet.

Dagsljusanvändningen i byggnader är ett av projekten som har genomförts i programmet med hjälp av statligt stöd från Energimyndigheten. Det har letts av *Lunds Universitet* och har genomförts i samverkan med *ARQ Stiftelsen för arkitekturforskning*.

Dagsljus är en parameter som blir alltmer betydelsefull. Användning av dagsljus i byggnader påverkar hälsa, välbefinnande och produktivitet och har en direkt påverkan på behovet av el för belysning. Det här projektet har undersökt dagsljusanvändningen i svenska byggnader, analyserat befintliga förhållanden och föreslår nya krav som stödjer och skyddar utnyttjandepotentialen av dagsljus.

Stockholm, 23 januari 2018

Anne Grete Hestnes,

Ordförande i E2B2

Professor vid Tekniskt-Naturvetenskapliga Universitet i Trondheim, Norge

Rapporten redovisar projektets resultat och slutsatser. Publicering innebär inte att E2B2 har tagit ställning till innehållet.

Sammanfattning

Detta projekt ger vetenskaplig information om dagsljusprestanda för flerfamiljshus i Stockholm och Örebro. Ett urval av 54 byggnader som består av 10 888 enskilda rum utvärderades med hjälp av avancerade dagsljussimuleringar. Byggnaderna som studerades valdes utifrån byggnadsår och byggnadstypologi, för att så bra som möjligt representera det befintliga byggnadsbeståndet som byggdes under förra seklet (1926 - 1991). Resultat visar att specifika byggnadstyper konsekvent ger dåliga dagsljusförhållanden jämfört med andra byggnadstyper. Vidare undersöker studien hur mycket rummen, lägenheterna och byggnaderna överensstämmer med den nuvarande punkt Dagslysfaktor (DF_p) och föreslår nya indikatorer som kan användas istället. Nuvarande krav på genomsnittlig dagsljusfaktor (DF_{avg}) har visat sig vara vilseledande på byggnadsnivån, eftersom rum på högre våningar påverkar medeltalet för hela byggnaden. På rumsnivå visar studien att det finns en hög korrelation mellan DF_p och median Daylight Factor (DF_{median}) över ett rutnät i rumsyta. Samma procent godkända resultat får man också om man använder en regel på lägenhetsnivå, i stället för rumsnivå. Resultat visar att en median dagsljusfaktorkrav över en lägenhetsyta eller på alla utom ett rum i lägenheten ger samma procent godkända resultat som den nuvarande rumsbaserade DF_p kriteria.

Nyckelord: BBR, bostäder, flerfamiljshus, dagsljusfaktor, regelverk

Summary

This research provides background scientific information on the daylight performance of multi-family apartment blocks located in Stockholm, and Örebro, Sweden. A sample of 54 buildings that consist of 10 888 individual rooms was evaluated using advanced daylight simulations. The studied buildings were selected based on their construction year and building typology in order to represent the existing building stock built in the previous century (1926 – 1991) as truthfully as possible. All simulations were performed including the existing surrounding urban context. Results show that specific building types consistently yield poor daylight conditions compared to other typologies. Furthermore, the study investigates the rate of complying rooms, apartments and buildings according to the current point Daylight Factor requirement (DF_p) of the building code, and proposes new indicators that can be used instead. An average Daylight Factor (DF_{avg}) requirement is proven to be misleading at building level, as rooms located on higher floors influence the average score for the building. At room level, it is shown that there is a high correlation between DF_p and the median Daylight Factor (DF_{median}) across a grid of points within the whole room area. The same compliance rates are also found by using a daylight requirement at apartment level, instead of room level. Results show that a median Daylight Factor requirement across an apartment area or which considers all but one room of the apartment yields the same percentage of successful outcomes as the current room-based compliance.

Key words: Daylight regulations, residential, daylight factor, compliance criteria

CONTENT

1 Introduction and background

The last decades have produced a plethora of research results emphasizing the connection between daylighting, health and well-being [1-3]. Daylight utilization is also promoted by the International Energy Agency as one of the most cost-effective strategies to reduce electricity use in buildings [4] while other organizations promote daylighting as a way to make buildings more resilient [5] and biophilic [6]. Recent Swedish studies have indicated that in offices, daylight utilization combined with absence detection may allow electricity savings of around 50 % for electric lighting compared to standard building practice [7]. Another study [8] showed that the electric lighting demand could be significantly reduced (i.e. by 23-42%) through daylight utilization in single family houses located in Stockholm, provided that electric lighting is switched off in the presence of daylight. Therefore, most building codes and environmental certification systems have today some form of minimum requirements for daylighting, most often expressed as minimum point or average daylight factor.

In Sweden, a first formulation of the daylight factor requirement appeared in the 1970s. This requirement was expressed as a minimum point daylight factor (DF_p) that was determined using a daylight protractor according to a method provided by Fritzell and Löfberg [9]. In order to simplify the method, the DF_p was abandoned in 1980s and replaced by a geometry-based calculation procedure, which considered the relation between the window glazing area, the room floor area and the window obstruction angle, as described in the standard SS_914201 [10]. This standard considers a DF_p measured at 0.8 m above floor level, 1 m from the darkest lateral wall, half way along the room's depth. This geometry-based calculation was valid for a maximum window obstruction angle of 30 degrees. For urban locations where the obstruction angle exceeded 30 degrees, no guidance was provided between 1994 and 2014 [11, 12]. A verifiable performance recommendation also including urban contexts was added later in the building code of 2014. This recent recommendation specifies a minimum point daylight factor (DF_p) of 1 % for all rooms used more than occasionally measured at the same point as described in standard SS_914201.

Recently, Swedish cities have experienced drastic urban densification due to an increase in population and housing shortage. It is estimated that roughly 700 000 new households have to be built by 2025 [13]. In this context, the recent DF_p requirement from the building code of 2014, is an additional constraint conflicting with urban densification. While the DF_p requirement has not been the most widely debated (compared to e.g. noise regulation and building heights), it is presently considered a serious bottleneck for the construction industry as it can be difficult to provide daylight-compliant spaces in dense urban areas. Practical experiences among architects and engineers have in fact indicated that the 1% DF_p requirement for all rooms is difficult to meet in current practice.

Given this context, this research project gathered academics and experts from the industry to provide scientific information that will allow a reformulation of the daylight requirement in the building code considering recent urban trends. Experts from Bau and White architects, Bengt Dahlgren, Skanska and NCC were consulted. The present report presents results from the first phase of this large research project.

The main aim of this phase was to obtain information about daylighting conditions in the existing building stock, with emphasis on multi-family dwellings built between 1926-1991. This information will provide a basis for a more appropriate and perhaps realistic reformulation of the daylight requirement in the building code.

2 Method

This project has been extended to a PhD thesis (after the initial project application) and some parts defined in the initial application (e.g. surveys to occupants and measurements) have only been initiated but the corresponding results have not been analyzed yet. The present report thus focuses on the results from the computer simulations.

In the first phase of this project, a total of 10 888 rooms in 3 151 apartments of 54 existing multi-family residential buildings were studied using advanced lighting simulations to assess their daylight performance according to various daylight indicators. The studied buildings belonged to 25 different housing developments in and around Stockholm, with a single exception located in Örebro. All buildings were simulated in their existing urban contexts, meaning that the surrounding buildings and obstacles were included in the simulations.

Furthermore, the sample was selected based on two criteria: a) *Construction year* and b) *Building typology.* Table 1 presents the aggregated data on the selected sample, which is sorted by construction year, from top to bottom. The two selection criteria are printed in red font. It is shown that different developments have different amounts of rooms, apartments and buildings.

2.1 Building sample selection criteria

The selection of the buildings was based on two criteria:

- Relevance of time-period based on statistics of the construction rate per decade.
- Relevance of the building typologies in relation to Swedish urban planning history.

The amount of apartments per decade was selected for this study in correspondence with statistical data on the amount of apartments per decade constructed in Sweden [14]. The building selection was made in accordance with the categorization of Swedish urban typologies as described by Rådberg and Friberg (1996) [15]. This study only included multi-family buildings, which represent 51% of the current residential building stock according to statistics [16]. Figure 1 shows the eight different typologies and their original footprints. The typologies differ in the number of floors (n) and in the constructed floor area (compared to the available plot area). The Floor Area Ratio (FAR) is the ratio of total floor area (gross floor area) to the area of each property.

2.2 Daylight performance simulations

The rooms simulated for their daylight performance were the ones where people stay more than occasionally, as described in the national building code [17]: kitchens, bedrooms, living rooms and dining rooms. Corridors, storage, hallways and the like were not evaluated. Each building and its surroundings were modeled using the Rhinoceros 3D modeler [18]. The buildings were modelled according to the latest available drawings (in raster or pdf format) retrieved from Stockholm City Planning Office [19]. The corresponding surroundings were generated by use of data on the three-dimensional building stock of Stockholm [20]. The terrain was modelled according to elevation data retrieved from Lantmäteriet [21]. The daylight performance simulations were performed by use of the Radiance simulation engine [22] via the Honeybee plugin [23] using the visual programming environment of Grasshopper [24]. Figure 2 shows the overall workflow used in the simulations. Table 2 shows the overall Radiance rendering settings used. A single simulation was performed per room and all modelled surfaces were assumed grey Lambertian diffusers according to table 3.

Table 1. Aggregated data of the selected building sample. The selection criteria are shown in red font and the data are sorted per construction year. Development includes many buildings built together at the same time on the same site.

Decade	Development Code	Building Code	Construction year	Nr of apartments	Nr of rooms per Typology							
					Low-rise tower	High-rise tower	High-rise enlongated	High-rise + Low-rise	Large courtyard	Semi-open courtyard	Post-modern	Exterior circulation
1921 - 1930	Q	38	1926	167					381			
	L	28	1929	232					541			
	P	37	1929	251					613			
1931 - 1940	M	29	1938	64		224						
		30	1938	64		224						
		31	1938	64		224						
		32	1938	64		224						
1941 - 1950	H	23	1944	38		136						
		24	1944	38		136						
	A	1	1945	9	33							
		2	1945	9	33							
		3	1945	9	33							
		4	1945	9	33							
		5	1945	9	33							
		6	1945	9	33							
	B	7	1945	162						486		
1951 - 1960	X	51	1952	33						105		
		52	1952	18						72		
		53	1952	57						162		
	E	11	1953	21						75		
		12	1953	8						29		
	F	13	1953	40			112					
	E	14	1953	8						29		
		15	1953	18						64		
		16	1953	12						54		
		17	1953	61						228		
	V	47	1954	50				180				
		48	1954	18				78				
	G	18	1957	39		148						
		19	1957	39		148						
		20	1957	39		148						
		21	1957	39		148						
		22	1957	39		148						
	C	8	1959	48				240				
		9	1959	36				168				
1961 - 1970	S	40	1967	309			1408					
	O	34	1968	9	32							
		35	1968	9	32							
		36	1968	9	32							
	T	41	1968	36				174				
		42	1968	4				24				
	U	43	1968	12	59							
		44	1968	12	59							
		45	1968	12	59							
		46	1968	12	59							
	D	10	1969	30								125
	N	33	1970	221			878					
1971 - 1980	J	26	1971	43			273					
	K	27	1971	88								277
	R	39	1976	56								216
1981 - 1990	I	25	1986	230							801	
1991 - 2000	W	49	1991	91							124	
		50	1991	17							63	
	Y	54	1991	130							470	

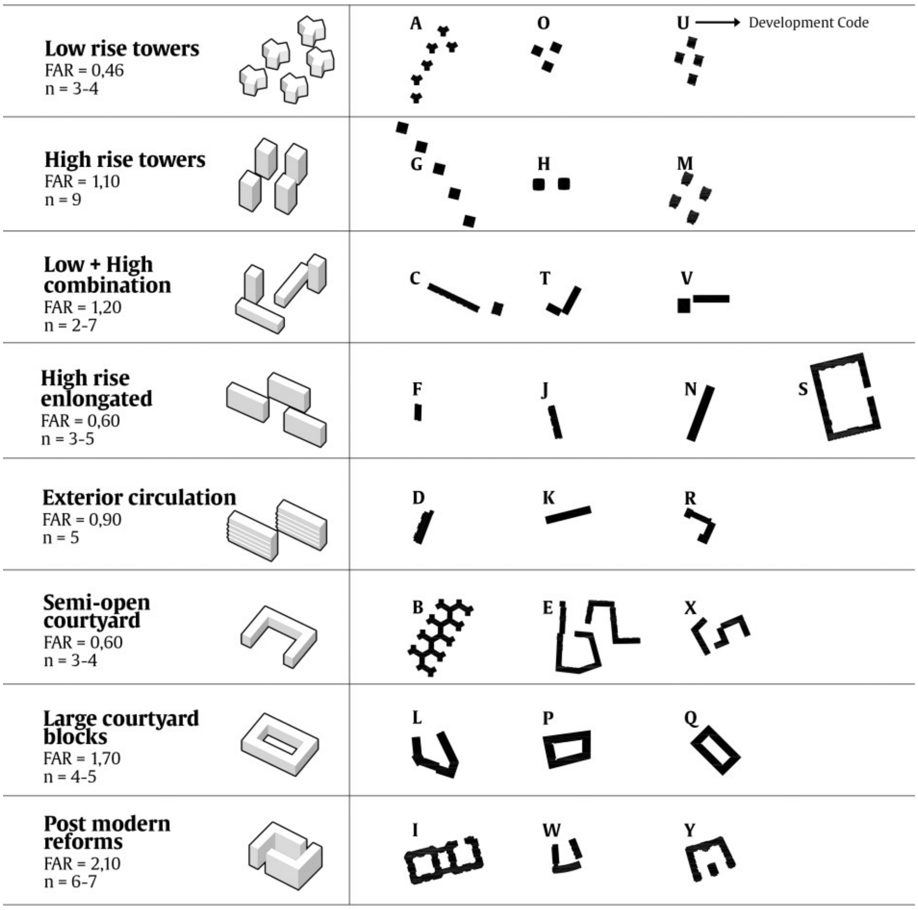


Figure 1. Scaled footprints of the analyzed developments, sorted per typological category.

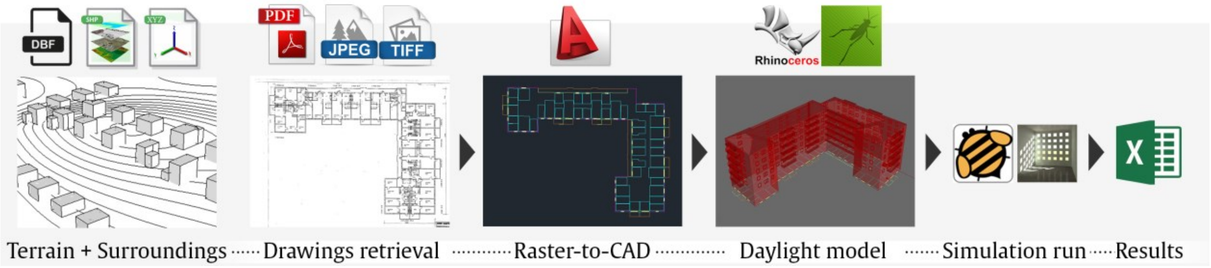


Figure 2. Overall workflow for the generation of illuminance data of distinct rooms per building.

Table 2. Selected Radiance rendering settings

Ambient bounces (ab)	Ambient division (ad)	Ambient sampling (as)	Ambient accuracy (aa)	Ambient resolution (ar)	Direct threshold (ds)	Direct certainty (dc)
7	2048	512	0.1	256	0	0

Table 3. Optical surface properties

	Radiance Material	Reflectance*	Transmittance	Specularity	Roughness
Walls (interior)	Plastic**	70 %	-	0	0
Ceiling	Plastic	80 %	-	0	0
Floor	Plastic	30 %	-	0	0
Window glass	Glass	-	70 %	-	-
Window frame	Plastic	80 %	-	0	0
Window head, jamb & sill	Plastic	50 %	-	0	0
Balcony ceiling	Plastic	70 %	-	0	0
Balcony floor	Plastic	30 %	-	0	0
Ground	Plastic	20 %	-	0	0
Surrounding buildings,	Plastic	20 %	-	0	0
Roofs	Plastic	30 %	-	0	0
Water	Plastic	50 %	-	0	0
Railing	Plastic	-	variable	0	0

**Overall reflectance (red, green, blue) **Plastic is a primitive in the program unrelated to the real building material*

2.2.1 Measurement grid

The main dependent variable under study was the point daylight factor (DF_p), which is used in the current legislation. Due to the geometrical uncertainties deriving from irregular room layouts, the definition of the point where DF_p is taken is not always based on a straightforward process. To facilitate the evaluation, a grid of points was introduced, to deduct the average and median DF for each room. These points were also located at 0.8 m above floor level and were set every 0.3 m across the floor area, in two different ways:

1) The point grid stretches throughout the total room area and

2) The point grid stops at 0.5 m from the room perimeter (figure 3).

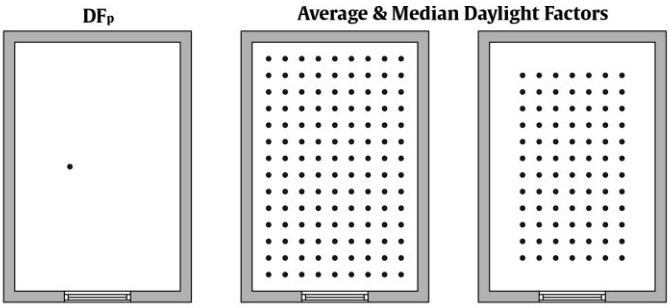


Figure 3. Three different measurements: Single point, Grid across total floor area and grid across floor area minus 0.5 m around the room perimeter.

2.2.2 Daylight metrics

The following dependent variables were analyzed at room, apartment and building level:

- **DF_p - Point Daylight Factor [%]**: The Daylight Factor measured in a single point, located one meter away from the darkest wall, 0.8 m above floor level halfway along the room's depth.

- **DF_{avg} - Average Daylight Factor [%]**: The average Daylight Factor from a total of point measurements. The points were located on a 0.3 m dense grid across the floor area, 0.8 m above floor level.
- **Median Daylight Factor [%]**: The median Daylight Factor of all Daylight Factor measurements across the point grid. The median value is defined as the value lying at the midpoint of an ordered data distribution, such that there is an equal probability of another value falling below or above it. (e.g. if DF_{median} = 1% then 50% of DF values are above 1 %).
- **Uniformity ratio [-]**: The minimum point Daylight Factor divided by DF_{avg}.
- **Sky exposure factor, SEF [%]**: The percentage of sky that is visible from a surface (in this study the window surface). This is equivalent to a solid angle calculation from a point on the window surface to the sky dome. The sky dome used was the continuous subdivision scheme proposed by Bourgois et. Al (2008) subdivided four times for higher accuracy.

2.3 Compliance criteria

The current legislation stipulates that all rooms of a building used more than occasionally should comply with the 1 % DF_p benchmark. The total area of these rooms will be referred to as the total daylit area in the sections that follow. Three more compliance criteria were evaluated in this study:

1. The criterion of all rooms complying with a specific indicator benchmark. This can be applied for all rooms of an apartment or all rooms of a building.

2. The criterion of the area of an apartment or building complying. This can be applied for a grid of points over the total daylit area of an apartment or the total daylit area of a building.

3. The criterion of all or all but one rooms in an apartment complying. This can be applied at apartment level, where a “passing apartment” is one where either all or all but one room achieve a benchmark.

3 Results

3.1 Overall point Daylight Factor (DF_p) performance

Figure 4 shows the DF_p obtained for all studied rooms in the 54 buildings. The current DF_p requirement of 1 % is shown by a vertical grey line and the median DF_p value of each building is shown with a linear marker. When more than half of the rooms of a building fail to reach the 1% benchmark, the median marker and the corresponding development code are shown in red.

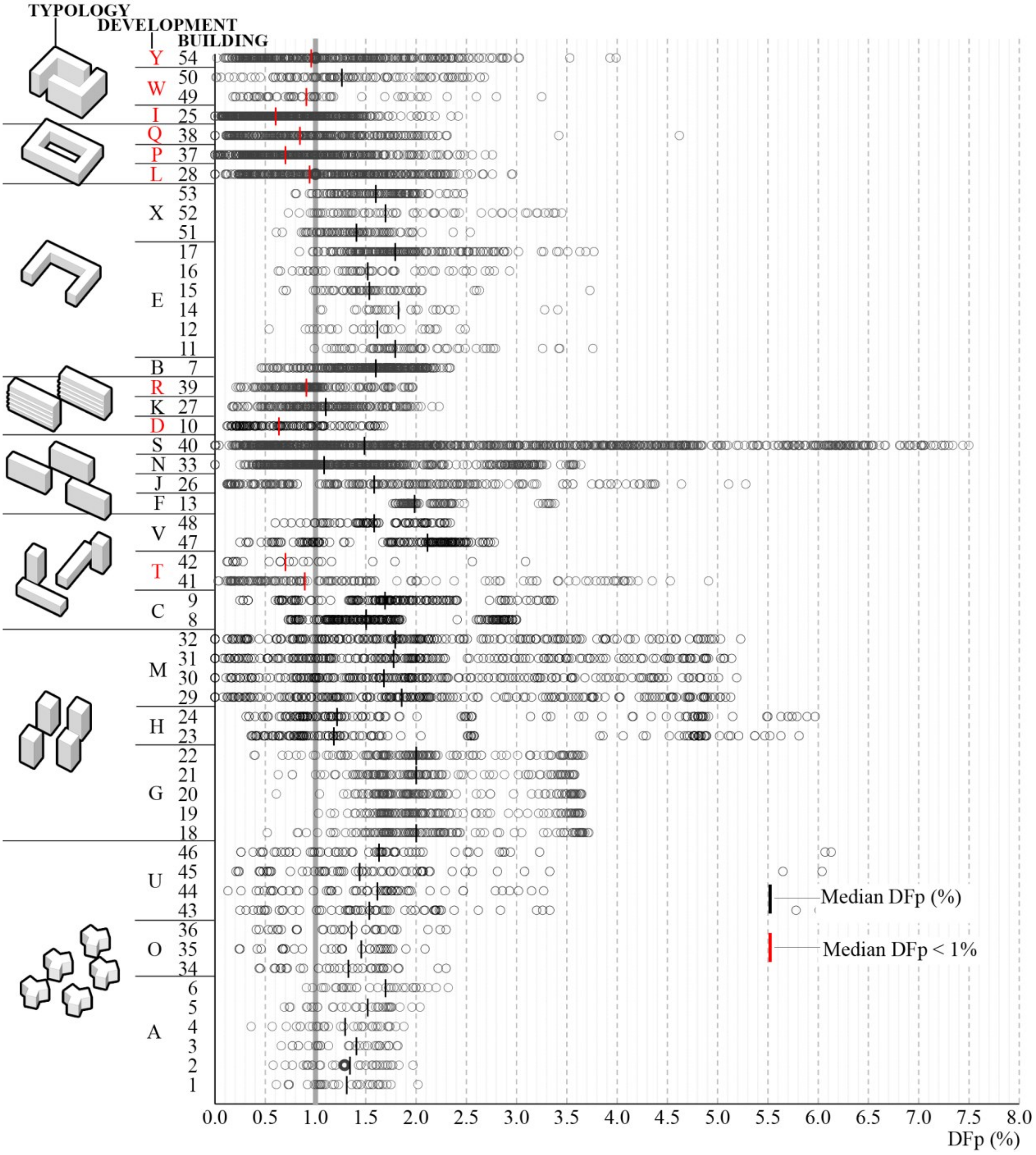
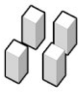
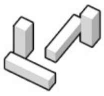
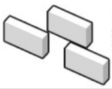
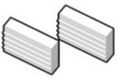
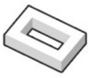


Figure 4. DF_p obtained for all 10 888 simulated rooms. The results are categorized in eight (8) typologies, 25 developments and 54 buildings. The median DF_p of all rooms per building is shown in a linear marker.

Figure 4 indicates that for the majority of buildings, more than half of the rooms are complying with the current requirement (median value of $DF_p \geq 1$ %). However, for 10 of these buildings, the majority of rooms obtained a DF_p below 1% (building 10, 25, 28, 37, 38, 39, 41, 42, 49 and 54). Examining figure 4, it is evident that buildings belonging to the same development (and thus located on the same site) exhibit a similar performance (e.g. buildings 11 – 17 or 18 – 22), in most cases.

The daylight performance is also shown to depend on the building typology. The poorest performance was found for the "Large courtyard blocks", the "Post-modern blocks" and the "External circulation" (loftgånghus) categories". There is also a poorly performing development (development T) belonging to the "Low + High" category. However, this poor performance is attributed to the amount of balconies existing in this development rather than its building massing.

Figure 5 ranks each typology based on the percentage of rooms with a $DF_p \geq 1$ % (Left to right = Best to worst). This figure shows that the best performing typologies have an average Sky Exposure Factor larger than 30%. It is also important to note that the average DF is not an accurate indicator, as it is greatly influenced by the amount of floors of a building. A higher building will have its upper rooms more illuminated, which will in turn increase the average DF at building level. The average uniformity ranges between 0.12 and 0.2.

Percentage of rooms with DFp≥1%	○ 93.2	○ 80.8	◔ 75.8	◑ 75.7	◑ 61.2	◕ 42.7	● 39.0	● 36.2
								
	Semi-open courtyard	High-rise towers	High-rise +Low-rise	Low-rise tower	High-rise enlongated	Exterior circulation	Large-courtyard blocks	Post-modern
Average DF (%)	◔ 2.5	○ 3.3	◑ 2.3	◑ 2.4	○ 2.7	● 1.7	● 1.5	◕ 1.9
Uniformity ratio (-)	◕ 0.15	○ 0.20	◑ 0.16	○ 0.18	◑ 0.15	◔ 0.16	● 0.13	● 0.12
Percentage of rooms without window (%)	● 0	○ 10	◑ 5	◔ 8	◑ 8	● 0	○ 10	◕ 1
Percentage of rooms with balcony (%)	◑ 28	○ 38	● 23	◑ 36	◕ 25	○ 59	● 3	◔ 36
Average Sky Exposure Factor (%)	◔ 31	◑ 30	○ 34	○ 32	◑ 26	● 24	◕ 24	● 22

	○	◔	◑	◕	●
Percentile:	≥80	≥60	≥40	≥20	<20

Figure 5. Development ranking based on percentage of rooms with $DF_p \geq 1\%$ (Left to right = Best to worst)

Figure 6 shows the distribution of DF_p for each room type studied. This figure shows that the kitchens are statistically the darkest rooms, and dining rooms the brightest. Nearly half of the kitchens fail to reach the required $DF_p \geq 1\%$. This is attributed to the fact that 21% of the evaluated kitchens are in the same room as the dining room but the kitchen is closer to the building core whereas the dining room is placed next to the facade.

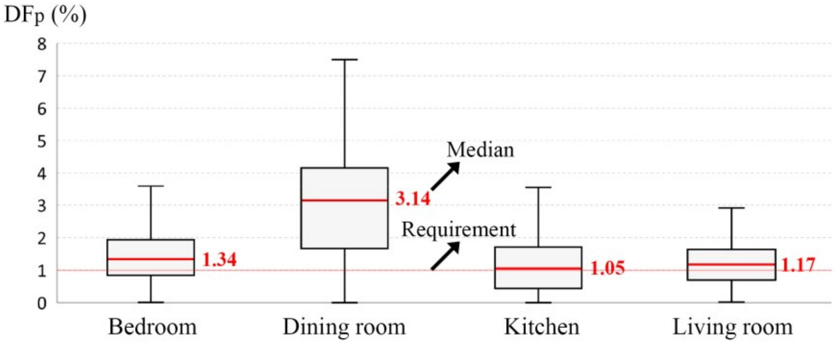


Figure 6. Box plot of DF_p per room type.

3.2 Compliance tests on the database

In the next phase of the research, the database was tested using the 1% DFp compliance rule at three different levels of analysis:
1) at room level,
2) at apartment level and
3) at building level.

The following terms are stated for ease of reading: A "passing room" is a room where the $DF_p \geq 1\%$ benchmark is achieved. A "passing apartment" is an apartment where all rooms pass the DFp benchmark. Finally, a "passing building" is a building where all rooms achieve the DFp benchmark.

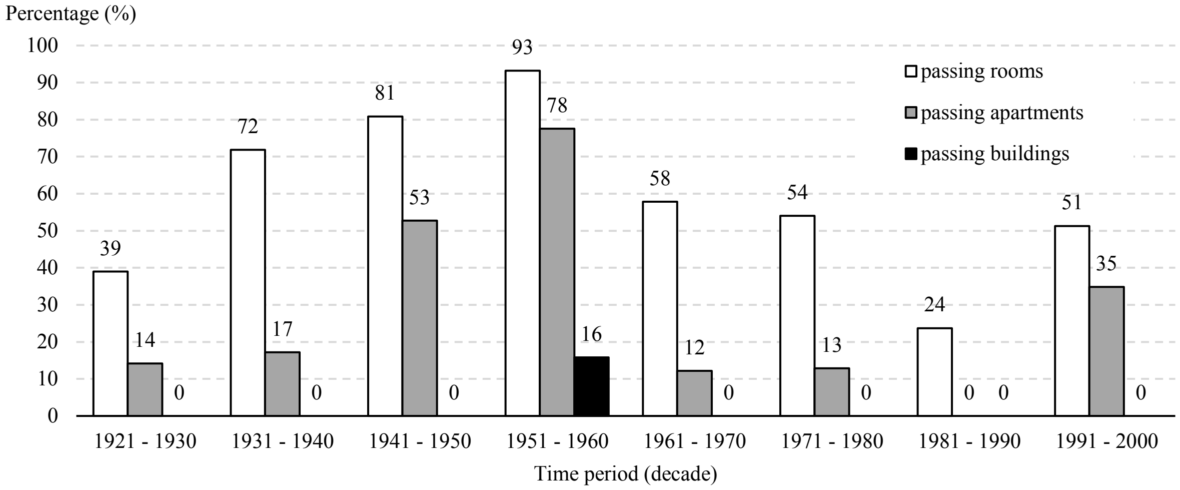


Figure 7. Percentage of successful outcomes for $DF_p > 1\%$ compliance at a) room level, b) apartment level, c) building level.

Figure 7 shows that at room level, more than 80% of rooms meet compliance for the building stock from the 1940-50s. However, less than 40% of the rooms studied meet the compliance for the stock from the 1920s and 1980s, the latter being the poorest decade in terms of building daylighting. Figure 7 also shows that already when considering apartment level instead, a significant drop in compliance is observed, where apartments from the 1940s and 1950s still outperform all other construction years. This drop implies that in many cases, apartments consist of heterogeneous rooms in terms of daylight level with some rooms performing better than others. Note that none of the apartments meets compliance for the 1980s. When requiring compliance at building level (i.e. all rooms of all apartments meet the $DF_p \geq 1\%$), only 16% of the 1950s buildings would comply, which equals 6% of the total amount of buildings studied (3 out of 54 buildings). The latter indicates that it is perhaps unreasonable to demand compliance for the whole building, as the majority of buildings of the existing building stock as represented by this sample would not comply to the current regulations. This analysis clearly shows that more flexibility is required in the regulations.

Figure 8 shows the compliance rates according to different criteria. The three different criteria for a pass or fail are printed in red font and are explained further down. For each of the three criteria, a different performance indicator (DF_p, DF_{avg}, DF_{median}) and a different level of spatial analysis (room – apartment – building) are considered.

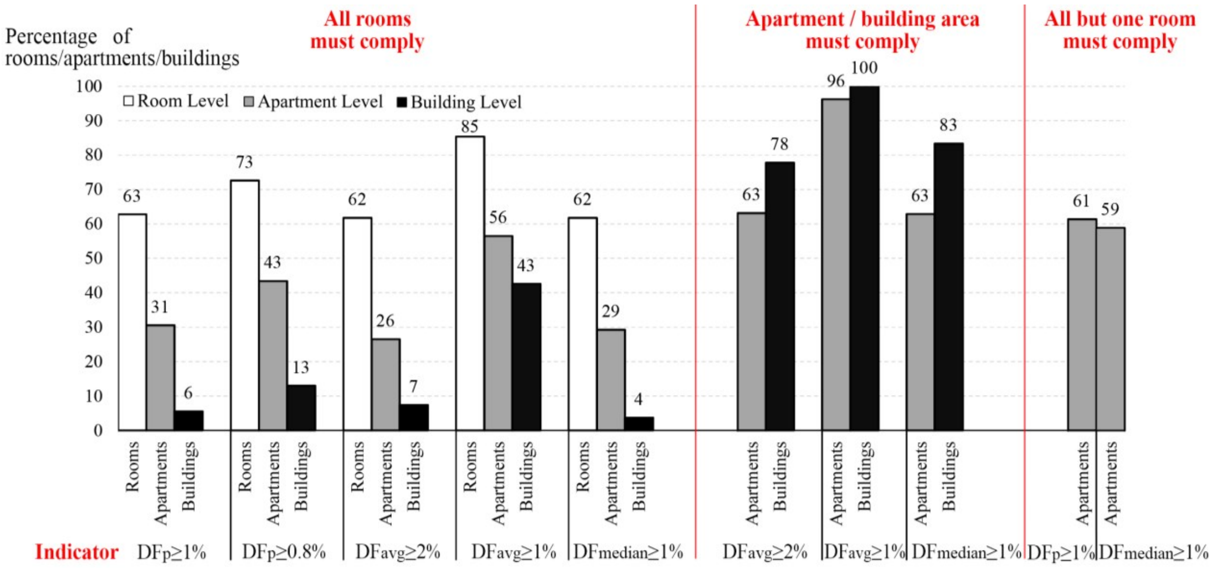


Figure 11. Percentage of passing rooms/apartments/buildings for different requirements.

The figure shows for each criterion:

Criterion 1 *(All rooms must comply). Under this criterion, the white bars show the percentage of compliant rooms. The grey bars show the percentage of apartments where all rooms comply. The black bars show the percentage of buildings where all rooms comply.*

- Reducing the DF_p threshold to 0.8% does not yield a significantly higher compliance rate for buildings (13%). This reduction of the requirement is therefore not a solution to solve the current bottleneck in regulations.
- Using the $DF_p \geq 1\%$ or the $DF_{avg} \geq 2\%$ or the $DF_{median} \geq 1\%$ yields the same share of complying rooms (white bars).

Criterion 2 *(The area of an apartment or the area of a building must comply). Under this criterion, the grey bars show the percentage of apartments for which the total daylit space complies with a given indicator. The black bars show the percentage of buildings for which the total daylit space complies with a given indicator.*

- Using any indicator at building level yields a higher share of "passing buildings". This is the result of the higher floors raising the overall value in question, and does not guarantee that rooms located lower in the building will be adequately daylit.
- Using the $DF_{avg} \geq 2\%$ or the $DF_{median} \geq 1\%$ at apartment level yields the same share of "passing apartments" (63% of apartments). This share is almost equal to the share of "passing rooms" for $DF_p \geq 1\%$ or $DF_{avg} \geq 2\%$ or $DF_{median} \geq 1\%$ of criterion 1 (62%-63% of rooms).

Criterion 3 *(Either all or all but one room of an apartment must comply). Under this criterion, the grey bars show the percentage of apartments where all rooms or all rooms but one comply with a given indicator.*

- *Allowing for a minimum of one room to fail the $DF_p \geq 1\%$ requirement, the percentage of passing apartments increases to 61%, compared to 31% with criterion 1, where all rooms of an apartment must comply.*
- The share of passing apartments using $DF_p \geq 1\%$ is approximately equal to the share of apartments with a $DF_{median} \geq 1\%$ of criterion 2 (61%≈63%).
- Using the $DF_{median} \geq 1\%$ yields slightly lower rate of passing apartments (59%).

Overall, it is deducted from the results that the $DF_p \geq 1\%$, $DF_{avg} \geq 2\%$ and the $DF_{median} \geq 1\%$ are closely interconnected, as they yield approximately the same compliance rates at room or apartment levels (62%-63%).

4 Discussion and conclusions

4.1 Overall results

Overall, this study shows the following:

Specific building typologies result in a higher percentage of non-compliant rooms ($DF_p \geq 1\%$). These are mainly the typologies built all around the block perimeter (large-courtyard blocks and post-modern reforms) and the "Exterior circulation" typology. These three have the lowest sky exposure factors on average (22%-24%), compared to the other typologies, which greatly reduces daylight penetration.

Among different room types, kitchens performed more poorly than other rooms, which is undesirable since people need more light in the kitchen due to the tasks performed there.

Only 6% of existing multi-family buildings (3 out of 54 buildings) in the studied sample comply with the current regulation, according to which, all rooms of a building must comply with the $DF_p \geq 1\%$ requirement. This low rate of compliance at building level of the existing building stock suggests that the current legislation is perhaps unrealistically ambitious.

Lowering the threshold from $DF_p \geq 1\%$ to $DF_p \geq 0.8\%$ would only increase the percentage of complying buildings from 6% to 13%, which does not solve the regulatory problem. This is not an adequate solution to the current bottleneck in regulations.

Of all studied rooms, 63% comply with the current regulation. A similar compliance rate (59%-63%) is found when using the following requirements:

i. Room $DF_{avg} \geq 2\%$ (meaning average Daylight Factor of all points of a room ≥2%). Compliance 62%.
ii. Room $DF_{median} \geq 1\%$ (meaning half of all points of a room should have a Daylight Factor ≥1%) Compliance 62%.
iii. Apartment $DF_{median} \geq 1\%$ (meaning half of all points of the apartment should have a Daylight Factor ≥1%). Compliance 63%.
iv. Apartment $DF_{avg} \geq 2\%$ (meaning average Daylight Factor of all points of an apartment ≥2%). Compliance 63%.
v. All or all but one room of an apartment should achieve a $DF_p \geq 1\%$. Compliance 61%.
vi. All or all but one room of an apartment should achieve a $DF_{median} \geq 1\%$. Compliance 59%.

The study also pointed out that the point-measurement used in the current regulations (DF_p) is difficult to determine in practice, especially for rooms with irregular shapes or rooms with more than one window. It is also prone to "game-playing" by practitioners, where the ambiguity of the location can lead to the deliberate "best" choice among possible locations, in order to comply with the regulation.

The area based metrics (DF_{avg} and DF_{median}) seem to be more intuitive and in line with current European and international trends. The authors consider that the DF_{median} in particular is more suitable, as by definition it guarantees that at least 50% of an area will be sufficiently daylit. Furthermore, in contrast to the DF_{avg}, it is not sensitive to extremely high values achieved closer to windows. The authors strongly suggest using a DF_{median} approach instead of the DF_p since it is also quicker when using computer simulations as one only needs to select a whole surface and calculate the median value. This process can easily be automatized. (For the point system, each point has to be determined individually and this process takes more time).

The $DF_{median} \geq 1\%$ can be deployed on the apartment level. This way, the designing freedom and flexibility for architects is increased and illumination of spaces will depend on their design priorities (e.g. a bedroom could be less daylit than a living room, with no major consequences for the well-being of the occupants. This can be either implemented on the total area of an apartment (requirement iii) or on each individual room, where maximum one room can be exempted (requirement vi).

4.2 Consequences of urban densification on energy use in cities

Overall, this study shows that daylighting availability in multi-family dwellings located in an urban environment is strongly affected by the sky exposure factor (SEF), which is directly related to urban densification patterns. In this study, the developments where the average SEF was below 24% (post-modern, large courtyards, exterior circulation) were the ones that had the highest occurrence of non-compliant rooms according to the DF_p criteria. Note that in the case of the exterior circulation type, the lower SEF was mainly due to the exterior circulation, and not the building massing itself. Interestingly, this typology is popular in current contemporary domestic architecture because it allows saving building costs while generally increasing the amount of dwellings per lot. This study clearly shows that this typology is not a solution to be privileged where daylighting is a priority.

In this study, the average SEF ranged from 34-22%, meaning that in the best cases, the average SEF was 34% of the maximum sky exposure (50%) while it was 22% in the worst case. The study shows that this relatively small change in average SEF (from 34 to 22%) has significant consequences on the DF_p compliance rate. One way to compensate for smaller SEF is to increase the window size, but this also generally increases heat losses and heating loads for all orientations except the south with a highly insulated building envelope, see [26].

Urban densification is positive in terms of cost reductions for large infrastructures but also in terms of a reduction of distances for transportation. This has long been at the forefront of sustainable urban planning principles. However, today's drastic urban densification is not only affecting the daylight compliance rate, it has direct consequences on the quality of indoor environments for people living in our Nordic climate dominated by dark overcast skies. While this has well documented short- and long-term effects on health and well-being, it also directly affects energy use since electric lighting must be switched on more often in poorly daylit dwellings. The question of relevance here is thus whether there is more to gain than to lose by densifying cities as is done presently.

Answering this question is not an easy task as one must consider the impact of urban densification on heating loads and overheating, on the use of electric lighting and reduction of transport energy. While studying transport energy is beyond the scope of the present project, the energy consequence of densification on the building energy balance including electric lighting will be addressed in the coming phases of this project. This analysis requires the use of the daylight autonomy metric (and not the daylight factor as presented here) since an annual calculation based on measured climate data is needed for a precise assessment. This part of the study is already initiated and will be presented in the next status reports.

5 Publications

The results were disseminated via one conference article, two conference presentations and two scientific posters:

1. Bournas I, Lundgren M, Alenius M, Dubois M-C (2017). Urban densification affects daylighting: existing daylight levels in Swedish multi-family housing as a base for future daylight requirement. 3rd International Conference on “Changing Cities": Spatial, Design, Landscape & Socio-economic Dimensions, 26-30 June 2017, Syros, Greece.
2. Dubois M-C & Rogers P (2017). Daylight levels in existing Swedish residential buildings as a base for modernized national regulations, Velux Daylight Symposium, Berlin, 3-4 May 2017.
3. Bournas I (2017). Scientific Poster titled “Low-energy daylit dwellings in the dense city - Benchmarks, metrics and tools securing good daylighting, low energy use and user acceptance”, Velux Academic Forum, Berlin, 2 May 2017.
4. Bournas I (2017). Presentation titled “Workflow for the generation of multiple illuminance files for distinct daylit spaces in apartment blocks”, IBPSA Nordic Conference 2017, Lund, 21 – 22 Sep 2017.
5. Bournas I (2017). Scientific Poster titled “Daylight utilization in the dense Swedish city - development of tools and methods as a base for future daylight requirements”, E2B2 Forskarmöte, Stockholm, 14 Nov 2017.

The results are also disseminated with the Master Programme ”Energy-efficient and Environmental Buildings”, coordinated by the Division of Energy and Building Design at Lund University.

One article for a peer review journal is presently under preparation based on the results presented in this report.

This project has been discussed both nationally and internationally, in scientific as well as business sector in different seminars e.g.

-Dubois M-C (2017-11-23). Norra Djurgårdstadens (NDS) competence seminar Stockholm, organized by White architects.

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Runt 35 procent av all energi i Sverige används i bebyggelsen. I forskningsprogrammet E2B2 arbetar forskare och samhällsaktörer tillsammans för att ta fram kunskap och metoder för att effektivisera energianvändningen och utveckla byggandet och boendet i samhället. I den här rapporten kan du läsa om ett av projekten som ingår i programmet.

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