

Article



# State of Knowledge of Thermal Bridges—A Follow up in Sweden and a Review of Recent Research

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**Abstract:** It is important to minimize transmission heat transfer losses through the building envelope when designing and building energy efficient buildings in heating dominated climates. In such a climate, a large part of the space heating demand is caused by transmission heat transfer losses through the building envelope. Calculations of these losses must be carried out in a correct way to ensure a properly sized heating system and a good indoor climate. Furthermore, underestimating the transmission heat transfer may lead to energy costs that exceed expectations. A Swedish study was published five years ago which concluded that the state of knowledge was low and simplified methods used were not accurate. Five years has passed since the previous study. The purpose of this follow-up is to investigate whether the state of knowledge among Swedish consultants has increased and to review the progress within the international field. The study shows that little has changed in Sweden. The state of knowledge regarding different measuring methods and the effect on thermal bridges is still not satisfying. Furthermore, the review of recent research shows that the relative effect of thermal bridges vary greatly. More guidelines and education/training are needed. Further research should be carried out with a holistic approach where thermal bridges are investigated with varying construction types, energy efficiency of building envelopes and different measuring methods.

**Keywords:** thermal bridges; EN ISO 13789; EN ISO 10211; transmission heat transfer; dimensions; buildings; review; survey; Sweden

# 1. Introduction

Globally, buildings account for 40% of the primary energy use and 24% of the generation of greenhouse gases [1]. Hence, the building sector has a large potential to reduce  $CO_2$  emissions and primary energy use, by reduced energy demand, increased efficiency in energy supply chains and greater use of renewable resources for materials and fuels. Different strategies can be used to grasp this potential, where one is to set requirements in building regulations, e.g., requirements on energy use or requirements regarding thermal insulation of building envelopes.

In order to strive for an increased energy performance of buildings within the European Union, the European Parliament approved the directive on Energy Performance of buildings (EPBD) in 2002 [2] and a recast in 2010 (EPBD2) which states that all buildings by the end of 2020 shall be "nearly zero-energy buildings" (NZEB) [3]. In short; A NZEB is a building that has a very high energy performance and the required energy should be covered to a very significant extent by energy from renewable sources. Furthermore, EPBD2 states that member states shall set energy requirements for building elements and/or building envelope. Methodology for calculations should take into account European standards and be expressed in a transparent manner.

To design and build an energy efficient house, different strategies may be applied. They differ slightly but a common first step is usually to reduce the energy demand, which in a heating dominated

climate is achieved by constructing an air tight and well insulted building envelope combined with balanced mechanical ventilation with high heat recovery efficiency. Designing a building according to these principles will result in that the majority of the heating demand is due to transmission heat transfer through the building envelope. Hence, it is important to calculate the transmission heat transfer in a correct way and not underestimate or exclude potential thermal bridges.

A heating dominated climate may be defined as a climate where 70% or more of the space conditioning needs is related to heating [4]. It should be noted that also in a heating dominated climate up to 30% of the space conditioning needs may be related to cooling. Hence, buildings still need to be designed to avoid excess temperatures during the warmer part of the year.

As mentioned, EPBD2 states that methodology for calculations should take into account European standards and be expressed in a transparent way. Standards are important as they provide reliability, predictability and security. Furthermore, they facilitate communication between different actors, minimizing the risk of misunderstanding. This leads to profits, both from a business perspective and from a macroeconomic perspective [5].

A commonly used standard to calculate transmission heat transfer through a building envelope is EN ISO 13789 [6] which in turn refers to two standards regarding thermal bridges; EN ISO 14683 [7] provides a simplified method including default values of linear thermal transmittance and EN ISO 10211 [8] provides a framework for detailed calculations of thermal bridges in building construction.

Regardless of method applied, to calculate transmissions heat transfer coefficients for a building, the building envelope needs to be divided into different building elements. Measuring in order to quantify the building elements may be conducted in different ways. Three different ways are clearly defined and referred to in all three standards mentioned above; internal, overall internal and external dimensions. The different methods are visualized in Figure 1.



**Figure 1.** Three different methods of measuring according to EN ISO 10211, EN ISO 13789 and EN ISO 14683.

Thermal bridges are defined as part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or a change in thickness of the fabric, and/or a difference between internal and external areas, such as occur at wall/floor/ceiling junctions according to EN ISO 10211 [8].

The linear thermal transmittance of the thermal bridge ( $\psi$ ) is calculated according to Equation (1).

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \tag{1}$$

where  $L_{2D}$  is the thermal coupling coefficient obtained from a 2-D calculation,  $U_j$  is the thermal transmittance of the 1-D element *j* and  $l_j$  is the length of the 1-D element *j*.

The point thermal transmittance of the thermal bridges ( $\chi$ ) is calculated as in Equation (2).

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{k=1}^{N_k} \psi_k \cdot l_k$$
(2)

where  $L_{3D}$  is the thermal coupling coefficient obtained from a 3-D calculation,  $A_i$  is the area of element i,  $\psi_k$  is the linear thermal transmittance calculated according to Equation (1) and  $l_k$  is the length of the thermal linear thermal bridge. Other symbols as described together with Equation (1).

As the measuring of areas and lengths may be conducted in three different ways (Figure 1), the specific values for thermal bridges may differ. In order to avoid misunderstanding and enable comparison, the chosen measuring method should always be included when specific values of thermal bridges are reported. Subscripts presented in Table 1 should be used, which is used in EN ISO 14683.

SubscriptDefinitionIInternal dimensionsOiOverall internal dimensionsEExternal dimensions

**Table 1.** Subscripts to clarify method of measuring.

A comprehensive review of the building codes in the European Union conducted in 2016 including 26 of the 28 members countries (Croatia and Luxemburg, not included) concluded that all countries have restrictive criteria in building regulations regarding U-values [9]. Furthermore, 23 of 26 countries (88%) include thermal bridges. However, most national regulations have adopted the simplified method according to EN ISO 14683.

Regardless of the standard used, different stakeholders may apply measuring methods differently, imposing a risk of misunderstanding. A consistent application of method for dimensions is important in order to correctly calculate the average U-value ( $\overline{U}$ ), according to Equation (3). Furthermore, simplified methods always have limitations. Poor calculations of transmission heat transfer through the building envelope may lead to increased heating demand, increasing the maximum power for heating that may have large marginal effects due to that the power demand will be high, since the energy demand in a heating dominated climate already is high. Furthermore, underestimating the transmission heat transfer may lead to undersized heating systems, poor indoor climate and energy costs that exceeds expectations. The resulting consequences may be uneconomical for the client, the builder and/or the consultant.

$$\overline{U} = \frac{\sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{k=1}^{N_k} \psi_k \cdot l_k + \sum_{j=1}^{N_j} \chi_j}{A_{om}}$$
(3)

where  $A_{om}$  is the enclosing area of a building. Other symbols as described together with Equations (1) and (2).

To investigate the state of knowledge and the risk of performance failure, a study was conducted in Sweden in which concluded that the state of knowledge were low and simplified methods used were not accurate [10]. The study further concluded that only 11% of the academic publications included in the study [11–28] clearly defined how they quantified building elements (i.e., measuring method).

Five years have passed since the Swedish study was published and the subject of thermal bridges has been under further research and development. The purpose of the follow-up study is to investigate whether the state of knowledge among Swedish consultants has increased since the previous study. Furthermore, recently published research articles are reviewed in order to investigate the progress within the international field. Also, the method used, to investigate the state of knowledge, is presented and evaluated in order for other researchers to use the method to investigate the state of knowledge within their geographical area of operation.

### 2. Methodology

## 2.1. The Survey

Major engineering, architect and construction firms in Sweden were contacted via their official contact information, available on their web sites. When contact was established, it was explained that a survey related to energy performance of buildings and thermal bridges would be conducted. Furthermore, they were asked whether they had employees, which had work assignments related to this area. If so, contact information in the form of e-mail addresses were gathered. This is the same method, which was used in the previous survey [10]. The new contact information was merged with the contact information from the previous survey. Through this method, 176 recipients were gathered. This method was chosen with the intention that those who were surveyed would have relevant competence and background.

The questions in the questionnaire were the same as in the previous survey, with two additional questions at the end, broken down in three sections. First, four questions were asked regarding measuring methods. Two questions were asked to identify how the respondents would quantify a building's envelope in order to calculate its energy performance, and how they would quantify a building's enclosing area. The questions were asked without any specific definition or reference to the Swedish building regulations. The same two questions were then asked once more; this time citing the definitions from the Swedish building regulations.

Secondly, the respondents were asked to review six different junctions, see Figure 2, and whether the transmission heat transfer would increase in addition to the losses included in quantified building elements or not. Regarding junction A–C, the calculated transmission heat transfer may not increase due to less insulation material or penetration of the insulation layer. i.e., whether the transmission heat transfer increases or not is related to how the respondent quantify building elements. Regarding junction D–F the insulation in the junction is penetrated by another material. However, whether the calculated transmission heat transfer increases or not in these junctions are also related to how the respondent quantify building elements. In junction E and junction F, the transmission heat transfer increases due to the wooden studs. However, the effect of different internal and external area is bigger. The effect of a junction regarding transmission heat transfer, based on chosen method for quantification of building elements, is presented in Table 2.



**Figure 2.** Schematic/simplified junctions as they appeared in the questionnaire. External environment is marked EXT. Internal environment is marked INT.

	Junction A	Junction B	Junction C	Junction D	Junction E	Junction F
Internal dimensions	Increase	Increase	Decrease	Increase	Increase	Decrease
Overall internal dimensions	No effect	Increase	Decrease	Increase	Increase	Decrease
External dimensions	No effect	Decrease	Increase	Increase	Decrease	Increase

**Table 2.** Summary of the effect of the junction on the calculated transmission heat transfer based on chosen method for quantification of building elements.

Finally, nine general questions regarding background and work methods were asked, compared to seven questions in the previous survey. The additional questions asked whether the respondent had answered the same questionnaire before and how they would rank the importance of different parts of a multi-family building envelope related to energy performance. The questions were given in Swedish to avoid misunderstanding due to language. The complete (translated) questionnaire is presented in Appendix A.

The survey was evaluated from three different aspects. First, it was evaluated how consultants in Sweden work today and how they quantify building elements. Secondly, based on how the respondents chose to quantify building elements,  $A_i$  in Equation (2), the respondents' answers regarding the junctions were analyzed. Finally, the execution of the survey was evaluated based on the time spent for the respondents.

The survey were conducted during September 2016. Two reminders were sent out. It was possible for the respondents to do a part of the survey, close the web survey, and start again where they left off, by using the link that was sent out. The previous survey were conducted in September 2010, using the same method as above [10].

## 2.2. Review of Research

A systematic desktop search was carried out in order to investigate the development within this field of research during the recent years through scientific databases available via Lund University; Science direct [29], Scopus [30] etc. The search term "thermal bridges" was used to search in titles and keywords. In order to narrow the desktop search, only research published after the previous study [10] were gathered and the search was restricted to the following journals; Applied Energy [31], Applied Thermal Engineering [32], Building and Environment [33], Energy [34], Energy and Buildings [35] and Sustainability [36]. Through this method a little over 200 publications were found. The abstracts were reviewed; articles which investigated the impact of thermal bridges were included, which narrowed it down to almost 60 articles. These articles were included in the review. If an article in the review gave references to other research, which were considered to be related to the impact of thermal bridges in buildings, these were also included in the review. Overall; 74 research articles and conference papers were reviewed. A summary of the sources is given in Table 3.

Source/Journal	Publications Reviewed
Energy & Buildings [35]	36
Energy Procedia [37]	15
Applied Thermal Engineering [32]	7
Applied Energy [31]	5
Sustainability [36]	3
Construction & Building Materials [38]	2
Building & Environment [33]	1
Civil Engineering and Management [39]	1
Energy [34]	1
Environmental Sciences Procedia [40]	1
IBPSA Building Simulation Conference 2015 [41]	1
World sustainable buildings Conference 2014 [42]	1

Table 3. Summary	of sources i	for reviewed	research
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## 3. Results

## 3.1. The Survey

Out of the 176 who received the questionnaire, 91 responded, which corresponds to 52%. The previous survey received 73 responses out of the 100 who received the survey (73%). Out of the respondent in the new survey, 93% had experience in energy calculations, compared to 84% in the previous survey. Furthermore, 74% had more than five years work experience, compared to 63% in the previous survey. The respondents' answers regarding experience in energy calculations and general work experience is presented in Figure 3. The most significant difference between the survey conducted in 2010 and 2016 is that the relative share of respondents' with experience in energy calculations and 6–10 years' experience has increased, while respondents with experience in energy calculations and 1–5 years' experience has decreased. Out of the 91 respondents, 13 respondents (14%) had answered the survey conducted in 2010. However, 17 respondents (19%) did not remember whether they had answered the survey or not.



**Figure 3.** Answers regarding experience in energy calculations (Q12), sorted by answers regarding work experience (Q17).

Some of the respondents spent more than 60 min on the survey; 14% in the new survey compared to 7% in the old survey. Most of the respondents who spent more than 60 min on the survey finished the survey on a different day compared to the starting day (69%). i.e., they did not complete the survey in one sweep. Most respondents spent 11 min on the new survey, compared to 8 min in the old survey. The median time were 13 min in the new survey compared to 10 min in the old survey. It should be noted that the new survey had two additional questions compared to the old survey.

Internal dimensions are most frequently used by the respondents to quantify building elements for energy calculations and has increased slightly compared to the previous study, see Figure 4. The use of overall internal dimensions has increased by almost ten percent, while external dimensions decreased by roughly the same share.



**Figure 4.** Distribution of answers to Q1 and Q2 for the old survey from 2010 and the new survey conducted in 2016.

Regarding quantification of enclosing area, the shift from external dimensions towards overall internal is greater compared to the shift in quantification of building elements. Measuring by overall internal dimensions are now the most common method, used by 40% of the respondents. However, the results show that that there is no measuring method which could be considered to be the norm in Sweden regarding quantifications related to energy calculations.

When the respondents were given the definitions of building elements ( $A_i$ ) and enclosing area ( $A_{om}$ ), as defined in the Swedish building regulations, the results were more uniform, see Figure 5. The definition of  $A_i$  is "The surface area of the structural element *i* in contact with heated indoor air" and the definition of  $A_{om}$  is "Total surface area of the building envelope facing the heated indoor air" [43]. Regarding  $A_i$ , there is an increased use of internal dimensions, almost 15% compared to previous research. Interpretations of  $A_{om}$  has slightly changed compared to the previous study.



**Figure 5.** Distribution of answers to Q3 and Q4 for the old survey from 2010 and the new survey conducted in 2016.

Regarding how thermal bridges are handled in general, there is a shift towards simplifications. In the old survey, the most common method to consider thermal bridges (44%) was to gather lengths of linear thermal bridges and quantities of point thermal bridges. These quantities were multiplied with default- and/or standard values based on guidelines, experience or available default values in the preferred software. The second most common method (22%) in the old survey was to increase the transmission heat transfer losses with a certain percentage. The third most common method (20%) was detailed calculations with numeric software.

The new survey showed that the most common method is to increase the transmission heat transfer losses with a certain percentage (49%). The second most common method (25%) is to gather lengths and quantities of thermal bridges combined with default- and/or standard values. The application of detailed calculations has decreased to 14%. The applied percentage factor to increase the transmission heat transfer losses has increased. In the old survey, almost 60% of the respondents who applied the percentage increase method used a percentage factor lower than 20%. In the new survey 60% of the respondents used 20% or more.

Regarding analysis and calculation of thermal bridges, 55% of the respondents in the new survey executed thermal bridges calculations, compared to 47% in the old survey. Out of the respondents who executed thermal bridges calculations, 83% explicitly used advanced software in the new survey (such as Therm [44], HEAT [45] and Flixo [46]), compared to 43% in the old survey.

As mentioned, a consistent application of method for dimensions is important. i.e., the total enclosing area must be the same as the sum of all building elements,  $A_i$ , to enable calculation of average U-value in a correct way. By cross examining the answers in this survey, related to how the respondents quantify building elements and how they quantify total enclosing area, it is possible to see the share of respondents who are not consistent.

The respondents who interpreted the definition of  $A_i$  as overall internal dimensions were most consistent; 68% quantify single building elements and enclosing area in the same way. The corresponding values for internal dimensions and external dimensions were 60% and 50% respectively. Overall 62% of the respondents were consistent and interpret the definition of building elements and enclosing area in the same way (question three and four, see Appendix A).

To further investigate the respondents' understanding, the answers from the assessment of the junctions has been sorted based on chosen dimensioning method for quantification of  $A_i$ . E.g., if a respondent answered that  $A_i$  is defined by external dimensions and afterwards answered that junction A is a thermal bridge; the answer is incorrect and therefore listed as incorrect. i.e., junction A may only be a thermal bridge if there are differences in external and external areas, which is not the case if one quantifies building elements based on external dimensions. The results are gathered and compared with the previous study in Figures 6 and 7.







**Figure 7.** Distribution of answers regarding if junction A–F, by chosen method for dimensioning of  $A_i$  and old/new (2010/2016) survey. Correct and incorrect answers.

Regarding the first three junctions (A–C), which may only be thermal bridges due to differences in the external and internal area, 51% of the respondents in the new survey gave a correct answer, regardless of chosen dimensioning method. This result is almost the same as in the old survey, where 50% gave a correct answer.

The fourth junction (D) is a thermal bridge regardless of chosen dimensioning method. The main reason for the thermal bridge is the partial penetration of the building envelope, by the concrete interior slab, with a material with a significantly higher thermal conductivity. The assessments showed a significantly higher correctness level in this case; 92% correct assessments in the new study. Also in this case the result is close to the same as in the old study, where 89% gave a correct answer.

As mentioned in the method section; in the last two junctions (E–F) the transmission heat transfer increases due to the wooden studs. However, the effect of different internal and external area is bigger. Regarding these junctions, 88% of the respondents in the new survey answered that these junctions would increase the transmission heat transfer losses in addition to the losses included in building elements, regardless of dimensioning method. The corresponding value in the old survey were 92%. The respondents in general, in both the old and the new survey, seem to make the assessment that the effect of the wooden studs are larger than the geometrical effect due to differences in internal and external areas.

The share of correct answers among the respondents who interpret quantification of  $A_i$  as internal dimensioning (the most common interpretation of  $A_i$ ) has increased slightly to 56% in the new survey. Also the share of correct answers among respondents who interpret quantification of  $A_i$  as overall internal dimensioning (the second most common interpretation of  $A_i$ ) has increased slightly to 67% in the new survey. The share of correct answers among respondents who interpret quantification of  $A_i$  as external dimensioning (the least common interpretation of  $A_i$ ) has decreased to 50% in the new survey. Overall, the share of correct answers, regardless of method for measurement, has increased slightly to 58% in the new survey compared to 56% in the old survey. The breakdown is presented in Table 4.

	t Year of Survey - 2010 2016 2010	Allocation of Answers			
Method of Measurement		Correct Answers	Incorrect Answers	No Answers	
Internal	2010	132	113	7	
	2016	217	159	14	
Overall internal	2010	79	45	2	
	2016	88	44	0	
External	2010	12	6	0	
	2016	6	6	0	
Total	2010	223	164	9	
	2016	311	209	14	

**Table 4.** Number of answers in the assessment of junctions based on correct, incorrect and no answers. Related to the respondents' interpretation of dimensioning for  $A_i$ .

In the third section of the survey, the respondents were given the three definitions of a thermal bridge according to EN ISO 10211 [8], and were asked which of these they considered to define a thermal bridge. The distribution of answers is given in Table 5. Only 18% of the respondents in the new survey chose all three definitions. However, this is an increase compared to the old survey where only 5% of the respondents chose all three definitions.

	Share of Respondents, Year of Survey	
_	2010	2016
Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity.	81%	84%
Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by a change in thickness of the fabric.	22%	29%
Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by difference between internal and external areas, such as occur at wall/floor/ceiling junctions.	19%	35%

Table 5. Share of answers "Yes", related to how the respondents defined a thermal bridge.

#### 3.2. Review of Research

Out of the reviewed research, the most common approach when investigating thermal bridges were case studies focusing on thermal bridges. Roughly 40% of the reviewed research were some sort of case study where thermal bridges were analyzed in the context of the effect on a building [47–79]. A large part of the studies, 28%, investigated thermal bridges in a limited context, usually a part of a wall section [80–101]. Most studies, which investigated the effect of thermal bridges in the context of a building, did not present specific values for the thermal bridges. Furthermore, they did not specify whether the quantification of building elements were based on internal dimensions, overall internal dimensions or external dimensions. One study was identified where the specific values for different thermal bridges were presented together with the chosen method, internal dimensions [74], for a complete building.

Out of the identified studies, less than 10% clearly defined the method for quantification of building elements [54,58,66,74,94,97,98]. Except for the study mentioned above [74], only two more studies were identified where both specific values for thermal bridges were presented in combination with a clearly defined method for quantification of building elements [97,98].

The previous study [10] highlighted that different stakeholders may apply different measuring methods, imposing a risk of misunderstanding. Out of the reviewed research, roughly 11% referred to results from this previous study [47,53,58,59,76,89,94,101]. However, only two of these studies clearly defined a measuring method [58,94].

Overall, the most common approach found to express the impact of thermal bridges was to quantify the effect in percentages. The effect varied commonly from 10% to 30%. However, examples were also found where the relative impact may be below 10% [48,53] and above 30% [10,57], where the low relatively impact was related to historical buildings with already poor insulation and the relatively high impact was related to buildings corresponding to passive house standard.

## 4. Discussion

#### 4.1. The Survey

Regarding the response rate on the questionnaire and the number of respondents, the quantity of recipients increased from 100 to 176 while the response rate decreased from 73% to 52%. At the same time, the quantity of recipients increased more than the decrease in response rate. Furthermore, the respondents in the new survey has longer experience and more direct experience of energy calculations. This indicates that the demand for professionals who carry out energy calculations has increased and could also be interpreted as increased work load on these professionals, as fewer respond to the survey.

Over all, the survey gathered answers from almost 100 respondents, where more than 90% had experience from energy calculations and more than 70% had more than five years work experience. This indicates that the intention to find professionals in this field succeeded.

The purpose of the survey was to, in an effective way, determine the state of knowledge among professionals who work with energy calculations, related to thermal bridges. Disregarding the respondents who finished the survey on a different day compared to starting day, 94% of the respondents spent less than 60 min to answer it. The respondents who spent more than 60 min to answer the survey may have started to answer the survey, taking a break for coffee or attending a meeting before finishing the survey. Overall, the time spent on answering, indicates that the survey may be an effective way to determine the state of knowledge.

Regarding quantification of building elements and buildings' enclosing area, the biggest shift, comparing the old and the new survey, was the increased use of overall internal measuring when quantifying a buildings' enclosing area. However, there is still a big spread among the answers. With the exception for the definition of  $A_i$  according to the Swedish building regulations (Question 3), there is no measuring method that is chosen by more than 50% of the respondents when asked to define building elements and buildings' enclosing area. The survey show that there is still no widespread and established view among engineers and architects in Sweden regarding how to quantify building elements as input for calculation of transmission heat transfer losses.

Several consultants are usually involved in the design and construction phase of a building. Hence, it is possible to imagine a scenario in which an architect will be asked to provide quantities of building elements and junctions, a construction engineer to calculate U-values and specific values for thermal bridges and a HVAC-consultant to do energy calculations and sizing of heating- and cooling system. In such a scenario, misinterpretations and therefore incorrect calculations of transmission heat transfer losses may occur.

An increased use of Building Information Modelling, BIM, may pave the way for more standardized and automatic way to use input data, which could minimize such errors. On the other hand, this could also be a potential source of error if quantity take offs (data export from the model e.g., floor-, roof-, wall areas etc. to text data) are used from the BIM model without a critical review of the data from the model.

Regarding how thermal bridges are taken into account, there is a trend among engineers and architects towards simplification. Almost a majority of the respondents (49%) used a method where they leave out the calculation of thermal bridges and instead increased the transmission heat transfer through the building envelope by a percentage factor (22% in the old survey). However, the percentage factor has increased, indicating that e.g., architects and engineers have a greater respect for thermal bridges today, while they unfortunately do not have the time to consider them in a thorough way.

This survey also indicated that engineers and architects do not fully understand when or where thermal bridges may occur. No substantial improvement was identified comparing the old and the new survey, especially not when a thermal bridge is due to differences between internal and external areas. This is concerning. If an engineer or architect does not consider a junction to be a potential thermal bridge, it is not likely that the junction will be investigated, which could lead to large errors in energy calculations and sizing of heating- and cooling systems.

This survey was carried out among Swedish engineers and architects and the results should therefore be viewed from that perspective. From a more global perspective, it would be beneficial to carry out a global survey based on the survey used here. Such a survey could highlight differences between different countries and regions and highlight where there is a need for more guidelines and standardization.

Furthermore, when defining answers related to the junctions as incorrect or correct, we assume that the respondents understands the task given to them. Some respondents may have misunderstood the survey. i.e., the results should be viewed keeping this in mind. However, as the majority of the respondents has a solid background within this field. This error should be low. In order to minimize this possible error further studies could review and try to improve the questions.

As most respondents only consider the definition of a thermal bridge to be one; "Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity", this is most likely the reason for the high share of incorrect answers. To ensure that respondents understand their definition, further investigations with surveys could be carried out in a way where the respondents are asked to review specific junctions based on their chosen definition or definitions.

## 4.2. Review of Research

The review of the recent research showed that there is a rather large quantity of research related to case studies and thermal bridges in their specific cases. Standard and/or default values exist today (e.g., ISO 14683 [7]). However, previous research showed that specific values may vary greatly. i.e., the case studies showed that it is not possible to define default values in a simple way.

Many of the investigated studies mainly discussed the impact of thermal bridges in relative terms. As the results show, the impact from thermal bridges may be below 10% and above 30%. It should therefore not be recommended to use relative terms in energy calculations and sizing of heating- and cooling systems for buildings. Hence, the research who presents the results in relative terms makes it difficult for other researcher to use in further studies. Furthermore, presenting results in relative terms makes it difficult for other researchers to verify the results.

Many researchers cite EN ISO 10211 [8]. This standard states that the method used for measuring when calculating thermal bridges should be presented together with the calculated values. Still, an overwhelming majority of the research fails to include this information when they present their results. This underlines the need to increase knowledge and compliance related to standards among researcher, reviewers and editors.

#### 5. Conclusions

#### 5.1. The Survey

The results from the survey show that little has changed in Sweden since the previous survey was conducted. Still, the state of knowledge regarding different measuring methods and the effect on thermal bridges is not satisfying. The share of correct answers, when assessing junctions as potential thermal bridges, has increased slightly to 58% in the new survey compared to 56% in the old survey.

When asked how to quantify a building envelope for energy calculations, there is no measuring method used by more than 50% of the respondents. More guidelines and education/training are needed. Hence, no clear norm/practice can be identified regarding measuring method used.

The survey usually took less than 60 min to answer. It would be beneficial to carry out a global survey based on the survey used here in order to highlight where there is a need for more guidelines and standardization.

#### 5.2. Review of Research

The literature review shows that thermal bridges are treated in different ways and that information about the method used for measuring, when calculating thermal bridges, is often not presented together with the results. More than 70% of the reviewed research focus on case studies, investigating the effect of thermal bridges where the most common approach was to quantify the effect in percentages. Less than 10% of the studies clearly defined measuring method used. Only three studies were found which included both specific values for thermal bridges and clearly defined measuring method used.

The relative effect of thermal bridges may vary greatly and should therefore not be considered in relative terms as input data in energy calculations and sizing of heating- and cooling systems for buildings. Further research should be carried out with a holistic approach where thermal bridges are investigated when the following is varied: Construction types (e.g., concrete sandwich walls, wooden frame walls, etc.), energy efficiency (e.g., quantity and type of insulation) and method of measuring (internal, overall internal and external).

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# Appendix A. Questionnaire

This questionnaire is translated from the original in Swedish.

# Introduction

This questionnaire roughly takes five-fifteen minutes to answer.

The questionnaire aim is to investigate how you interpret different definitions and junctions between different building elements. The purpose is to identify if there is a need for clarifications, guidelines, etc. in relation to calculations and quantifications of thermal bridges and building envelopes related to energy performance of buildings.

The questionnaire begins with four questions regarding how you interpret different definitions. Then you will give your opinion regarding six different junctions between different building elements, whether these are thermal bridges or not. The investigation ends with nine general questions related to your work and background.

All answers are processed anonymously.

In case of any questions, please contact: bjorn.berggren@ebd.lth.se Lund University, Div. of Energy and Building Design.

1. If you were given the task to quantify a building envelope for energy calculations, which of the methods below would you choose?



**Figure A1.** Different methods of measuring, figure included in questionnaire. (**a**) Internal dimensions; (**b**) Overall internal dimensions; (**c**) External dimensions.

- □ Internal dimensions, measured between the finished internal faces of each room (Figure A1a).
- □ Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A1b).
- □ External dimensions, measured between the finished external faces of external elements of the building (Figure A1c).

## $\Box$ Other, please describe:

2. If you were given the task to quantify a building's enclosing area, which of the methods below would you choose?



**Figure A2.** Different methods of measuring, figure included in questionnaire. (**a**) Internal dimensions; (**b**) Overall internal dimensions; (**c**) External dimensions.

- □ Internal dimensions, measured between the finished internal faces of each room (Figure A2a).
- □ Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A2b).
- □ External dimensions, measured between the finished external faces of external elements of the building (Figure A2c).
- $\Box$  Other, please describe:

3. In the Swedish building regulations, the term  $A_i$  is used and referred to as: "The surface area of the building element i in contact with heated indoor air ( $m^2$ ). For windows, doors, etc.,  $A_i$  is calculated using external frame dimensions." Which of the definitions below, do you think best describes this definition?



**Figure A3.** Different methods of measuring, figure included in questionnaire. (**a**) Internal dimensions; (**b**) Overall internal dimensions; (**c**) External dimensions.

- □ Internal dimensions, measured between the finished internal faces of each room (Figure A3a).
- □ Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A3b).
- □ External dimensions, measured between the finished external faces of external elements of the building (Figure A3c).
- $\Box$  Other, please describe:

4. In the Swedish building regulations, the term  $A_{om}$  is used and referred to as: "Total surface area of the building envelope facing the heated indoor air  $(m^2)$ ." Which of the definitions below, do you think best describes this definition?



**Figure A4.** Different methods of measuring, figure included in questionnaire. (**a**) Internal dimensions; (**b**) Overall internal dimensions; (**c**) External dimensions.

- □ Internal dimensions, measured between the finished internal faces of each room (Figure A4a).
- □ Overall internal dimensions, measured between the finished internal faces of external elements of the building (Figure A4b).
- □ External dimensions, measured between the finished external faces of external elements of the building (Figure A4c).
- $\Box$  Other, please describe:

You will now be asked to examine six different junctions between building elements. For each junction, we want you to answer whether you consider the junction to be a thermal bridge or not.

By thermal bridge, we imply a part of the building envelope where the transmission heat transfer losses increases in addition to the transmissions heat transfer losses which are already included in relation to the building elements.

5. The figure below describes an interior concrete floor slab connected to an exterior concrete wall. The exterior wall is insulated on the exterior side. Would you consider this junction to be a thermal bridge?



Figure A5. Schematic/simplified junction, figure included in questionnaire.

- □ Yes
- □ No

6. The figure below describes a concrete wall corner. The exterior wall is insulated on the exterior side. Would you consider this junction to be a thermal bridge?



Figure A6. Schematic/simplified junction, figure included in questionnaire.

- $\Box$  Yes
- □ No

7. The figure below describes a concrete wall corner. The exterior wall is insulated on the exterior side. Would you consider this junction to be a thermal bridge?



Figure A7. Schematic/simplified junction, figure included in questionnaire.

□ Yes

□ No

8. The figure below describes an interior concrete floor slab connected to an exterior infill wall. The infill wall is insulated. Would you consider this junction to be a thermal bridge?



Figure A8. Schematic/simplified junction, figure included in questionnaire.

- □ Yes
- □ No

9. The figure below describes a wall corner for an insulated wood framework wall. The corner requires one extra wood stud (marked with red). Would you consider this junction to be a thermal bridge?



Figure A9. Schematic/simplified junction, figure included in questionnaire.

□ Yes

□ No

10. The figure below describes a wall corner for an insulated wood framework wall. The corner requires one extra wood stud (marked with red). Would you consider this junction to be a thermal bridge?



Figure A10. Schematic/simplified junction, figure included in questionnaire.

- □ Yes
- □ No

You will now be asked nine general questions.

- 11. What is your profession?
- □ Architect
- $\Box$  Structural engineer
- □ HVAC engineer
- □ Energy engineer
- $\Box$  Other, please describe:

12. Do you have experience from energy calculations/simulations?

- □ Yes
- □ No

13. According to you, what is the most common way to consider thermal bridges in energy calculations/simulations?

□ Increasing the heat transfer through the building envelope by a percentage factor, please give a percentage (%):

- □ Gather quantities of thermal bridges and applying default- and/or standard values from software, EN ISO 14683, etc.
- □ Gather quantities of thermal bridges and applying results from detailed calculations (HEAT, COMSOL, THERM, etc.).
- $\Box$  Other, please describe:
- 14. Do you have experience from thermal bridges calculations?
- □ No
- □ Yes, please shortly describe preferred software, methods, etc.:
- 15. According to you, who should be responsible for thermal bridges calculations?
- □ Architect
- □ Structural engineer
- □ HVAC engineer
- □ Energy engineer
- $\Box$  Other, please describe:

16. According to you, which of the following definitions define a thermal bridge? (It is possible to choose one, two or three definitions)

- □ Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity.
- □ Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by a change in thickness of the fabric.
- □ Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by difference between internal and external areas, such as occur at wall/floor/ceiling junctions.
- 17. How long is your work experience?
- $\Box$  <1 year
- $\Box$  1–5 years
- $\Box$  6–10 years
- $\Box$  >10 years

18. Did you participate in the previous survey, conducted roughly five years ago?

- □ Yes
- □ No
- $\Box$  Do not remember

19. In relation to an apartment building with a well-insulated building envelope, how would you rank the following measures in order to reduce the transmission heat transfer losses through the building envelope? (1 = highest priority, 8 = lowest priority)

- \_\_More insulation in the building foundation
- \_\_More insulation in the roof construction
- \_\_More insulation in exterior walls

- \_\_Glased elements with lower U-value (not regular windows)
- \_\_\_Doors with lower U-value
- \_\_Improving thermal bridges
- \_\_Improving air tightness

Thank you for your participation!

The questionnaire is now completed.

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