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Evaluating the effectiveness of improved workmanship quality on the airtightness of Dutch detached houses

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Abstract

Increasing the airtightness of buildings can contribute in coming to energy neutral buildings. This paper evaluates two possible measures: modest technical improvements and coaching of construction teams. Beforehand, the specific leakage rate of 44 detached houses was measured using a blower door test and by means of statistics, the most pressing problems were determined. An educational session was developed to explain construction workers the relevance of and their own influence on building airtight houses. The effectiveness of the technical improvements and the education was assessed by evaluating 14 new houses. This evaluation showed a significantly improved airtightness.

Keywords: airtight houses, air permeability, blower door test, education, workmanship quality

1. Introduction

Achieving energy neutral buildings is an ambition expressed in the legislation of many countries, especially European. The positive effects of insulation and energy efficient heating systems on the energy performance of a building are compromised when, during the heating season, a house leaks heated air and cold air enters. Therefore, increasing the airtightness of buildings can contribute to accomplishing energy neutral buildings and comfort, next to increasing occasionally air quality, sound insulation, fire resistance and humidity control [1]. Scholars [2–5] conclude

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estimations ex ante on the airtightness of houses are not straightforward, but often depend on the quality of workmanship and the applied design. Other researchers also stated that attention to detail and enhancing supervision in order to improve the quality of workmanship, helps in achieving a better airtightness in buildings [6]. Laverge et al. [4] compared the air leakage between dwellings built with standard workmanship and dwellings built with extra attention for airtightness. They found significant differences between these two groups. Kalamees [5] determined typical air leakage locations and concluded that quality of workmanship and supervision has a significant effect on the airtightness. Sinnot and Dyer [7] concluded that "the results clearly demonstrate that good design, detailing, specification of materials and construction practice are of fundamental importance when constructing new houses". All these studies were not aimed at exploring the effects of workmanship, but finally had to conclude that workmanship affected air leakage. Therefore, the aim of this research is to assess the effects of workmanship quality on the air leakage rate in newly built detached houses, by determining the effects of improving the quality of workmanship of construction workers on the air leakage in buildings.

Nomenclature

BD-test	Blower door test	
n_{50}	Air change rate at 50 Pa	h^{-1}
NrPA	Number of problem areas per building	-
q_{50}	Air permeability across the building envelope area at 50 Pa	$m^3/s \cdot m^2$
TL	TotalLeakage per building	-
w_{10}	Specific leakage rate across the usable building floor area at 10 Pa	$dm^3/s \cdot m^2$

2. Research method

Dutch legislation uses the specific leakage rate w_{10}, hence this value was used in this research, instead of the more commonly internationally used air permeability (q_{50}) or air change rate (n_{50}). The w_{10} is the volume of air flow per second per square meter floor area at a differential pressure of 10 Pa, that occurs at seams between components in a building envelope [1]. To determine the current airtightness of houses without any intervention, the w_{10} of a first set houses was measured, using a blower door test (BD-test) according to the Dutch norm NEN 2686, [8] and the European norm ISO 9972, [9]. Observations were made for areas that negatively affect the airtightness, which are called problem areas. For each building the total number of problem areas (NrPA) was determined. The severity of these problem areas was defined by TotalLeakage (TL) [6] and adapted to fit this research. To compute the TL, each found problem area is scored on a scale from 1 to 4. A score of 1 indicates the leak is small and not severe. A score of 4 indicates a large and severe leak. The TL is the sum of all these scores for one building.

The results from the baseline measurements were analyzed using statistical methods to determine where improvements were possible to reduce the air leakage rate. This included the compilation of the most severe problem areas by 1) considering how often they occur, 2) the severity based on the TL and 3) partial impacts of problem areas on the total air leakage. The quality of workmanship in the evaluated buildings was assessed by comparing the w_{10}, NrPA and TL per building crew. Based on these analyses, an improvement strategy was developed and applied to reduce the air leakage rate in newly built houses. By measuring the specific leakage rate, NrPA and TL of the new buildings and by comparing them to the baseline results, the effectiveness of the improvement strategy was assessed.

3. Baseline measurement results and defining problem areas

The current specific leakage rate (w_{10}) was measured in 44 newly built detached houses to assess the baseline of the current air leakage rate of the houses built by different construction teams of one contractor. All measurements were performed by two operators using the same method. The average measured w_{10} in 44 houses was 0.678 $dm^3/s \cdot m^2$ with a standard deviation (SD) of 0.296. The average NrPA was 9.6 (SD = 3.7) and the average TL was 19.2 (SD = 7.5). Translating the w_{10} into the internationally used q_{50} and n_{50}, the average q_{50} was 2.868 $m^3/s \cdot m^2$ (SD = 1.215) and the average n_{50} was 2.653 h^{-1} (SD = 1.137).

3.1. Severity of problem areas

The problem areas per building were documented, which resulted in an overview of all common occurring problem areas. The 'occurrence' of each problem area, that occurs in more than 20% of our 44 cases, is shown in Table 1. It was analyzed which problem areas result in a high 'average TL', which indicates a high severity. For example, the first problem area has a relatively low TL (1.62), when this problem area occurs. The fifth problem area has an average TL of 3.03, which is perceived as a severe problem area. The 'partial impact' of the problem areas specifies the partial impact of one problem area on the total air leakage. The partial impact was determined by measuring a baseline w_{10}, (temporarily) sealing/taping off the leak and measuring the new w_{10}. This method showed for example that the drafts around an inner door leading to an uninsulated garage can contribute to 0.112 $dm^3/s{\cdot}m^2$ of the air leakage rate. The 'theoretical partial impact' is based on a partial airtightness coefficient (c-value) [1]. The c-value specifies the theoretical quality of a connection per length of that connection and states the litres of air that leak per second per meter length of a connection per Pascal ($dm^3/s{\cdot}m{\cdot}Pa^n$). To estimate the theoretical partial impact of the top 10 problem areas, c-values of these problem areas were calculated by averaging the c-values of four representative houses. The theoretical partial impact shows that, especially, the leakage around window frames and roof ducts has a large impact on the total air leakage.

Table 1. Occurrence of problem areas, average TL per problem area, partial impact per problem area and recommended solutions

Problem areas	Occurrence in 44 cases	Average TL	Partial impact *($dm^3/s{\cdot}m^2$)*	Theoretical partial impact *($dm^3/s{\cdot}m^2$)*	Recommended solutions
1 Seams between roof panels are not air tightly sealed	27%	1.63		0.019	Thoroughly apply flexible spray foam between the roof panels *
2 Roof ridge is not airtight	30%	1.47		0.047	Apply an impermeable tape on the roof ridge
3 Gable inside not air tightly sealed	23%	1.42		0.027	Apply a foam tape on the gable
4 Passages of pipes in floor slab of utility closet are not sealed	75%	2.13	0.034	0.005	Use spray foam to seal each individual passage*
5 Passages through hollow core floor slabs are not sealed	77%	3.03	0.047	-	Apply tape on the ends of the hollow core floor slabs and fill passages with concrete
6 Roof ducts are not airtightly installed	43%	2.55		0.057	Using cuffs (correctly) around the roof ducts*
7 Window and door frames are not air tightly installed	50%	1.66		0.278	Apply a tape on the connection between the inner leaf and the mounting frame
8 Drafts beneath and around door to garage	27%	2.83	0.112		Apply an airtight seal in the door frame and a door sill underneath the door
9 Junction of the ground floor with the external wall is not airtight	41%	2.11		0.011	Thoroughly grouting the wall and specifically the footing*

* Problem areas that were solved with improved workmanship quality

3.2. Quality of workmanship

In this research, quality of workmanship is assessed as the resulting quality of work, based on the sense of responsibility employees have regarding the building, the knowledge they have of airtightness in buildings and how they apply this knowledge in the building process. Based on observations and interviews with buildings crews, it was deduced that the builders were unaware of the importance of airtightness in building and were lacking knowledge to build airtight buildings. This is also illustrated by the presence of problem areas. Often it appeared that these problem areas could easily have been prevented with more attention to detail. The shortcoming in workmanship quality is also illustrated by the large variation in w_{10}, NrPA and TL per building.

The building crews were ranked on their performance and divided into two groups. The first group being building crews that performed well considering the average w_{10}, NrPA and TL and the second group, performing bad considering these variables (Table 2). Evaluating the differences between these groups using multiple analysis of variance (MANOVA) [10], a significant difference was established (sig < 0.0001). The between-subject effects test showed that the two groups of building crews differ significantly on all three variables (w_{10}: sig = 0.001, NrPA: sig = 0.001, TL: sig = 0.001) at a significance level < 0.05. This result indicates there are differences between the performance of building crews. Hence, the first group of building crews performed better than the second group. It is assumed these differences in results can be attributed to the differences in workmanship quality.

Table 2. Comparing the performance between two groups of building crews. Average w_{10}, NrPA and TL per group, with standard deviation.

	Average w_{10} ($dm^3/s{\cdot}m^2$) and SD	Average NrPA and SD	Average TL and SD
First group that performed well	0.548 (0.151)	7.8 (2.7)	15.8 (5.4)
Second group that performed bad	0.835 (0.352)	11.5 (3.7)	23.8 (8.2)

Conclusively, nine of the most occurring problem areas were identified and their severity was determined based on their partial impact and average TL. Some of these areas were severe because the connections between building parts were not sufficiently sealed and thus require more attention to detail. It is expected that the air leakage can be reduced with more attention to detail and thus improving the quality of workmanship and also reducing the differences between building crews. Besides this, the air leakage can be further reduced by applying other materials in the building or adapting certain building details. This leads to two different strategies to improve the airtightness of houses. The first strategy concentrates on improving building details. The second strategy aims at improving workmanship quality.

4. Improvement strategies

The improvement strategies encompass technical solutions and educational sessions. The first strategy aimed at adjusting and improving building methods, so the airtightness of connections between building components is increased. These technical solutions had to be implementable in the current building method, cost effective and easily usable for the construction workers. The solutions are based on recommendations of building material suppliers. Using a multi-criteria analysis, the most suitable solutions were selected, based on the costs, effectiveness and difficulty of applying. The solutions for each problem area are shown in the sixth column of Table 1.

The second strategy, educational sessions, aims at creating awareness and increasing knowledge among construction workers about reducing air leakage in buildings. Awareness is the first step in increasing the airtightness of buildings, because the construction workers then know problems exist and know that they can influence the air leakage rate of buildings. After awareness is created, the next step is increasing knowledge on specific points so the construction workers can come to a more airtight building.

Problem-based learning is an often used method in education and “aims at acquiring knowledge by means of a problem or task and not at solving a problem by applying existing knowledge” [11]. This method helps understanding why a solution is required, by first focusing on the problem, which is proven to be effective because “people are most strongly motivated to learn things they clearly perceive a need to know” [12]. Jennings [13] states that context is critical for learning and “only by applying newly-acquired knowledge and skill in the context of work, will it become embedded in long-term memory.” Hence, the educational session is best executed in the workplace, so examples from practice can be applied directly. Combining the information on problem-based learning and learning in the workplace, the educational session was executed as follows: Approximately ten construction workers were present at a session, that took place on the construction site. The first part of the session consisted out of a short presentation with pictures of various encountered problem areas, concerning the building air leakage. This presentation showed the construction worker the need for airtightness in buildings. The second part of the session entailed a tour through the house. During the tour, the fan of the blower door was active, so a pressure difference was applied on the building envelope and the air leaks became tangible. Using a fog machine and infrared camera, air leaks were made visible. This tour directly showed the construction workers the problem areas in practice. The final part of the session was a discussion session with the construction workers on possible solutions. Solutions for the problems were proposed by the trainers or by the construction workers, before the best suitable solution for a problem area was established together.

5. Evaluation of improvement strategies

After implementing the two improvement strategies, their effectiveness was evaluated by measuring w_{10} in a new set of 14 houses. The average w_{10}, after implementation of improvements, was 0.498 $dm^3/s{\cdot}m^2$, the NrPA was 8.0 and the new average TL was 13.1 (Table 3 and Figure 1a). Performing a MANOVA, a statistically significant difference between the two sets of measurements was detected (sig = 0.030). The between-subjects effects test showed that only the w_{10} (sig = 0.035) and the TL (sig = 0.008) have a statistically significant difference between the baseline group and the intervention group. However, the NrPA was not significantly reduced (sig = 0.164). These results indicate the mean w_{10} and the mean TL were significantly reduced after implementing the improvement strategies.

Table 3. Average w_{10}, q_{50}, n_{50} NrPA and TL, with standard deviation. Comparing the baseline and intervention situation

	n	Average w_{10} ($dm^3/s{\cdot}m^2$)	Average q_{50} ($m^3/s{\cdot}m^2$)	Average n_{50} (h^{-1})	Average NrPA	Average TL
Baseline	44	0.678 (0.296)	2.868 (1.215)	2.653 (1.137)	9.6 (3.7)	19.2 (7.5)
Intervention	14	0.498 (0.164)	2.157 (0.724)	1.312 (0.434)	8.0 (3.3)	13.1 (6.2)

To evaluate the improvement in workmanship quality, the performance per building crew in the baseline situation was compared to the performance in the situation after implementing improvements. This evaluation was executed on five building crews. Analyzing the means per building crew for the w_{10}, NrPA and the TL (Figure 1b), it is evident that the values of most of these variables were reduced after the intervention. Performing a MANOVA, no statistically significant differences at the $p < 0.05$ level were detected (Crew 1: sig = 0.410; Crew 2: sig = 0.696; Crew 3: sig = 0.796; Crew 4: sig = 0.966; Crew 5: sig = 0.875). This illustrates the performance of building crews has improved after the implementation of the improvements, but this could not be confirmed with a statistical analysis.

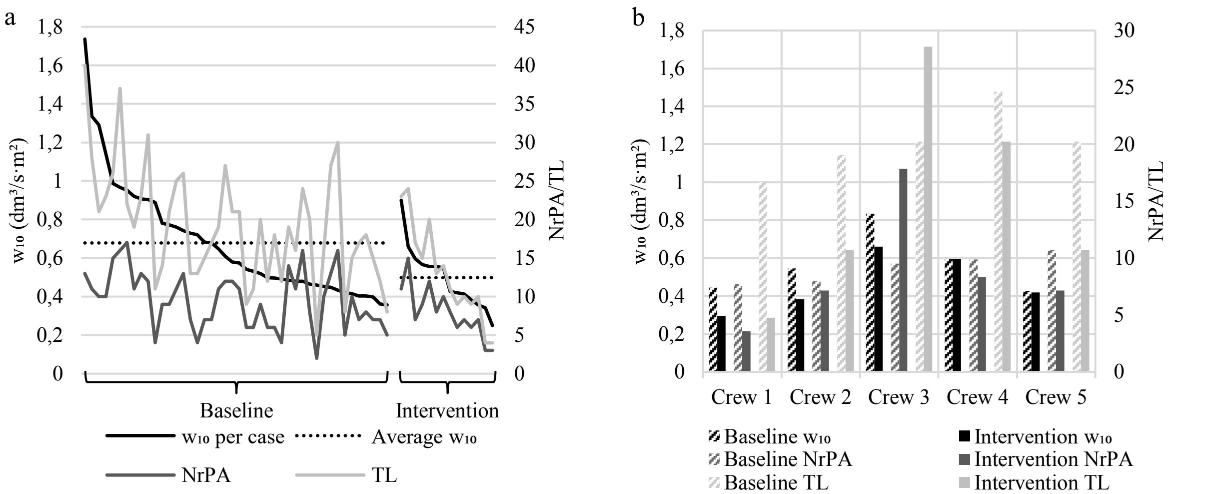

Figure 1. (a) Results in w_{10}, NrPA and TL sorted in descending order and comparing the baseline results (n=44) with the results after the intervention (n=14). (b) Comparing the w_{10}, number of problem areas and TotalLeakage per building crew for the baseline and intervention

6. Discussion

The aim of this research was to assess the effect of improving workmanship quality on the air leakage rate in newly built houses. Because the technical solutions and the educational session were applied simultaneously on all buildings, the individual effect of the technical solutions and the educational session could not be determined. This was inevitable because of time constraints and practical reasons. The findings suggest that, the implementation of an educational session and small technical improvements, significantly reduces the air leakage rate. This supports the conclusions of, among others, Bramiana et al. [6] that workmanship quality affects the air leakage in buildings.

The research is executed using the houses of one contractor. This contractor builds detached houses, but it is highly likely that the results of this study are generalizable to a larger population of building companies in the Netherlands or other parts of Northern Europe. Because the concept of applying minor technical improvements and the concept of the education session is applicable on all types of houses and buildings and not only limited to or this company.

7. Conclusion and recommendations

Based on the results, it is concluded that applying minor technical solutions and providing an educational session for building crews are suitable for reducing the specific leakage rate. After implementing these two strategies, the specific air leakage rate (w_{10}) was significantly reduced from 0.678 $dm^3/s{\cdot}m^2$ (n = 44, SD = 0.296) to 0.498 $dm^3/s{\cdot}m^2$ (n = 14, SD = 0.164) and the TotalLeakage (TL) was significantly reduced from 19.2 to 13.1. The number of problem areas (NrPA) per building was not significantly reduced (from 9.6 to 8.0).

The quality of workmanship was considered a significant influence on the air leakage rate, based on the large variation in results between similar buildings and the differences in performance among building crews. This conclusion is supported by observing the building crews, which indicated that building crews who expressed interest in building airtight buildings and who put a lot of effort in achieving this, achieved a lower air leakage. Therefore, the educational session, which aimed at increasing the quality of workmanship, was successful. This was achieved by teaching building crews the importance on building airtight houses and handing them knowledge about how they can achieve this. Moreover, a sense of competition emerged among building crews. They were keen on achieving the most airtight building, what further increases their drive to build airtight buildings.

This research was limited to the houses of one contractor, which strengthened the results, but simultaneously limits them. Therefore, it is recommended to implement the improvement strategies also to other building companies, to determine its overall effectiveness. Furthermore, longitudinal effects of the implemented strategies have to be evaluated. The decay of materials can negatively affect the air leakage rate in the long term, and the effect of the educational session may reduce over time. It is expected that regularly repeating the educational session will help to maintain the required quality of workmanship.

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