Potential of space zoning for energy efficiency through utilization efficiency

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Potential of space zoning for energy efficiency through utilization efficiency

Energy efficiency improvements for buildings are required globally to reduce greenhouse gas emissions. Energy efficiency is typically calculated in relation to building size (kWh/m^{2}a), which ignores utilization. A utilization perspective entails a paradox in terms of energy efficiency: When utilization increases, so does energy consumption, encouraging minimizing the use of buildings. This paper advocates the use of a utilization efficiency indicator to reveal the impact of building use on energy efficiency. As a concrete design strategy, this paper explores the energy efficiency impact of space zoning, in this context meaning grouping rooms with similar utilization to optimize building systems. To this end, multiple whole building simulations on different utilization variants have been conducted. The results show that such design can improve concrete energy efficiency through more efficient utilization. Simultaneously, the importance of proper space zoning and utilization is highlighted, as otherwise simply increasing usage can also have a negative energy efficiency impact. This study raised the need for systematic utilization design to be included throughout the design process.

Keywords: Energy efficiency, Utilization efficiency, Building use, Occupancy, Utilization design, Spatial design, Space zoning, Utilization zoning, Multi-functionality, Indicator

Word count: 8 718 excluding lists of references, tables and figures.

1. Introduction

Improving energy efficiency is one of the main strategies for reducing greenhouse gas (GHG) emissions and therefore minimizing human-induced climate change. Several studies indicate that the building sector represents roughly 40% of both global energy use as well as GHG emissions (e.g. European Commission, 2010, 2016a; IPD, 2010; Vehviläinen et al., 2010). The European Commission has set in the Energy Performance of Buildings Directive EPBD that all member countries need to create their own definition of nearly Zero Energy Building (nZEB) and implement it in the construction field. The directive also states that by the year 2020 all EU countries together must reduce their energy consumption as well as GHG emissions by 20% from the 1990s levels to achieve targets set in the Kyoto Protocol (European Commission, 2010) and updated in the Paris Agreement (United Nations, 2015). Following this, the new target for GHG reductions is set to be 40% by the year 2030 (European Commission, 2014). Accordingly, in several European Union countries such as Finland, the empirical environment of this study, there are now new laws in progress.

Despite the above requirements, there is no unambiguous definition for energy efficiency. Directive 2012/27/EU on Energy Efficiency (European Commission, 2012, p. 10) defines energy efficiency in general as ‘the ratio of output of performance, service, goods or energy, to input of energy’ and energy efficiency improvement as ‘an increase in energy efficiency as a result of technological, behavioural and/or economic changes’. In the context of buildings, both definitions are clearly tied to the actual output, product, of the building, which can be for example usable floor area or money (González, Díaz, Caamaño & Wilby, 2011). Currently the energy efficiency of buildings is usually evaluated as energy consumption per unit of size, the unit describing either volume (kWh/m^3) or floor area (kWh/m^2). Of these, floor area is used in the widely adopted indicator Specific Energy Consumption (SEC) as well as

Finland’s National Building Code (Ministry of the Environment, 2011a). This approach unavoidably disregards the building as a whole: its spatial program, and using floor area even its three-dimensional properties. In practice minimizing the volume of the building has a direct effect on energy consumption, through for example heating demand, as well as the amount of money and materials invested (Lylykangas, Andersson, Kiuru, Nieminen & Päätalo, 2015). Alternatively, the same approach can be used in a different way by maximizing the use of a given space.

Studies have shown that most of the environmental impacts of buildings generated during their operation (e.g. Junnila, 2004; Sartori & Hestnes, 2007; 80–90% in Junnila & Horvath, 2003). It has also been noted that the use of buildings has a significant effect on their energy consumption (Airaksinen, 2011; Thewes, Maas, Scholen, Waldmann & Zürbes, 2014). Additionally, as the amending Directive 2016/0376/COD on Energy Efficiency (European Commission, 2016b, p. 2) notes, ‘[t]he cheapest energy, the cleanest energy, the most secure energy is the energy that is not used at all’. All of the above highlights the importance of not only constructing structurally energy efficient buildings but also making the most of them to reduce total energy use on a larger scale. This of course requires efficient spatial design decisions, especially in the early design phases where their energy efficiency impact has been noted to be greatest (e.g. Lechner, 2015).

Despite the identified need for designing functionally efficient buildings, there is no established method for proactively calculating the energy efficiency effect of use during the design process, although some indicators have been proposed. Instead, most of the effort on improving the energy efficiency of buildings has focused on technical measures (Sekki, Airaksinen & Saari, 2015) and monitoring the realized situation afterwards (e.g. Castanga, Antonucci & Lollini, 2016; Huovila, Tuominen & Airaksinen, 2017; Sekki, 2017) (see section 2. Indicators for evaluating usage and energy efficiency of buildings). To comprehensively address the issue of energy efficiency, implementing new indicators to complement the dominant area based methods is required. Accordingly, in this paper energy efficiency of a building is viewed as energy consumption in relation to the utility the building provides.

1.1. Research objectives

This research evaluates the significance of usage of buildings on their energy efficiency and examines a utility based indicator to complement and also question the established floor area based calculation convention. As a concrete solution, the research studies space zoning, a way to group spaces with similar utilization, as one design strategy to create more energy efficient spatial design based on the use of buildings.

The beginning of this paper (section 1. Introduction) establishes the background of this study from the perspectives of energy efficiency, usage of buildings and spatial design, as well as clarifies the objectives and scope of this research. Next section (2. Indicators for evaluating usage and energy efficiency of buildings) collates existing official as well as unestablished methods for observing energy efficiency in the context of the European Union. On the basis of this overview, the paper proposes an additional calculation method based on usage of buildings. Theory and calculations (section 3) introduces a case study, in which several variants of architectural space zoning are formed according to the usage of buildings, and subsequently used in energy simulations. Next (section 4. Results and discussion), the simulation results are examined using various calculation methods to show the potential impact of space zoning through building use and technical solutions, and to illustrate the difference in the results depending on the perspective used. Finally, Conclusions (section 5) sums up the main findings of this paper.

1.1.1. Scope of the research

From an energy efficiency perspective, the use of a building typically consists of the number of users and the time they spend in the building. These can be expressed as occupancy level (the percentage of occupants currently present of a standard number) and operating times (number of daily hours, and yearly days), for which standard values are listed in part D3 of the National Building Code of Finland (from here on mainly referred to as D3) (Ministry of the Environment, 2011a). Thus the amount of use can be calculated by multiplying occupancy level by operating times, as is common practice, or by totaling the hours each user spends in the building, as is more precise. (Forsström et al., 2011; Huovila et al. 2017; Ministry of the Environment, 2011a). In this paper, to highlight that the question is about the actual designed number of people, not the generalized percentage, the word 'utilization' is used for describing when and how the building is occupied. Additionally, the terms 'use' or 'usage' are employed on topics not related to the specific method of calculation.

As a concrete means for improving energy efficiency through architectural design, this paper studies utilization zoning. Spaces are grouped together based on their utilization period without changing the physical form or elements of the building, and building services run according to the occupancy of each space. Thus, space zoning as a type of multi-functionality and/or flexibility is used as a way to improve 'the ratio of output of performance, service, goods or energy, to input of energy' (European Commission, 2012, p. 10). This also presents architectural spatial design and building system solutions as parts of a single system, as is the case in reality. It should be noted that in the context of this study, spatial design and space zoning cover the layout of the building and not for example its volume or feeling of space. Even though space zoning cannot be seen actually as a totally new invention, the context and the way it is used here introduces a novel perspective.

The research is primarily focused on EU member countries, which are influenced by the union's common directives and typically use local floor area based energy efficiency calculation methods. This paper particularly encourages policy makers to question the currently limited perspective on evaluating energy efficiency, but also offers investors and designers incentives and new ways to consider the issue. For conciseness, deeper observations about the relationship between space efficiency and functionality, aesthetics or economics are excluded, although they are recognized as having potential for complementary research. This study also works on the building scale and does not handle areal observations in a wider context.

1.1.2. Research questions

With the goal of examining and encouraging the inclusion of usage and spatial design perspectives in energy efficiency evaluation and design, two connected research questions were set.

(1) How does the design of utilization of buildings – use and corresponding space zoning – affect energy efficiency?

(2) How does the effect of designing utilization of buildings appear using established and alternative indicators?

2. Indicators for evaluating usage and energy efficiency of buildings

‘Today there are 35 different national and regional methodologies to calculate the energy performance of buildings [within the European Union]’ (European Commission, 2016a, p. 48). Because all the member countries need to create or update their energy efficiency criteria to reach nearly Zero Energy Buildings, this number is likely to rise. There has been public discussion about unifying the methods (González et al., 2011; Kalliomäki, 2016), but different climate conditions and architectural traditions among other issues are preventing actual change.

In addition to national premises, different calculation methods are also employed depending on the perspective used. For example, in the Netherlands costs are integrated into the energy efficiency calculation (€/m^{2}a) (Alsema, Anink, Meijer, Straub & Donze, 2016). In Norway the Research Centre of Zero Emission Buildings has proposed integrating GHG emissions into the indicator (kg CO_2eq/m^{2}a) (Fufa, Schlanbusch, Sørnes, Inman & Andersen, 2016), which has also been presented in the Roadmap project commissioned by the Finnish Ministry of the Environment (Bionova Oy, 2017), so that energy efficiency would be one part of a larger scheme of environmental impact observations.

There have been several suggestions for ways to take buildings' use into account in energy efficiency calculations (Dooley, 2011; Forsström et al., 2011; Huovila et al., 2017; Sekki et al., 2015). From the perspective of this research the proposed indicators can be categorized into two groups, independent and integrated, based on whether they include building size (typically floor area) in the denominator. Independent indicators do not, while integrated indicators adjust the floor area based Specific Energy Consumption (SEC) by adding one or more factors into the formula. Examples of existing methods in these categories are presented in Table 1.

Table 1. Existing indicators for energy efficiency, buildings' use and spatial design divided into independent and integrated methods.

	Indicator name	**Unit**	**References**	**Explanation**
Independent indicators	Energy intensity of usage (EIU)	kWh/a kWh/pers	Forsström et al., 2011; Huovila et al., 2017; Sekki et al., 2015	a = yearly operating times pers = number of people
	Energy intensity of occupancy (EIO)	kWh/(pers*h)	Huovila et al., 2017	pers*h = sum of the number of hours that each occupant spends in the building during a year (total person hours)
	Space efficiency	m^2/pers	Huovila et al., 2017; Lylykangas et al., 2015; Sekki et al., 2015	
	Economic energy intensity (EEI)	kWh/€	Forsström et al., 2011	
Integrated indicators	Specific energy consumption (SEC)	kWh/m^2 kWh/m^2a	Ministry of the Environment, 2011a	The traditional indicator for energy efficiency, used for example in Finland (E-value)
	SEC per intensity of occupancy (SEC_{IO})	kWh/m^2(pers*h)	Dooley, 2011; Huovila et al., 2017	
	SEC adjusted for utilization rate (SEC_{UR})	kWh/m^2r	Forsström et al., 2011; Huovila et al., 2017; Sekki et al., 2015	r = utilization rate of the building measured as a ratio of actual daily usage hours to the highest possible usage hours, $0 \leq r \leq 1$
	SEC adjusted for occupancy and space efficiency ($SEC_{U,S}$)	kWh/m^2u	Huovila et al., 2017; Sekki et al., 2015	u = $(pers*t_{avg})/(A/a_{ref}*t_{ref})$, where t_{avg} = average number of hours present daily per person A = total area studied a_{ref} = amount of space per person available in typical case t_{ref} = normal working hours
	Energy performance of buildings (EPG)	€/m^2a	Alsema et al., 2016	used e.g. in the Netherlands (Energie Prestatie van Gebouwen)
	Material performance of buildings (MPG)		Alsema et al., 2016	used e.g. in the Netherlands (Milieu Prestatie van Gebouwen)
	Carbon equivalent footprint of buildings	kg CO_2eq/m^2a	Bionova Oy, 2017; Fufa et al., 2016	proposed e.g. in Norway (Zero Emission Building, ZEB)

As they are not the current norm, independent indicators rarely included in energy efficiency calculations. Their independence, however, is precisely what allows them to reveal totally new perspectives and bring additional value into the ensemble. A good example is space efficiency (m^2/person), which is often excluded from energy efficiency calculations (Lylykangas et al., 2015), even though unconstructed space naturally decreases environmental loads as well as energy consumption during construction, operation as well as maintenance, thus being an important part of the environmental impact of any building.

The advantage of integrated methods is that as modifications to the currently dominant formula they result in a single, familiar figure that is quick to interpret. Still, the amount of different important perspectives increases as energy efficiency calculations get more and more detailed. Combining a large number of perspectives such as economical aspects, GHG emissions, space efficiency and utilization into a single formula quickly becomes exceedingly complex, and also weakens the understanding of the impact of each individual factor.

2.1. Introducing utilization efficiency

It is clear that when a building is in use, it consumes energy. Thus, any integrated indicator will present minimizing use as having a positive effect on energy efficiency. This of course is paradoxical in practice. As buildings are becoming increasingly multifunctional, their degree of use increases, and so does the need for an energy efficiency indicator that takes this into account. Previous work has explored integrating building use into SEC, but little difference was found between the results produced by the two (Sekki, 2017), likely due to both still having floor area as the denominator. This section introduces utilization efficiency, an independent indicator which shows the ratio between buildings' energy use and utility, meant to complement existing energy efficiency calculation methods.

For utilization efficiency to consider building use comprehensively, both occupancy as people density and operating time as utilization degree are needed. Thus, the denominator becomes the sum of hours all users spend in the building during the observation period (here a year), named person utilization hours [$\Sigma(\tau_{pers} * t_{pers})$], and the complete formula for utilization efficiency as follows:

$$\text{Utilization efficiency} = \frac{\text{Energy consumption}}{\text{Person utilization hours}}\ ,\ P_{utilization} = \frac{E}{\Sigma\ (\tau_{pers}\ t_{pers})}\ , \qquad (1)$$

where $P_{utilization}$ is utilization efficiency [kWh/(pers*h)], E delivered energy consumption (kWh per year), τ_{pers} number of people (pers, number of people) and t_{pers} utilization time (h, hours per year).

In contrast to SEC and other integrated indicators, the utilization efficiency value of a building improves when either the number of users or the time in use increases, even though this also raises absolute energy consumption and energy consumption per square meter. As with SEC and its derivatives, the smaller the utilization efficiency value, the more energy efficient the building is. As a tool utilization efficiency is independent of the type of building.

3. Theory and calculations

To address the research questions, simulations were performed on a number of variants created from a real case building. All of the results were observed using the point of views of traditional energy efficiency as well as utilization, and with independent as well as integrated formulas, to see the difference between the approaches. Thus, the indicators used were delivered energy consumption [kWh/a], delivered energy consumption per floor area [kWh/m^{2}a], delivered energy consumption per floor area adjusted for utilization [kWh/m^2(pers*h)] and the proposed utilization efficiency [kWh/(pers*h)].

3.1. Case study: Jätkäsaari primary school in Helsinki, Finland

For this study, a real project was chosen instead of a purpose-built shoe box model. As the calculations require a degree of architectural as well as building systems engineering, such a model would have had to be rather complex, and therefore it was deemed practical to approach the issue from the other direction by simplifying an existing complex design. The chosen project is the winner of an architectural competition, finished in 2015, in which the task was to design a new cityscape enriching, architecturally high quality and energy efficient school for the new urban Jätkäsaari neighborhood in Helsinki, Finland (Fig. 1). The building is designed for 900 people, where 800 are students and 100 personnel. The project is scheduled to be completed in 2019. During the competition phase and following development the design has gone through a review by a board containing experts on both energy efficiency and school design. (City of Helsinki, 2015.) Therefore, its properties regarding both energy efficiency and functionality as a school have been confirmed thoroughly. Here it should be noted that although due to their increasingly multi-purpose nature a school building is a logical candidate for this study, and the interior arrangement of this one suits the purposes of space zoning, the methods and results are not tied to a specific building type. Nor do the calculation results need to be directly generalizable to other buildings, so a less generic study object does not affect their validity.

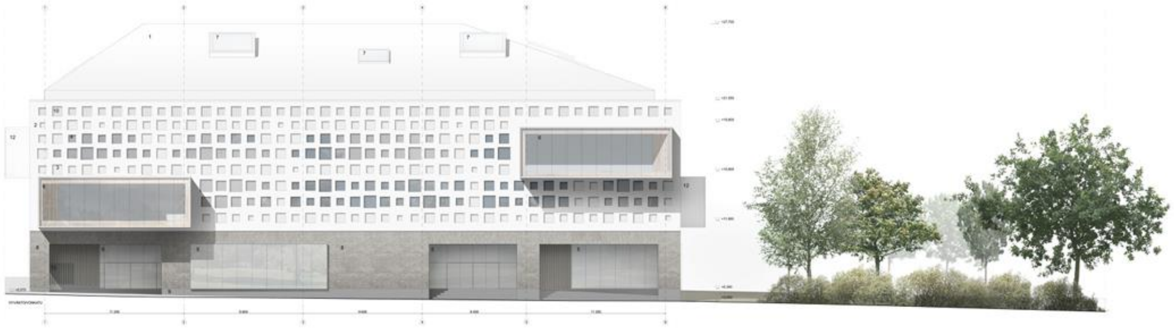

Fig. 1. Façade of Jätkäsaari primary school by Aarti Ollila Ristola Architects (AOR) (2017).

3.2. Simulation model

All calculations were performed using IDA Indoor Climate and Energy (IDA ICE) 4.7.1., a validated dynamic building performance simulation software by Equa Simulation AB, which is among the leading simulation software globally. IDA ICE simulates energy consumption as well as indoor climate using adaptive time steps, thus giving more accurate results than the established monthly calculation method. Additionally, IDA ICE takes into account the thermal capacity of building components. (Equa Simulations AB, 2017.)

For the simulations, a simplified building information model (BIM) was constructed in Graphisoft ArchiCAD 19 and transferred to IDA ICE in the IFC format (Industry Foundation Classes). This model was based on .dwg design documents from the draft design phase received from the project's architects. The simplifications made consisted mainly of merging rooms with similar indoor environment requirements and use patterns with the same type: small rooms such as toilets, closets, and to a lesser degree some medium size spaces such as some class or storage rooms. This led to the removal of some existing partition walls and interior doors, as well as the addition of some new partition walls to connect isolated rooms for modeling technical reasons. Also, some small bends have been straightened to expedite simulations. The windows, which have been shown to have a significant impact on simulation results (e.g. S. S. Kim, Nae & Y. D. Kim, 2016; Yong et al., 2017), notably remained untouched. The central atrium space, which goes vertically through the whole building and is characteristic to the design, has remained as it is with only added closable walls around its open space to assist in the simulations. The simplifications in general help avoid errors and overly long calculation times in the simulation process. The precise energy consumption figures obtained from the simulations are affected by the aforementioned changes, but as the focus is not on this particular building but on space zoning and utilization efficiency in general, this has no impact on the applicability of the study. Figure 2 illustrates the differences between the original and simplified floor plans. The climate data used in the simulations is based on the building location in Helsinki.

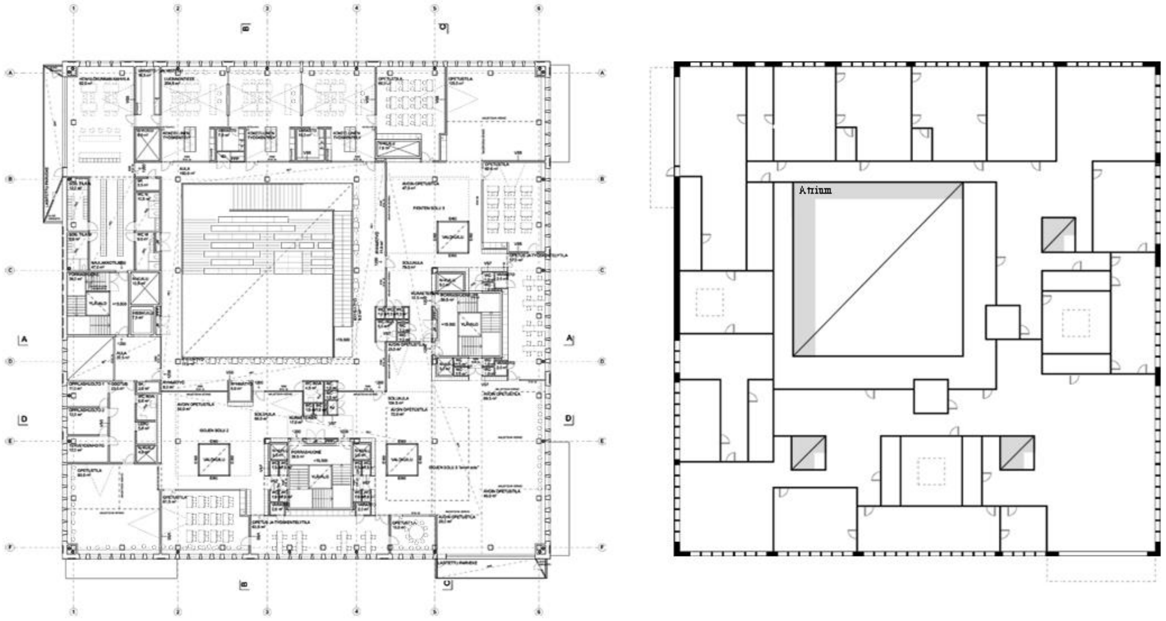

Fig. 2. Floor plan (2nd floor) of Jätkäsaari primary school in the real design by AOR Architects and in the simplified BIM used in the simulation.

The properties of the construction elements used in the BIM follow the Finnish National Building Code (Ministry of the Environment, 2011a), where the thermal transmittances (U-values) are set as follows: external walls 0.17 W/m^{2}K, roof 0.09 W/m^{2}K, external floor 0.16 W/m^{2}K, doors and windows 1.0 W/m^{2}K. Air tightness (q50) was set to 4 m^3/(h m^2) and the windows' solar factor (g-value) to 0.54.

3.3. Defining parameters for the simulated variants

Utilization itself consists of the number of people in the building, as people density, and the time when the building is in use, as utilization degree. Technical solutions also have a big influence on the end results and are therefore important to consider. Any of the above by themselves, however, do not lead to architectural changes, and therefore D3 values (Ministry of the Environment, 2011a) were used for them. In this section, these factors are discussed as background for the utilization zoning variants defined in section 3.4.

To observe utilization degree in multi-functional buildings, it needs to be divided into main and additional utilization. This is in particular because the Finnish Building Code

(Ministry of the Environment, 2011a) only recognizes the main use of a building. This is represented by main utilization degree, the time when all the occupants are using the building for its primary function. Additional utilization degree, respectively, covers the so-called extra use outside the main operating hours and possibly function. Even though the separation of multifunctional buildings' main and additional use is getting more difficult, it can still typically be defined based on the time allotted for each particular type of usage. The separation of main and additional utilization was used as a base for creating the following space zoning variants. All of the most relevant parameters of this topic used in the simulations are gathered in Table 2 next to the standard values from the Finnish National Building Code for comparison.

Table 2. Summary of the utilization related parameters used as base data in the simulations compared with Finnish National Building Code D2 (Ministry of the Environment, 2011b) and D3 (Ministry of the Environment, 2011a).

		Main utilization		**Additional utilization**	
Context		D2/D3	Article	D2/D3	Article
Number of people		1433	900	0	300
People density (pers/m^2)		1/5	1/7.96–1/1.0	-	1/23.89–1/3.0
Utilization factor		0.06	0.06	0	0.06
Time		08:00–16:00	08:00–16:00	-	16:00–22:00
Utilization time	(h/24h)	8	8	0	6
	(d/7d)	5	5	0	7
Airflow	Min. (dm^3/sm^2)	0.15	0.15	-	0.15
	Max. (dm^3/sm^2)	3	4	-	4

3.3.1. People density

According to the Finnish Building Code (Ministry of the Environment, 2011a), the people density number for educational buildings is 1 person per 5 m^2, which is the value IDA ICE uses. It should be noted that this is not actual design guidance, but rather an estimate for fitting for example building services. For Jätkäsaari primary school, this ratio would result in 1433 users.

To create realistic utilization zoning variants for this study, the people density number found in the Finnish Building Code (Ministry of the Environment, 2011a) as well as recommendations by Building Information Group were used as a basis. According to the latter, the theoretical floor area requirement in educational spaces, with furniture and equipment, is 2.51 m^2/student, which is a calculated average of guidelines for different kinds of rooms and uses (Building Information Group RTS, 2008). For a minimum variant of utilization zoning, a value of 1 m^2/person was used by considering the building's atrium a 'performance or information space' (Building Information Group RTS, 1998). In this extreme case, all of the design specified 900 people could be located within the atrium and lobby. Of course, all of these values are more or less theoretical.

3.3.2. Utilization degree

Utilization degree represents the building's yearly operating time. In this article, the main utilization degree is calculated according to the Finnish Building Code (Ministry of the Environment, 2011a). Built into the code are utilization factors, which depict a building's typical amount of use compared to a theoretical maximum and change according to use classifications defined per building type. The timetable used for utilization influences energy consumption directly and through internal heat gains from people, devices and lighting, as well as ventilation with constant air volume (CAV). IDA ICE software uses the schedule for the year 2016, when there were 261 normal days, 105 weekends (Saturday to Sunday) and altogether 366 days as the year was a leap year. The main utilization degree counts all weekdays (Monday to Friday) notwithstanding holidays.

Because the Finnish Building Code has no guidelines for additional use, its amount has been decided seeking a balance between realism and clarity in scenario setting. Compared to increasing the main utilization degree, these improvements are arguably more realistic. In practice, additional use could be more extensive during for example weekends and holidays. In this study, however, only evenings in addition to the standard main use of 8 hours/weekday are used for consistency and to simplify the simulations, using an identical amount of additional use for each day of the year from Monday to Sunday.

3.3.3. Technical solutions

The building service systems considered in this research are heating, cooling, ventilation, domestic hot water, lighting and occupant electricity consumption. Of these, heating, cooling, ventilation and lighting can be designed to accommodate themselves to the utilization on the building, thus avoiding excess use of energy, or alternatively they can be controlled by the user or a preset timetable.

The temperature in the simulations was controlled by an ideal heater and an ideal cooler. The ideal heater and cooler use a PI-controller to keep the temperature between a desired range, here 21–25 °C. This type of control accommodates the need for heating energy whenever there are changes in how the room is used. Interior heat gains were 18 W/m^2 from lighting, 8 W/m^2 from devices and 14 W/m^2 from people as set in the Finnish National Building Code (Ministry of the Environment, 2011a). District heating was used in the simulations.

The use of domestic hot water (DHW) naturally has an effect on energy consumption. However, it can be argued that the use of DHW would only change as a function of people in the building as a whole and not vary in any significant manner on the basis of utilization: whether the people are concentrated in certain rooms or spread around evenly, for example. Therefore, this research does not cover any effect the utilization may or may not have on the use of domestic hot water. In all simulated variations, a standard amount of DHW (188 dm^3/m^2 a) was used as set in D3 (Ministry of the Environment, 2011a). Similarly, occupant electricity consumption is considered likely to change only if the number of people changes regardless of their location. In the calculations rooms in use were set to use electrical appliances as stated in D3, and empty rooms had no consumption nor thermal loads from electrical devices.

Although lighting could be controlled even more energy efficiently based on specific uses for various areas, a more simplified model was used in this research to illustrate the overall effects of utilization. In the calculations it was assumed that rooms in use would have their lights on and empty rooms would have their lights off. The research does not cover whether this control would be achieved automatically or manually, nor possible related user operation issues.

Of all the building service systems ventilation is arguably among the ones utilization can have the biggest effect on in terms of use and thus energy consumption. Ventilation is also in many cases one of the main consumers of energy in buildings (O. Seppänen & M. Seppänen, 2007). One of the main purposes of the ventilation system is to ventilate out used indoor air with risen CO_2 and humidity levels and replace it with outdoor air. The people inside the building being the main source of CO_2 and humidity, it is natural that utilization of the building has a major effect on the need for ventilation. When ventilation is sized based on the full capacity of the building, the actual utilization based need can often be much less. Thus, of all technical systems, in this research the main emphasis is given to ventilation and what effect utilization may have on it. As an additional benefit, this limits the number of changing factors and keeps the focus on architectural spatial design solutions instead of turning it to technical decisions.

In this study ventilation was set to have CO_2 control, accommodating the airflow in each room based on the local CO_2 levels. The CO_2 control was set at 700–1100 ppm of CO_2 concentration, and within this range the flow rate would change linearly. For reference, in the Finnish Indoor Quality Classifications guidelines there are three levels given for CO_2: Level S1 (the best air quality) 750 ppm, level S2 900 ppm and level S3 1200 ppm (Säteri, 2008), all based on the standard CSN EN 15251 (European Committee for Standardization, 2007). Minimum and maximum flow rates were set at 0.15 and 4.0 dm^3/sm^2 respectively, in all rooms, and the people distributed evenly. The supply air temperature used was 18 °C, specific fan power (SFP) value 2 $kW/m^3/s$ and efficiency of ventilation heat recovery 45%. Extract air was added and distributed between zones to achieve balanced ventilation. Even though such equipment does not yet exist on this scale of air volume, the aim was to find out the possible potential of such a system. The ventilation runs as described during utilization, as well as one hour before and after, and on minimum settings at all other times.

3.4. Defining utilization zoning variants

According to the main research questions, there were two primary goals in creating the simulation variants: to study the effect of varying utilization zoning on energy efficiency, and to study the way in which different indicators reflect this effect. To this end, eight variants in two categories were created, as detailed in Table 3 for their differences and visualized in Figure 3. The other parameters used in the simulations were as defined in section 3.3.

Table 3. Properties of the variants used in the calculations.

Studied property	**Variant ID**	**Number of users present**	**Utilization time**		**Area in use**	**Areas in use**
			(h/24h)	**(d/7d)**	**(m^2)**	
Main utilization zoning	MZ1	900	8	5	7168	All
	MZ2	900	8	5	4466	Floors 1–2
	MZ3	900	8	5	2353	Floor 1
	MZ4	900	8	5	900	Atrium + lobby
Additional utilization zoning	AZ1	900 / 300	8 / 6	5 / 7	7168 / 7168	All / All
	AZ2	900 / 300	8 / 6	5 / 7	7168 / 4466	All / Floors 1–2
	AZ3	900 / 300	8 / 6	5 / 7	7168 / 2353	All / Floor 1
	AZ4	900 / 300	8 / 6	5 / 7	7168 / 900	All / Atrium + lobby

When there are two values given in a column, the first applies during the main utilization hours and the second during the additional utilization hours.

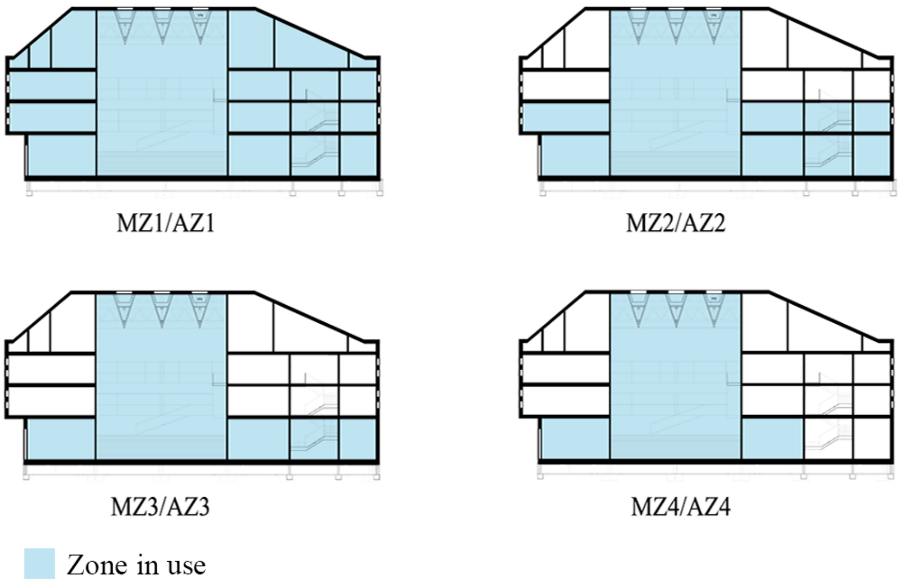

Fig. 3. Variants used in this study. The sections are modified from drawings by AOR Architects.

Each of the variants within the categories of main and additional utilization was created by varying only the amount of area in the building that's in use. The model components themselves were kept fixed, with only the building services adapting to the currently active areas as described in section 3.3.3. A distinction was made between the building's main operating hours and additional use, but the variants' utilized areas were kept the same between these categories for consistency.

4. Results and discussion

The results of the simulations ran on the studied variants are shown together in Table 4, and further illustrated by Figure 4. The figure is presented using ratios (%) instead of exact units to make comparing changes in different indicators easier. The area used as the denominator for the integrated methods is calculated in the MZ cases as the area in use in each zone (i.e. not counting the unused areas), and in the AZ cases as the sum of the total area in main utilization and the area in use in additional utilization. This theoretical formula does not consider main utilization's idle time's overlap with additional utilization but is sufficiently accurate to illustrate the difference between independent and integrated methods. The results with all of the presented indicators show that space zoning has an impact on energy efficiency, the impact varying based on the indicator.

Table 4. Numeric results of the variant simulations using delivered energy consumption [kWh/a], utilization efficiency [kWh/(pers*h)], delivered energy consumption per floor area [kWh/m^2a], and delivered energy consumption per floor area adjusted for utilization [kWh/m^2(pers*h)].

	kWh/a (independent)		**kWh/(pers*h) (independent)**	
Variant ID	**Value**	**% of base***	**Value**	**% of base***
MZ1	628 587	100.0 %	0.557	100.0 %
MZ2	583 106	92.8 %	0.517	92.8 %
MZ3	541 695	86.2 %	0.480	86.2 %
MZ4	510 800	81.3 %	0.453	81.3 %
AZ1	845 777	134.6 %	0.555	99.6 %
AZ2	764 116	121.6 %	0.502	90.1 %
AZ3	708 523	112.7 %	0.465	83.5 %
AZ4	687 534	109.4 %	0.451	81.0 %

	kWh/m^2a (integrated)		**kWh/m^2(pers*h) (integrated)**	
Variant ID	**Value**	**% of base***	**Value**	**% of base***
MZ1	87.7	100.0 %	0.000078	100.0 %
MZ2	130.6	148.9 %	0.000116	148.7 %
MZ3	230.2	262.5 %	0.000204	261.5 %
MZ4	567.6	647.2 %	0.000503	644.9 %
AZ1	117.99	134.5 %	0.000077	98.7 %
AZ2	118.04	134.6 %	0.000087	111.5 %
AZ3	121.7	138.8 %	0.000099	126.9 %
AZ4	153.2	174.7 %	0.000114	146.2 %

* % of base indicates the value in relation to the base case, MZ1.

Fig. 4. Variant simulation results in relation to the base case MZ1.

Firstly, when the zone in use gets smaller, the area needing increased ventilation also decreases, leading to increased utilization and therefore energy efficiency, even when the actual amount of use and number of users stays the same. Accordingly, the impact of main utilization zoning on both delivered energy consumption (kWh/a) and utilization efficiency [kWh/(pers*h)] is identical (almost 19% between the extremes), as is logical when both the period of time and the number of users stay fixed. The integrated indicators of kWh/m^{2}a and kWh/m^2(pers*h), however, reveal that the results are totally opposite when using the traditional floor area based indicator and its derivatives. For examining utilization related energy efficiency as described in this paper, this justifies not tying the indicator directly to floor area.

For additional utilization zoning, the difference between cases AZ1/AZ4 is about 25 percentage points in delivered energy consumption, actually more than between the main utilization variants, and almost 19 in utilization efficiency, which is proportionally very close. For additional use a very notable finding is that not all additional use has a positive effect on energy and utilization efficiencies: Having only a small amount of additional use relative to the amount of space is not particularly beneficial, as can be seen in Figure 4 by comparing the first few AZ variants to MZ1. However, additional use where zone size corresponds to the number of users is highly advantageous: Moving towards AZ4 and keeping the comparison to MZ1, utilization efficiency improves more and more while delivered energy consumption increases less and less.

Because the high atrium space in the case building reduces the difference in floor area between the extremes MZ1/MZ4 and AZ1/AZ4, the impact on results observed using integrated methods could be even bigger with solid floors, as the area of each non-ground floor would increase by roughly 600 m^2. The results with independent methods would stay the same, as would the building volume itself. Correspondingly, larger buildings could have even more significant results for optimizing utilization zoning, as there would be more underused space to cut for a given amount of use. As an alternative approach, follow-up research could be conducted where the smallest zone for additional utilization were just one room with its own entrance. This kind of zoning would allow building subsystem optimization, when for example only a small group of people needs to have a place for a meeting in the evening. Relatedly, from the calculations one can conclude that the bigger the difference in floor area between the zones is, the bigger is the impact of space zoning on energy and utilization efficiencies.

In practice the need for different amounts of area at different times can be solved by designing multi-functional buildings divided into several differently sized utilization zones. Utilization zoning as an architectural spatial design strategy can be seen as increasing the designer's responsibility on energy efficiency. In multi-storey buildings zoning can be implemented floor by floor, like in most of the variants in this paper (MZ1–3/AZ1–3). In a single-storey building or on the first floor it can be enabled with several entrances. On upper floors the zones should be formed in connection to the staircases to maximize flexibility. These simple space and architectural design solutions would often be comparatively easy to implement in real cases. Practical applications for additional utilization zoning are for example having wood and handicraft classes or sports facilities in school buildings be separate zones from the rest of the building, so that they are also available for use by the community outside school hours. On a general level, it can be said that diverse space zoning sizes or small zones with multiple combination possibilities enable diverse building use at all times of the day.

It should be noted here that as far as technical solutions go, this paper only studied the impact of utilization zoning through ventilation and lighting—taking other building services into account might increase the effects still. For example, optimizing heating in a similar way could add to the differences, but would also lead to discussion about at least the possible risks regarding indoor climate and construction elements' properties, which were not within the current scope. Nevertheless, even based on these observations the impact of utilization zoning on energy consumption materializes mainly through the effect it has on building systems.

4.1. The impact of individual parameters

The end results of the simulations consist of several individual parameters, of which the most important ones' (for this study) impacts are analysed separately in this section. The best results are reached by combining the best solutions for each individual parameter.

4.1.1. The impact of people density

People density has a significant impact on the end results as it is one of the key factors in utilization efficiency, as described in section 3.3.1. In the simulations, the designed number of 900 people was used instead of the D3 standard use value of 1433 (Ministry of the Environment, 2011a). Raising the amount of people so radically would create a significant difference in the simulation results, making the building systems run with much bigger volume than actually needed in this case.

If only the number of people were to increase with other parameters unchanged, the energy consumption of the building would actually decrease slightly due to the increase in heat gains from people and the corresponding decreased need for mechanical heating. More remarkable, however, would be the different degree of change between utilization efficiency and delivered energy consumption as the former would increase radically and the latter just slightly.

From a spatial design point of view, one could argue that advocating the design of building systems optimized for a smaller number of people could impair the flexibility of utilization, as currently they are designed more or less according to peak utilization, thus giving looseness for different uses. For this reason, adaptive building system solutions such as CO_2 control systems are needed. Additionally, there is a need for proper designing of building usage in the early design phase when the space planning and building system solutions decisions are also made. At that point the building's flexibility could be taken into account simultaneously with its concrete, comprehensive energy efficiency.

When increasing the amount of people in a certain area is encouraged, it is necessary to consider the matter of architectural quality. People density is a significant factor in terms of for example spaces' functionality and pleasantness, even if such quality is difficult to measure. Therefore, the results of this paper should not be misinterpreted and misused by cramming as many people as tightly as possible, but instead used to improve the utilization of buildings—

especially multi-functional ones—by spatial design. Still, alternative ways of assessment might exist. In the case of a school, for example, instead of energy efficiency related units building quality could also be (retroactively) measured using learning outcomes through for example ECTS credits, which the properties of the physical learning environment affect.

4.1.2. The impact of utilization degree

It is important to notice that increasing utilization degree will also increase absolute energy consumption because of the extended building systems running time. An unused building would consume less energy—and therefore be more energy efficient using SEC—than a building that were in use around the clock, while utilization efficiency shows opposing results.

An interesting aspect to consider is also the observation, that the building still has almost half of its total energy consumption even when it is not in use. In a complementary simulation where utilization degree was set to zero and other parameters kept fixed, the building still had 45% of its energy consumption compared to the standard case (MZ1). The explanation for this might be found from the fact that building services are still constantly running at the minimum air volume of 0.15 dm^3/sm^2 and the building is heated to 21 °C with no internal heat gains. As in the case of heating, this paper does not take a stand on decreasing the minimum amount of ventilation but notes that health issues should always be the first priority.

The main utilization time of 8 hours/day and 5 days/week used in the simulations comes from the National Building Code and is a realistic value according to normal Finnish working days for personnel in a school as well as other employees in for example libraries or offices (Ministry of Justice, 1996). In the case of a primary school, 8 hours can also be seen as the maximum length of a school day. Thus, to extend the main utilization degree to be more than 8 hours is more or less theoretical in this case. This of course depends on the main use of the building, but often increasing additional utilization is more realistic. Even though the impact of additional utilization on energy efficiency is smaller than the impact of main utilization, it can still be highly advantageous.

In general, changes to additional utilization degree have a similar impact on energy use as main utilization degree: When utilization time increases, energy consumption rises. For additional utilization, this study covers use during the evenings. Further research could be done on extending additional utilization to all day long during the weekends as well as holidays. At schools especially there is much potential during weekends, summers, Christmas and Easter, and other such periods like autumn and winter holidays. From a utilization efficiency perspective, the most efficient building is the one that is always in use. This also challenges spatial design to respond to various types of uses and functions calling for, for example, new kinds of building security systems. This can more or less be seen as the future direction, where purpose-built buildings are transforming into multi-functional and flexible ones.

In terms of buildings that are always in use, the challenge is to find functions that cover all the times of day all year round, as is the theoretical maximum situation, and also have enough use to be sustainable. For example, in a multi-functional school the main use in daytime is educational but in the evenings the spaces might be used for various hobbies, adult education, music institute functions, or even a public cafeteria. In the weekends, there could also be concerts, exhibitions and so on. Overnight use is also possible with accommodation facilities, e.g. for camp schools. Multi-functional buildings themselves are of course not a new idea, but considering the energy efficiency improvement potential in systematically designing such functions is something that is currently un- or underutilized.

4.1.3. The impact of technical solutions

Ventilation responding to the carbon dioxide created by the occupants is a significant, or even the most significant individual factor in the studies of this paper. With a CO_2 control system, the energy consumption of ventilation drops considerably compared to using constant air volume as per D2 (Ministry of the Environment, 2011b). In a comparison simulation performed using the base case MZ1, the difference in total building energy consumption was over 40%. When people density and utilization degree stay fixed, utilization efficiency gets better in proportion to energy consumption. Thus, ventilation system choice alone does not affect utilization efficiency without corresponding zoning. Nevertheless, ventilation control system analyses are essential when pursuing energy efficiency through increasing the amount of utilization.

Contrasting the significance of space zoning alone against ventilation system choice, it can be noticed that the impact of the former on energy efficiency is not as big as that of the latter (CAV vs. CO_2 control system). Still, to optimize the CO_2 control system, utilization based space planning is needed. That is why it is essential to design building use and space planning together with building system design, these in this case being utilization zoning and ventilation system design. Even though CO_2 control is already gaining traction and is as such not a new suggestion, there is still room for improving its use through spatial design. Additionally, and conversely, this can make increased flexibility and multi-functionality of buildings possible.

4.2. Employing utilization efficiency

To employ utilization efficiency along with corresponding utilization zoning as a part of the construction process, it needs to be noted by several parties such as policy makers, investors, architects and building service engineers. End users also have an important role in making the designed situation actually come to be. First of all, for utilization efficiency to be taken into account systematically in energy efficiency calculations and the design process, political decision making is needed to establish uniform methods and subsequently allow comparisons between different buildings. Secondly, investors have an important role in requiring utilization efficiency calculations from the designers or alternatively performing them themselves. In the end, investors are actually the main parties benefiting from an increase in utilization efficiency due to the ensuing optimized energy consumption and concrete economic advantages. As already mentioned, in practice the designs for utilization, space, and building systems need to proceed hand in hand requiring intensive collaboration between the respective parties.

Because utilization efficiency's main purpose is to be a tool for design and thus to be used already very early in the design process, it could be included even in the concept design phase as a Key Performance Indicator. Later on, a report on utilization efficiency could be presented similarly to energy efficiency calculations and documents. For example, in Finland there is the obligatory Energy Performance Certificate (EPC), which has to be given in connection with building permit, and the utilization efficiency report could be done next to it as an additional clarification. While the EPC is made by an energy engineer in collaboration with other designers, the utilization efficiency report could be the responsibility of an architect, also created in collaboration with an investor or their consultants as well as building system engineers. Also, even though utilization efficiency is primarily meant to be a design tool, the realized situation also needs to be verified. This can be done using the same formula.

Whether used for design or later evaluation, to advance the implementation of the method a set of system boundaries for the indicator is required. These would of course have to be defined separately for various uses, as for example a school has a practical people density drastically different from a hotel—5 m^2 versus 21 m^2 per person respectively in D3 (Ministry of the Environment, 2011a). Similarly, there are significant differences in realistic operation schedules and energy uses between different functions. For multi-use buildings, a combination of different values could be calculated according to the design and reviewed during possible renovations. More broadly, climate and geographic location—nationally or internationally—could be taken into account. As utilization efficiency is relatively easy to calculate, it can be used for simple intermediate calculations to compare several draft design solutions. These can be developed into a more accurate assessment in a later design phase. To be simplest for the designer, the formula could also be integrated into Computer-Aided Design (CAD) tools such as the Graphisoft ArchiCAD software used in this paper.

To reach energy efficiency in buildings, tradeoffs among architectural design solutions, structural choices, and building services are usually made to reach a comprehensive end result. After being integrated into the design process, this could be extended to utilization efficiency too. As an example, ineffective utilization could be compensated for by using better structures with appropriate thermal transmittance, and vice versa for example by optimizing the amount of materials as well as their emissions to reach required GHG targets. As with most other energy efficiency strategies, utilization efficiency too is also applicable to renovation projects, which at least in Finland actually represent the majority of the cases in need of energy efficiency improvements and new kinds of solutions. In a broader perspective, utilization efficiency could also be used on a regional level by observing all buildings' utilization efficiencies and examining them together.

Even though this paper concentrates on energy efficiency as the main strategy to reduce GHG emissions, due to the independent calculation method utilization efficiency is also easy to implement for other perspectives. For carbon footprint, for example, the formula could be $kgCO_2$ eq/(pers*h) instead of kWh/(pers*h).

4.3. Applicability of the research

As a limitation of this study it is important to emphasize how utilization efficiency as a tool should not be used. The formula is purposed to encourage designing building use as a part of the overall design process as well as to reveal the perspectives ignored by the traditional energy efficiency formulas. For emphasis, it bears repeating that the goal is not to compress as many people into as little space as possible or to minimize the amount of space for a certain amount of people, but to avoid situations, where the building is in ineffective use despite available space and all building service systems running on full power. Architectural quality and the wellbeing of occupants are always of paramount importance and preserved with the appropriate use of this tool.

One could argue that the original utilization will inevitably change during the building’s operation, in both short and long terms, which can be considered natural for all kinds of buildings. Correspondingly, the building’s utilization efficiency can change compared to the initial stated figure. For longer term changes, such as in changing of the main purpose of the building, new utilization calculations and design therefore need to be done, as this indicator should not limit the flexibility of the building by tying it to its initial uses.

As this work only had a single case building, in follow-up research and development other building types and forms, as well as other case buildings, could also be studied. These kinds of additional studies might for example reveal if space zoning is more suited to buildings with particular massing or if utilization efficiency gives significantly different results in different sized buildings. Also, as noted earlier the decisions made regarding building systems had their own effect on the results and could therefore be a topic for further examination. The concept of space zoning is also applicable to other perspectives than the utilization one addressed in this paper: zones can also be formed according to spaces’ indoor climate requirements, natural or artificial lighting, or similar structural choices such as by combining wet rooms into groups. Here, space zoning according to similar indoor circumstances might also have a notable impact on energy efficiency.

This paper concentrated on utilization’s impact on energy efficiency on the scale of one building. To take the wider context into account and design proper utilization, location in the urban structure is necessary to consider, especially for a multi-functional building. The context of a big city is conducive to multi-functional buildings having possible uses all day round, but the situation is different in small towns, where there might not be enough potential users. On the other hand, these kinds of multi-functional buildings could enable varied facilities in small towns without separate construction investments and maintenance costs, thus enriching local service offerings and activities.

5. Conclusions

From existing literature, different methods can be found for evaluating energy efficiency, usage and spatial design of buildings, both separately and combined. In this study, these methods were divided into two groups: integrated and independent, depending on if they are tied to a unit of size or not. The chosen perspective affects the way buildings are not only observed but also designed. The results of this study showed that designing the building systems according to utilization based spatial design can have a significant effect on concrete energy efficiency. Thus, this point of view is vital to include in the design process.

Observing energy efficiency using only the common floor area based method emphasizes the impact of building systems, disregarding the concrete effect of use and its related spatial design aspects. This paper examined and advocated the use of a complementary indicator called utilization efficiency to bring the perspective of actual building usage more integrally into the design process. The central observation made using this method is that true energy efficiency can in practice require choices opposite to those guided to by the established floor area based convention. As a result, it is clear that there is a need for such additional indicators when trying to reach energy efficiency, to represent the reality of buildings as complex entities comprising both technical as well as utilization and space related aspects.

To both study the suitability of current calculation methods for approaching energy efficiency from a usage perspective, and to develop concrete design strategy, eight different space zoning variants were formed based on varying utilization using Jätkäsaari primary school. A remarkable finding was that both energy efficiency as well as utilization efficiency can be improved through utilization zoning and using CO_2 controlled ventilation. Still, it is notable that only adding a small amount of additional utilization actually had a negative effect on energy efficiency, if not accompanied by proper space zoning. This result highlights that utilization should be planned, which is not systematically called for in current construction processes but should be included already in the early design phases next to conceptual space and building system designs. The results and concepts, although here studied in a Finnish context, are adaptable to buildings and building processes internationally by consulting local codes where needed.

It is central to this study that increasing utilization also increases energy consumption causing a situation contradictory to the established perspective on energy efficiency. The results obtained show that when increasing utilization efficiency of a building, energy consumption rises less than would be in direct proportion to the change, and thus increasing utilization is in fact beneficial to concrete energy efficiency. Designing how buildings are used, increasing their utilization, and avoiding vacancy has substantial potential for energy efficiency improvements. Ultimately, the best complete design solutions are reached as the combination of efficient utilization parameters (people density and utilization degree), sensor based building systems (CO_2 controlled ventilation) and appropriate spatial design (utilization zoning), all designed as a coherent whole.

References

Aarti Ollila Ristola Architects (22.8.2017). *Nemo* [WWW]. Retrieved from http://aor.fi/School-of-the-future-for-800-pupils-in-the-new-urban-district-of

Airaksinen, M. (2011). *Energy use in daycare centers and schools*. Energies 4 (2011) 998–1009.

Alsema, E. A., Anink, D., Meijer, A., Straub, A. & Donze, G. (2016, October). *Integration of Energy and Material Performance of Buildings: I=E+M. SBE16 Tallinn and Helsinki Conference: Build Green and Renovate Deep,* Tallinn and Helsinki. Energy Procedia 96 (2016) 517–528.

Bionova Oy (2017). *Tiekartta rakennuksen elinkaaren hiilijalanjäljen huomioimiseksi rakentamisen ohjauksessa* [Roadmap to take into account the carbon footprint of a building's lifecycle in the construction guidance].

Building Information Group RTS (1998). *RT 96-10656: Esitys- ja informaatiotilat* [Performance and information spaces] (Guidelines).

Building Information Group RTS (2008). *RT 96-10939: Koulurakennus, tilasuunnittelu* [School Building, Space planning] (Guidelines).

Castagna, M., Antonucci, D. & Lollini, R. (2016, October). *Monitoring of CasaNova Low Energy District: Result and Discussion. SBE16 Tallinn and Helsinki Conference: Build Green and Renovate Deep,* Tallinn and Helsinki. Energy Procedia 96 (2016) 895–906.

City of Helsinki (2015). *Jätkäsaaren peruskoulu ja Busholmens grundskola: Yleinen kaksivaiheinen arkkitehtuurikilpailu: Kilpailuohjelma* [Jätkäsaari Primary School and Busholmens Primary School: General Two-Step Design Competition: Competition Program]. Kiinteistövirasto, Tilakeskus, Opetusvirasto. Helsinki.

Dooley, K. (2011). *New Ways of Working: Linking Energy Consumption to people.* SB11 Helsinki Sustainable Building Conference Proceedings, Helsinki.

Equa Simulations AB (22.8.2017). *IDA Indoor Climate and Energy: A new generation building performance simulation software* [WWW]. Retrieved from http://www.equa.se/en/ida-ice.

European Commission (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union, L 153/13.

European Commission (2012). *Directive 2012/27/EU of the European Parliament and of the Council.* Official Journal of the European Union.

European Commission (2014). *COM/2014/015: A policy Framework for Climate and Energy in the Period from 2020 to 2030.* Communication from the Commission to the European parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

European Commission (2016a). *SWD/2016/4040 Commission staff working document: Good practice in energy efficiency.* Part 1/4: Accompanying the document Proposal for a Directive of European Parliament and of the Council amending Directive 2012/27/EU on Energy Efficiency.

European Commission (2016b). *Directive 2016/0376/COD of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency*.

European Committee for Standardization (2007). *CSN EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics.*

Forsström, J., Lahti, P., Pursiheimo, E., Rämä, M., Shemeikka, J., Sipilä, K., Tuominen, P. & Wahlgren, I. (2011). *Measuring Energy Efficiency: Indicators and potentials in buildings, communities and energy systems* (VTT Research Notes 2581). Kuopio: VTT Technical Research Centre of Finland.

Fufa, S. M., Schlanbusch, R. D., Sørnes, K., Inman, M. & Andersen, I. (2016). *A Norwegian ZEB Definition, Guideline* (ZEB Project report 29–2016). Oslo: SINTEF Academic Press.

González, A. B. R., Díaz, J. J. V., Caamaño, A. J. & Wilby, M. R. (2011). *Towards a universal energy efficiency index for buildings.* Energy and Buildings 43 (2011) 980–987.

Huovila, A., Tuominen, P. & Airaksinen, M. (2017). *Effects of Building Occupancy on Indicators of Energy Efficiency*. Energies 10 (2017) 628.

IPD (2010). IPD Environment Code: Measuring the environmental performance of buildings.

Junnila, S. (2004). *The environmental impact of an office building throughout its life cycle* (Doctoral dissertation). Helsinki University of Technology, Construction Economics and Management, A Research reports 2, TKK-RTA-A2: Otamedia Oy. ISBN 951-22-7284-9, ISBN 951-22-7285-7 (pdf), ISSN 1795-2700.

Junnila, S. & Horvath, A. (2003). *Life Cycle Environmental Effects of an Office Building.* Journal of Infrastructure Systems 9 (2003) 157–166.

Kalliomäki, P. (2016, September). *Mikä muuttuu energia- ja sisäilmasäädöksissä* [What will change in energy and indoor climate regulations]. *FINVAC Rakennusten energiaseminaari 2016* [Buildings' energy seminar 2016]. Helsinki: The Finnish Association of HVAC Societies.

Kim, S. S., Nae, M. J. & Kim, Y. D. (2016). *Policies and Status of Window Design for Energy Efficient Buildings.* Procedia Engineering 146 (2016) 155–157.

Lechner, N. (2015). *Heating, Cooling, Lighting: Sustainable Design Methods for Architects* (4th ed.). Hoboken, New Jersey: John Wiley & Sons Inc. ISBN 978-1-118-58242-8.

Lylykangas, K., Andersson, A., Kiuru, J., Nieminen, J. & Päätalo, J. (2015). *Rakenteellinen energiatehokkuus: Opas 2015* [Structural energy efficiency, Guide 2015]. Helsinki: Ministry of the Environment.

Ministry of Justice (1996). *Työaikalaki 9.8.1996/605: 6 § Yleissäännös: 3. Säännöllinen työaika* [Law of working hours 9.8.2996/605: 6 § General provision: 3. Regular working hours]. Helsinki: Edita Publishing Oy. Retrieved from http://www.finlex.fi/fi/laki/ajantasa/1996/19960605 (21.8.2017)

Ministry of the Environment (2011a). *The National Building Code of Finland: D3 Rakennusten energiatehokkuus* [D3 Energy efficiency of buildings] (Guidelines 2012). Helsinki.

Ministry of the Environment (2011b). *The National Building Code of Finland, D2 Rakennusten sisäilmasto ja ilmanvaihto* [D2 Indoor climate and ventilation] (Guidelines 2012). Helsinki.

Sartori, I. & Hestnes, A. G. (2007). *Energy Use in the Life Cycle of Conventional and Low Energy Buildings* (A review article). Energy and Buildings 39 (2007) 249–257.

Sekki, T. (2017). *Evaluation of Energy Efficiency in Educational Buildings* (Doctoral dissertation). Aalto University, Department of Built Environment: Unigrafia Oy. ISBN 978-953-60-7359-0 (printed), ISBN 978-952-60-7358-3 (pdf), ISSN-L 1799-4934.

Sekki, T., Airaksinen, M. & Saari, A. (2015). *Impact of building usage and occupancy on energy consumption in Finnish daycare and school buildings.* Energy and Buildings 105 (2015) 247–257.

Seppänen, O. & Seppänen, M. (2007). *Rakennusten sisäilmasto ja LVI-tekniikka* [Indoor climate and HVAC technology of the buildings] (4th ed.). Sisäilmayhdistys ry, SIY Sisäilmatieto Oy. Helsinki. ISBN 951-97186-5-6.

Säteri, J. (2008). *Sisäilmastoluokitus 2008: Sisäympäristön uudet tavoitearvot* [Finnish Indoor Quality Classification 2008: New guildeline levels for indoor climate]. Sisäilmayhdistys ry. Espoo.

Thewes, A., Maas, S., Scholen, F., Waldmann, D. & Zürbes, A. (2014). *Field study on the energy consumption of school buildings in Luxemburg.* Energy and Buildings 68 (2014) 460–470.

United Nations (2015). *FCCC/CP/2015/L.9/Rev.1: Adoption of the Paris Agreement.* Framework Convention on Climate Change, Paris Agreement.

Vehviläinen, I., Pesola, A., Jääskeläinen, S., Kalenoja, H., Lahti, P., Mäkelä, K. & Ristimäki, M. (2010). *Rakennetun ympäristön energiankäyttö ja kasvihuonekaasupäästöt* [Energy use and greenhouse gas emissions of the built environment] (Sitra’s statements 39). Helsinki: Sitra.

Yong, S.-G., Kim, J.-H., Gim, Y., Kim, J., Cho, J., Hong, H., Baik, Y.-J. & Koo, J. (2017). *Impacts of building envelope design factors upon energy loads and their optimization in US standard climate zones using experimental design.* Energy and Buildings 143 (2017) 1–15.

Table 1. Existing indicators for energy efficiency, buildings' use and spatial design divided into independent and integrated methods.

Table 2. Summary of the utilization related parameters used as base data in the simulations compared with Finnish National Building Code D2 (Ministry of the Environment, 2011b) and D3 (Ministry of the Environment, 2011a).

Table 3. Properties of the variants used in the calculations.

Table 4. Numeric results of the variant simulations using delivered energy consumption [kWh/a], utilization efficiency [kWh/(pers*h)], delivered energy consumption per floor area [kWh/m^2a], and delivered energy consumption per floor area adjusted for utilization [kWh/m^2(pers*h)].

Figure 1. Façade of Jätkäsaari primary school by Aarti Ollila Ristola Architects (AOR) (2017).

Figure 2. Floor plan (2nd floor) of Jätkäsaari primary school in the real design by AOR Architects and in the simplified BIM used in the simulation.

Figure 3. Variants used in this study. The sections are modified from drawings by AOR Architects.

Figure 4. Variant simulation results in relation to the base case MZ1.