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Life cycle inventory library for embodied emissions in ventilation components

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ABSTRACT

Technical components are generally poorly described in environmental assessments of buildings. In this work, an extensive library of life cycle inventories for generic ventilation components and dimensions have been developed and documented. Components are described as unit processes and can be used to improve the understanding and coverage of ventilation systems in environmental assessment of buildings, and as potential building blocks for optimization of ventilation system design with minimum life cycle emissions. The ventilation components library has been tested on a modern and energy-efficient office building. Results show that more than 78 % of the climate footprint was covered directly by the library, while the main part of the remaining footprint was associated with non-standardized and building specific components. The coverage was even higher for other environmental impact categories. To assess the coverage of the library and estimate the full impacts for a complete ventilation system, inventories were developed also for the building specific components. Results from this showed an estimated total weight of 6.84 kg/m^2 floor area, and a climate footprint of 22.7 kg CO$_2$-eq./m^2 floor area. Air handling units and circular ductwork were by far the top contributors with a combined 55 % of climate emissions, with roughly equal shares from both.

1. Introduction

Providing housing is a basic necessity for any society but is also a considerable driver for resource use and corresponding emissions of greenhouse gas emissions (GHG) and other potential environmental impacts. On a global scale, the built environment sector is estimated to account for more than a third of annual global carbon emissions with 37 %, and buildings responsible for three quarters of these emissions [1]. Projections of global population growth estimates a global population of 8.5 billion by 2030 and 9.7 billion by 2050 [2]. Furthermore, providing adequate housing is an inherent part of the UN Sustainability Goals [3]. National and international legislation and the building sector need to find strategies and solutions in concert to provide both adequate and sustainable housing.

Energy use and GHG emissions for buildings are commonly attributed to two aspects; the operational energy use and the energy and emissions embodied in the materials that make up the building. Operational energy use refers to the energy needed during operation and use of the building, including energy for heating, cooling, ventilation, lighting, and technical appliances. Operational emissions are the emissions associated with producing this energy. Embodied energy and emissions refer to the energy and emissions associated with producing the materials, components, and installations necessary to construct the building and its technical components for building services systems, the construction phase itself, maintenance, refurbishing and final deconstruction of the building. Current regulations have focused on the operational energy use and associated GHG emissions [4,5].

A summary and overview of the work within the IEA EBC Annex 57 project on evaluation of embodied energy and GHG emissions in the building sector have found that the measurement and reduction of embodied energy and GHG emissions have been excluded from current legislation [6]. Furthermore, the authors conclude that there is an increasing recognition of the importance of investigating the embodied as well as the operational impacts, showing a 35-fold increase in

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publications on embodied energy and GHG emissions from 1990 to 2013, and particularly for the last decade of the investigation period.

The focus and efforts made to reduce energy consumption and strive towards zero or near-zero emissions buildings have reduced the GHG emissions from operational energy through reduced energy consumption in general and through increased use of renewable energy sources. This has shifted the relative contributions between operation and embodied impacts. At the same time, reduction in operational energy has in many cases been achieved through increased material use, thereby shifting the relative contribution further [7]. It has been argued that in order to avoid problem shifting between life cycle stages, more attention should be paid to the construction products [8]. Results from current studies indicate that embodied impacts can already be 50–70 % of total life cycle impacts for a building evaluated over 80 years [9]. A recent global study of embodied GHG emissions found an increase in relative and absolute contributions from embodied emissions to the total life cycle emissions, and furthermore that the share of embodied emission accounts for 20–25 % of life cycle emissions for buildings following the current energy performance regulations, 45–50 % for highly energy-efficient buildings and even above 90 % in extreme cases [10]. This is supported by findings from surveying 16 LCA studies where technical installations are included, finding a contribution from these systems ranging from 10 % to 53 % of embodied GHG emissions [11]. Increasing importance of embodied impacts for energy-efficient buildings is also exemplified by findings in a Norwegian study on zero emission buildings [12]. An average of 65 % of GHG emissions are attributed to the building envelope across a selection of seven case buildings evaluated over a 60-year period. The UK CBxchange, a public forum for building energy professionals, argues that regulations to improve operational energy efficiency has increased the embodied energy and impacts, and in order to minimize operational consumption, designers have utilized more highly processed materials, complex plant equipment and sophisticated, automated control systems [13]. A study on the environmental impacts from technical installations where literature is also reviewed, finds that there is a consistent pattern where higher efficiency systems correlates with higher embodied impacts [11].

One of the key strategies to reduce operational energy use has been to design tighter constructions which require increased material use and more efficient ventilation systems to maintain thermal comfort and indoor air quality. Figures for Norway show that the use of natural ventilation in new buildings has been reduced from almost 60 %–11 % in a 30-year period starting from the mid-70s [14], and that more recent regulations have in practice made mechanical ventilation mandatory [15]. However, while the embodied impacts of building materials have been widely studied in life cycle assessments (LCA) of buildings in recent years, the embodied impacts in technical equipment for building services systems has received scarce attention, and in particular studies combining both the building envelope and technical equipment [8,16]. The general transition to mechanical ventilation further emphasizes the need for improved knowledge and documentation of the emissions embodied in ventilation components. Smaller duct diameters reduce material (embodied emissions), but also introduces higher pressure drops which increase the fan power and the corresponding energy use (operational emissions).

A ventilation system comprises the air handling unit(s) and ductwork and represents an essential building services system that provides both thermal comfort and indoor air quality. It is the most material intensive building service system, and the one that occupies the largest share of the building volume, especially in commercial buildings. Furthermore, it is in many cases also the most energy consuming system. A number of studies refer to a general lack of data and poor representation in terms of life cycle inventory (LCI) data and quality for building services systems [11,15–23]. It is therefore important to improve the understanding of the role of ventilation systems in terms of both energy and materials related emissions, and the trade-off between them.

In contrast, and due to available data, advanced Life Cycle Cost (LCC)-methods are more widespread when designing and optimizing building services systems. In studies where LCA-methods are applied to building services systems optimization techniques for environmental assessment are rarely used due to lack of LCI-data on component level [8,24,25]. This is also reflected in a general lack of Environmental Product Declarations (EPD) for ventilation components. As a result, ventilation systems are often omitted or only included in a crude manner based on highly simplified inventories or as an estimated increase in total embodied impacts.

The recently introduced Norwegian version of Product Category Rules (PCR) specifically for ventilation components, which provides guidelines for the development of EPDs, acknowledge the need for LCI data on component level [26]. The declared units are changed from “1 kg of product” in the previous version [27] to “1 m of product” for ductwork and “1 piece of product” for duct connecting components (fittings) and air handling units in the new PCR. The change in declared unit significantly improves the ability to implement LCA in ventilation system design and optimization. Furthermore, it has the advantage of supporting more detailed information on component level that might be useful for implementation in BIM (Building Information Modelling) models and libraries.

This study aims to enhance the knowledge about emissions embodied in building ventilation systems and provide a components library for use in further studies.

In this study we have two main objectives:

1) Provide a detailed, consistent and generic life cycle inventory library for common ventilation systems, distinguishing between standardized ventilation ductwork components and air handling units to describe a full system, and a wide range of dimensions for these. The selection of components reflects standard ductwork dimensions with known pressure drop coefficients.
2) Demonstrate and test the use of the ventilation components library on a BREEAM Outstanding certified office building to evaluate; a) the library’s usability and coverage, and b) to estimate embodied emissions intensity (per floor area) from ventilation systems for an energy-efficient office building.

Although not a specific objective of the work, an additional motivation for the library development is to provide LCI building blocks for use in an optimization algorithm to optimize the design of ventilation systems and dimensions in order to minimize the total life cycle impacts of buildings, as put forward for life cycle costs in Ref. [28], and for life cycle emissions in Ref. [22]. This implies considering the trade-offs between emissions embodied in materials and emissions from operational energy use.

The ventilation component inventories presented in this work are modelled to be consistent with, and restricted to, the product stages A1-A3 in the EN 15804 standard for Environmental Product Declarations (EPD) for construction works and services [29]. The inventory library contains the building blocks to describe the embodied impacts from ventilation systems, and in a building context they can be combined with scenarios for product stage B4 concerning replacements through the building lifetime, and stage B6 for the operational energy use for ventilation services in the building.

The ventilation library presented here builds on the work presented in Ref. [22], which includes a preliminary version of the ventilation library as described in Ref. [30]. Compared to the 2016 study, this iteration of the ventilation library has been fully revised with respect inventory descriptions and material composition. Additional components and dimensions have been added, and not least, the inventory modelling is completely reworked to provide methodological consistency in system boundaries, selection of inventory processes for material and resource use, and setup of the inventory modelling. Furthermore, a critical review of the data quality has been carried out and necessary adaptations from this implemented. In this work we also present fully transparent inventories for potential use by others. Finally, the ventilation library is tested for a specific case building to evaluate how well it covers a full ventilation system, and to provide insight into the total embodied emissions. In total, it gives more robust results and will provide a better foundation for exploring the trade-offs between embodied emissions and operational lifetime emissions, and further optimization of the ventilation system layout.

2. Life cycle inventory for ventilation systems

The number of LCA studies that specifically concerns ventilation and includes material use and embodied emissions from these is very limited, which is also emphasized in several of the same studies [11,15,21–23,31,32]. Several of the studies on ventilation systems are MSc. theses, and the available LCI information in some of these are as complete or more complete than many of the scientific articles, indicating that the topic is in the start of attracting more attention. The lack of data is also demonstrated by the coverage in LCI databases. The most commonly used European LCI database ecoinvent includes inventories for only two dimensions of circular and rectangular ducts [33]. The lack of comprehensive and updated information on technical systems in existing databases is also emphasized in Ref. [11].

In an early study from 2005, an LCA of two ventilation units with heat exchangers for residential houses in cold climate is carried out and includes materials and impacts from the ventilation units in addition to operational energy use [32]. However, ventilation ductworks are not included. A Dutch study from 2010 has performed an LCA on heating and ventilation systems in a multi-family apartment building [31]. Material inputs are provided as aggregated amounts together with the heating system. A study from 2011 presents an environmental assessment of technology alternatives for heating and ventilation of highly energy efficient residential buildings [19]. The author of the study emphasizes the challenge of finding good quality information about ventilation systems and uses a product declaration for a specific system as a proxy and stating considerable uncertainty for the use of this. An LCA study of a passive house with mechanical ventilation from 2012 also makes use of available information from other studies and adaptations for a specific system and producer, but without providing new ventilation inventory data [20].

A more detailed approach is presented in a study from 2017 of different ventilation systems for a classroom [21]. The authors provide detailed material inputs in addition to operational energy use, including information about material types, quantities, and dimensions. Although the inventory has good quality it is intended for description of a specific system/building, and not as a generic library.

A study from Austria highlights the lack of LCA studies of buildings incorporating building technical equipment as part of the assessment and presents results for a case study including detailed inventories for electrical installations, heating, solar heating, sanitary and ventilation systems [8]. However, the inventory has not been provided. The authors conclude that technical equipment can have a significant contribution to total impacts, and particularly for some impact categories, and should therefore be included in LCA of buildings.

The share of embodied energy in technical systems have been reviewed for a number of certified sustainable buildings in Denmark [16]. The authors find large variations in the share of embodied energy from technical systems, but also a general underestimation of the contributions. This is attributed to underrepresentation of the technical systems and a general lack of inventory data. The authors conclude that there is need for more detailed and harmonised description on how technical systems should be included in building-LCAs and that the availability of improved inventory data for technical systems should be a priority. Ventilation systems were part of the technical systems and found to be particularly important for cases with residential housing.

In a study from 2018 the authors have investigated the precision in adding a general surcharge to cover installation systems and distribution ductwork for the ventilation system of a passive housing block compared to a detailed inventory for the same [34]. According to the authors exact information on material use has been available from tendering documents, although it is not presented. The authors find the embodied emissions from a passive house to be higher than for a conventional, and that a surcharge of 10 % for the ventilation system corresponded well with the bottom-up calculations when assuming a 50-year evaluation period. The idea of adding a surcharge to compensate for the lack of relevant inventories for technical installations have also been put forward by the authors of a recent study on early-stage building design [35].

One of the most detailed studies for ventilation systems is presented in a recent study from 2020, where the authors provide a detailed LCA of HVAC (Heating, Ventilation and Air-Conditioning) systems [23]. The study links LCA information to a BIM model to make a detailed assessment of the carbon emissions embodied in HVAC systems. The study covers a wide range of components and results for an office case building which also includes replacement and disposal in a 60-year lifetime perspective. Embodied impacts for the HVAC systems were found to be in the range of 15–36 % of total embodied impacts.

In a recent study from 2024 the authors have assessed the importance of technical installations in whole-building LCA of a single family dwelling, including both heating and ventilation systems [11]. The authors present detailed inventories for a range of individual components and find that technical installations account for 12–33 % of embodied impacts for a new building. Also, in this recent study the authors highlight the general lack of good quality LCA data for technical systems, the low number of studies taking them into account, the varying level of detail provided in literature and the challenging task of finding and preparing good data.

The most detailed inventory for ventilation system components is found in a study from 2016 of a Norwegian office building [15]. In this study, the author has used detailed information from a BIM model for investigating the environmental impacts from the ventilation system, including both embodied and operational energy impacts. The inventory comprises extensive coverage of ventilation components of different types, geometry, dimensions, and weights. The inventory developed forms part of the basis for this article but is expanded and with a more consistent and detailed inventory modelling to enhance the generic use of the inventory.

A first attempt to optimize ventilation systems design in order to minimize life cycle GHG emissions on a building level is attempted in a study from 2016 [22]. Inspired by work on optimization of life cycle costs (LCC) for an HVAC duct system [28], the authors introduced a life cycle approach where an evolutionary optimization technique was used to assess greenhouse gas emissions caused by the complex interrelationship between a passive house office building and its ventilation ductwork system [22]. As an analogy to investment cost, a dataset of life cycle unit inventories was developed for standard circular ventilation ductwork components to represent embodied emissions from material use. Like energy cost in the LCC-optimization, the emission intensity of the electricity mix was used for the assessment. This allowed the authors to explore trade-offs between embodied and operational emissions over the lifetime of the building by varying the ductwork dimensions and through pressure drop calculations estimate the required fan power and resulting operational energy use. Possible effects on building heights and associated material use were also included in a simplistic manner.

Lack of good quality inventory data on technical installations such as ventilation systems is emphasized in most of the studies referred to above. There are few studies dealing directly with embodied impacts of such systems, and even fewer providing generic inventory data that can be used further in other studies. The most promising sources of information are BIM models or detailed information from tendering documents. However, obtaining detailed information about components and dimensions used still requires linking of this information with material quantities in the form of a life cycle inventory library with sufficient resolution to distinguish between dimensions and material use and composition. In this study we aim to bridge the gap between knowledge about the building blocks in ventilation systems and the necessary material use and embodied impacts for the same building blocks in order to offer a comprehensive and transparent life cycle inventory library that can be used to model most types of common ventilation systems.

The different studies discussed above includes embodied impacts in different ways and with different level of detail, and the results vary considerably concerning the share of total impacts. However, the studies that rely on more detailed inventory information, such as [11,15,21,22,34] tend to report a higher share from embodied emissions, indicating that better information is needed and that efforts to describe technical installations are worth pursuing. This is supported by findings reported in Ref. [6] where embodied GHG emissions from a Norwegian case study was found to be twice as high when assessing an "as built" version with a highly detailed inventory compared to the design stage utilizing a simplified inventory [36].

In the conclusions from the work with IEA EBC annex 57 on embodied GHG emissions, the authors call specifically for initiatives to closing the data gaps in the field of building services and equipment, and for finding new methods and models for incorporating embodied emissions in the design process [6]. The work we present here is an attempt to close the data gap for ventilation systems. Furthermore, providing a library for a range of components and dimensions carries the potential for future integration with BIM tools or other tools for both the design stage and detailed planning.

3. Method and inventory description

3.1. Library overview

Ventilation systems are designed and constructed from a range of components that are largely standardized in terms of dimensions and geometry, and described in widely used handbooks and guides like the American ASHRAE handbook and the British CIBSE guide [37,38]. In this work we aim to provide a wide range of dimensions for the standardized ductwork components that make up the major parts of ventilation systems for both commercial buildings and larger apartment buildings. Not every dimension is provided for all component types, and the priority has been to provide commonly used dimensions for the Nordic countries. However, the selection and application are not restricted to the Nordic region. For the more complex components with more variation in design solutions between different manufacturers we have developed examples of representative components so that a full ventilation system can be modelled from the inventory library. The inventory is organized to reflect the way in which ventilation systems are designed in BIM models where pre-defined and standardized components can be selected from a library. From an engineering perspective, standardized unit components are described with standardized pressure drop coefficients for fan power calculation, as well as associated cost. Including environmental information in the same format as in design system design modelling and cost calculations offers the potential for evaluating environmental, cost and energy performance in combination. It will for example facilitate optimization routines for finding design solutions that are optimized in terms of energy use and environmental impacts while also being acceptable from a cost perspective. An overview of component inventories and dimensions range is presented in Table 1. Appendix A is referred to for a full list of components and dimensions.

As can be seen from the table above, a wide range of dimensions are covered in the inventory library. Circular bends and T-pieces have many inventories to cover different angles and inlet/outlet variations. Additional generic unit inventories for glass wool insulation mats and cellular rubber insulation mats are provided for combination with other components to make inventories for insulated ventilation components and systems.

Table 1
Inventory overview – component types and dimensions.

Component	Dimensions, min [mm]	Dimensions, max [mm]	Inventories (#)
Ducts, circular	ø63	ø1250	15
Ducts, rectangular	600x400	4000x1000	10
Bends, circular	deg15 – 100 deg30 – 100 deg45 – 125 deg60 – 125 deg90 – 63	deg15 – 500 deg30 – 500 deg45 – 500 deg60 – 400 deg90 – 1250	41
Bends, rectangular	deg45 – 800x200 deg90 – 400x1000	deg45 – 800x200 deg90 – 1000x2000	6
Saddles, circular	deg90 – ø125/ø125	deg90 – ø630/ø500	30
T-pieces, circular	ø80/ø80	ø1250/ø1250	104
Reducers, circular	ø125/ø160	ø400/ø315	11
Fire dampers, circular	ø125	ø160	2
Flow dampers	ø100	ø500	7
Silencers, circular	ø100 – ø300/ø100	ø400 – ø900/ø400	12
Silencers, rectangular	1000–1000x400	1000–1600x800	4
Air diffusers	ø100	ø400	7
Air handling units	288–1620 m^3/h	9000–50 400 m^3/h	18
Generic unit inventories			
Galvanized steel plate	t = 0.5 mm	t = 1.0 mm	3
Insulation mat	t = 25 mm	t = 50 mm	2
Cellular rubber insulation mat	1 m^2	1 m^2	1

3.2. Calculation of material inputs for ventilation components

Most of the component inventories developed in this work rely on weight and geometric calculations for establishing the material composition. For the more complex components such as air diffusers and air handling units, material composition is based on material specifications from Environmental Product Declarations (EPDs). This approach corresponds well with the approach described in Ref. [11], which is one of the studies with the best coverage of individual ventilation components, indicating a concurrence with regard to how data can be found and developed. Furthermore, the authors also report the same challenge of low availability of detailed material composition and in many cases resulting reliance on primary materials and estimates of the total component weight. Total weight is available for all inventory components from product data sheets, while the weight of individual materials such as rubber gaskets, welding seams, zinc layer etc. is generally not specified. However, galvanized steel makes up the main share of most of the ventilation components. For components without specific information on material composition, the material weights are calculated as follows:

1. Total weight from product data information
2. Calculation of surface area and other relevant geometric factors
3. Calculation of material weights for the non-steel material inputs using material densities, thickness etc. in combination with geometric information
4. Steel weight as balanced output

Surface area is calculated for all components to estimate the amount of zinc-coating for the galvanized steel plates. This is done in two ways, depending on geometrical complexity; i) basic geometrical shapes that can be calculated directly, ii) calculation of an estimated area of galvanized steel plate. The latter is calculated according to Equation (1) after first subtracting all parts of the component that are not steel plate.

$$Est.\ area = \frac{Weight\ of\ component\ (excl.\ \ non\text{-}steel\ materials)}{(Density, steel * Plate\ thickness) + (Density, zinc * Coating\ thickness * \#of\ coated\ sides)} \qquad \text{Eq. (1)}$$

The following paragraphs presents a brief description of the inventory development for the different component types. A full inventory description for individual components is provided in Appendix C. Most components have standardized geometry and well-known pressure loss coefficients. Material composition for the components is based on data from multiple manufacturers, and the choice of reference product and manufacturer depends on the availability of necessary specifications for material composition calculations.

3.2.1. *Circular ducts*

Both circular and rectangular ducts are used worldwide. Circular spiral ducts have better flow characteristics compared to rectangular due to lower pressure losses and is the preferred geometry for the Nordic and European market. These ducts are produced in 15 standard dimensions, and other components like bends, saddles, flow dampers, reducers etc. are dimensioned according to these. Circular spiral ducts are easy to manufacture, and a range of manufacturers exist. For the inventory description we rely on product data from the Danish manufacturer Øland AS, which have an extensive production line of ventilation components that are considered representative [39]. Spiral ducts are manufactured from sheet metal using a spiral helix machine where the sheet metal coils like a screw and the edges are folded and pinched together. The folding process means that material weight cannot be calculated directly from plate thickness since this would underestimate material use. Rather, total weight and estimated surface area are used to find coating area and resulting steel input. The thickness of the steel plate varies according to the dimension of the ductwork, with thicker plates for larger dimensions.

3.2.2. *Circular bends*

Similar to circular ducts, the product catalogue from Øland is the basis also for circular bends inventories [40]. The inventories include angles of 15, 30, 45, 60 and 90° with different diameters. Bend radius is equal to the diameter of the openings, and the bends are stamped and welded along the inner and outer radius. In addition, they have inserts in both ends, ranging from 40 to 100 mm in length depending on size and dimension. These are calculated separately and included in the full inventory for each bend variant. Included in the full inventories are also one EPDM rubber gasket in each end. Surface area for zinc-coating is calculated according to estimated area in Equation (1).

3.2.3. *Rectangular ducts and bends*

Rectangular ducts are produced from galvanized steel plates that are bent and with edges folded and pinched together. For weights and dimensions we have used product information from Lindab for their LKR series of rectangular ducts [41]. Rectangular ducts are less standardized in terms of dimensions than circular ones (at least for the European and Nordic market) since rectangular ductwork is more often tailormade to fit the building geometry, and the selection of dimensions in the library is therefore more limited than for circular ductwork. However, rectangular ductwork can more easily be modelled specifically from simple calculations of geometry and plate thickness. Similar to rectangular ducts, product information about weight and dimensions for rectangular bends are obtained from Lindab and their LBR series [41].

3.2.4. *Circular saddles*

A range of 90° circular saddles are modelled based on the Øland product catalogue [42]. The outlets are stamped, galvanized, and equipped with an EPDM rubber gasket. Galvanized area is calculated from Equation (1).

3.2.5. *Circular T-pieces*

An extensive list of T-piece dimensions are modelled based on the Øland product catalogue [43]. The inventory includes dimensions from ø80 to ø1250 for the main run and the same range for combinations of different dimensions for the branch connection collars. This leads to more than 100 specific component alternatives. The components are assumed stamped and with the branch connection collar welded to the main run. Surface area for zinc-coating is calculated according to estimated area in Equation (1) and an EPDM rubber gasket is included for both branch and run.

3.2.6. *Circular reducers*

Inventories for circular reducers are based on the Øland product catalogue, and include dimensions from 125/160 to 400/315 [44]. The reducers are stamped, galvanized and with an EPDM rubber gasket. Galvanized area is calculated from Equation (1).

3.2.7. *Circular fire dampers*

The modelled fire dampers consist of a circular duct piece equipped with a mechanical spring release mechanism. The mechanism is activated in case of fire to prevent air circulation and spreading of the fire in the duct system. The fire dampers are more complex than the ductwork and consist of a wider range of material inputs. Material composition is estimated from an environmental product declaration (EPD) from Wildeboer Bauteils with composition indicated in percentage intervals which combined with total weight gives the final material inputs [45]. Galvanized area is calculated from Equation (1).

3.2.8. *Flow dampers*

Seven different inventories for flow dampers have been developed. The flow dampers are based on the ADAPT Damper models from Swegon, including connection box, motor and electronics [46]. Material composition is provided in an EPD for the specific ADAPT Dd 250-M model [47]. The product data sheet gives total weight for all seven variants of the damper, and inventories for other dimensions is scaled according to total weight using the same material composition. Surface area is calculated from Equation (1) to specify the zinc-coating amount for the galvanized steel.

3.2.9. *Circular silencers*

Inventories for circular silencers are modelled based on product information data sheets for the LKR series from Trox Auranor [48]. Area and volume are based on geometrical calculations. Volume calculations are used to find volume of stone wool for insulation and area is used to estimate galvanizing area. Connection collars are welded, and welding length is given by their circumference.

3.2.10. *Rectangular silencers*

Rectangular silencers are modelled for larger dimensions typically used in commercial office buildings and for corresponding air handling unit sizes, based on [15]. Like circular silencers, area and volume are based on geometrical calculations. Stone wool is used as insulation material, welding length is given by the circumference of the connection collars and zinc-coating is calculated from the surface area.

3.2.11. *Air diffusers*

Air diffusers come in many different variants and dimensions. In this component library, inventories for seven ceiling mounted exposed air diffusers with dimensions typical for commercial buildings have been developed. These are modelled with a commissioning box inside a supply air diffuser. Due to data availability the commissioning box is modelled according to a building product declaration for a wall mounted unit from Swegon [49]. Additional sizes of the commissioning box are scaled by weight assuming the same material composition. The supply air diffusers, that hold the commissioning boxes, are based on the ROFB series from Øland for weight information and calculation of surface area for zinc- and powder-coating [50].

3.2.12. *Air handling units*

Air handling units are represented by 18 different sizes, covering air volumes from 288 to 50 400 m^3/h. The inventories are based on the Swegon Gold RX series [51]. An EPD for the GOLD RX 20 (air volume range = 1080–7560 m^3/h) is used as the basis for material composition [52]. Material composition is assumed to scale with the total weight of the unit, with the exceptions of electronics for the control unit, which is assumed constant for all sizes, and filters which are assumed to scale with max volume at SFP = 1.5 and pressure = 300 Pa from product technical information [51]. The material composition of the motor is modelled with high uncertainty. Following personal contact with the producer and own assumptions, the motor has been modelled as a mix of ferrite (permanent magnets), copper and aluminium, with 50/25/25 percentage shares, respectively. Estimation of energy use during manufacturing is based on personal communication with the producer and is assumed to scale with component weight. Due to lack of specific information, the same energy use is assumed for all sizes.

3.2.13. *Supplementary generic inventories*

A few supplementary inventories are supplied to expand the possible combinations of ventilation components. More specifically, this includes cellular rubber mat (13 mm thickness) for modelling of ductwork transporting cool air, insulation mats with mineral wool and one-sided aluminium sheeting (25- and 50-mm thickness) for ductwork transporting temperate air, and generic galvanized steel plates (0.5, 0.7 and 1 mm thickness). All supplementary inventories are provided per m^2 and facilitate expanding the library beyond simple steel ductwork.

3.2.14. *Background processes*

The focus of the inventory development has been development of foreground processes to describe a wide range of components. The ventilation systems library is constructed from generic ecoinvent v3.8 background processes [33]. The unit processes used in the library are listed in Appendix B. This ensures consistency regarding system boundaries and general LCI methodology, provides full value chain coverage and transparency, regionalized market processes for geographical representation, and assessment across a wide range of impact categories. ecoinvent processes are consistently chosen as allocation recycled content unit processes and ReCiPe Midpoint in hierarchist version is used for the impact assessment modelling [53]. Material processes are consistently chosen based on a global market perspective. By relying on ecoinvent processes for the background system we get a flexible inventory that can be adapted and tailored for more specific contexts if needed.

Galvanized steel is the dominating material input in terms of weight for most of the component inventories. For the mix of steel types, we rely on the mix assumed for ventilation ducts and bends in ecoinvent 3, consisting of 37 % low-alloyed steel and 63 % unalloyed steel, and both sourced from a global market. Unalloyed steel consists of 100 % primary converter steel, while the low-alloyed market mix consists of 57 % primary converter steel (blast furnace and basic oxygen furnace production) and 43 % secondary steel (electric arc furnace production). This gives a ratio of primary/secondary steel of 21/79. Processing into steel plates is performed by sheet rolling.

The galvanizing process is represented by an ecoinvent zinc-coating process for coils per m2 surface area. However, the average thickness of the zinc-coating layer for circular spiral ducts is specified as 19 µm, giving an input of 275 g zinc/m^2 for a two-sided galvanized steel plate [54]. The equivalent input in the ecoinvent zinc-coating process is 679 g/m^2, and the process is scaled accordingly for use in the ventilation components library. All galvanized components are assumed to have the same average galvanized layer thickness for the steel plates.

Energy for manufacturing of the different types of ventilation components is inherently difficult to obtain. Aggregated energy use is more common than specific energy use per component or unit of production and will also vary between manufacturers. Obtaining reliable energy use for all the specific component types and dimensions is considered too resource consuming to justify the expected precision level and relative impact contributions compared to the material inputs. The modelled inventories will anyway allow for adjustments in energy use and energy mix. As a proxy for energy use in ventilation duct manufacturing, we have used the energy use for the ventilation duct inventories available in ecoinvent, which consist mainly of galvanized steel, and have normalized this according to the steel content. For other component types, the energy use is based on other available ventilation components, more specifically ventilation elbow and connection piece, requiring more processing and with 30 % higher energy consumption than simple ventilation ducts. This energy use has been used for all non-ventilation duct inventories, with exception of air handling units where company specific energy use was available. Air handing units are more complex in terms of material composition with higher share on non-steel material inputs, making normalization according to steel content less relevant than for other ventilation components. For consistency and due to lack of component specific data, the energy inputs are kept as in the original ecoinvent processes, but with a flat distribution of 1/3 each of electricity, industrial heat from natural gas and industrial heat from other sources than natural gas, and for all inputs reflecting European production.

Infrastructure for production is based on the generic ventilation components factory found in ecoinvent. Like energy inputs, infrastructure consumption is assumed to scale with the steel weight of the respective components.

A full list of GHG emission factors for all components and dimensions are provided in Appendix D.

3.2.15. *Component dimensions and resolution*

An important motivation for the ventilation library is to provide sufficient resolution in dimensions of component types so the results can later be used for optimization of ventilation designs with respect to reduced environmental impacts. Fig. 1 shows a simple example of variation in climate emissions from the range of circular duct diameters available in the library.

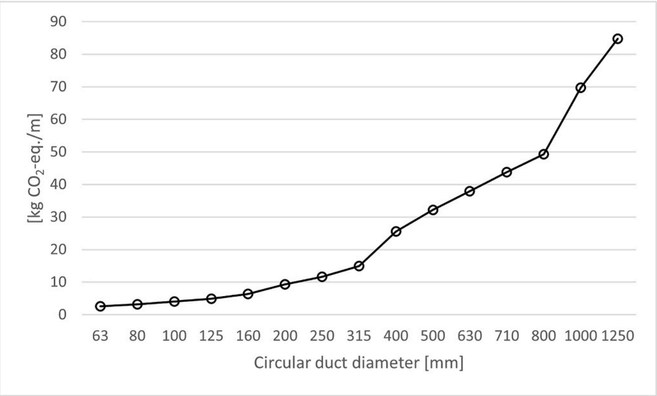

Fig. 1. Climate footprint per meter of different diameters of circular ducts.

As can be expected, the curve shows increasing emissions with increasing diameters, highlighting that choice of correct dimension matters when modelling ventilation systems. As previously noted, databases like ecoinvent offer few alternative dimensions and are therefore not well suited for detailed analysis of ventilation systems, and even less for optimization with regards to life cycle impacts. Some breaks can be observed in the curve in Fig. 1, and these are primarily associated with increases in circumference and surface area, although increasing plate thickness also contributes for the largest diameters. Results from simple interpolation between few single data points to cover multiple dimensions should be used with care since the deviations can be significant for specific dimensions.

4. Application of ventilation library – a case study

Ventilation systems are comprised of many different components with standard dimensions. The LCI component library presented here includes a wide range of components and common dimensions for these. However, specific buildings are designed with specific solutions that requires some extent of tailoring. The ventilation library developed here has therefore been tested on a case building to assess the usability and coverage of the library, and to provide an example of the resulting carbon footprint. As study object we have used a BREEAM Outstanding certified office building from 2013. The building has four stories, a gross floor area of 2998 m^2, maximum air flow rate of approximately 12 $m^3/h/m^2$ and is located in Bergen on the western coast of Norway. This area is mild and temperate, with frequent precipitation.

4.1. Ventilation library coverage

A key motivation for developing the ventilation library has been to enable modelling of ventilation systems and associated environmental impacts with improved precision and flexibility to better understand their contribution to the environmental footprint of buildings. Achieving this implies that the library should be able to represent considerable parts of actual ventilation systems. For the case building, a detailed list of ventilation components was extracted from a BIM model of the finished building and then manually matched with the available components and dimensions in the ventilation library. As expected, not all components are represented directly by the ventilation library. These components can be divided into three main categories:

- Category C1: Components with standard dimensions, but not covered in the list of available dimensions in the ventilation library.
- Category C2: Building specific components with non-standardized dimensions.
- Category C3: Ventilation component types that are not included in the ventilation library.

One simple way to evaluate how well the ventilation library covers the specific ventilation system in the case building is to count the number of units that are found directly in the library. The two first columns in Table 2 presents the results from this comparison. Two main observations can be made from the comparison:

- Some component types are not included in the ventilation library.
- The included component types are relatively well covered.

The first observation is no surprise since the aim of the ventilation library is not to be exhaustive, but rather to include the most important components and dimensions. For the component types included in the library there seems to be a relatively good coverage with six out of 13 component types having 100 % coverage and five component types ranging from 64 % to 97 %. For rectangular bends the dimensions in the case building are larger than what is covered by the library, while rectangular reducers have not been included as a separate category in the ventilation library.

Assessing how well the library covers a real-case ventilation system by counting the number of units included tells only part of the story since it does not provide information about the relative importance of what is included relative to what is not included in terms of environmental impacts. We have therefore developed inventories for all component types and dimensions not covered in the ventilation library. The motivation for this is threefold; i) provide a more precise estimate of the environmental footprint of a complete ventilation system, ii) investigate the importance of the components not included in the library for the environmental footprint of a complete ventilation system, and iii) ensure that potentially important case-specific components or dimensions are included and exemplify their contribution. Proxy inventories for the missing components and dimensions are developed

Table 2
Data coverage of the ventilation library for a specific case-building.

Component	Amount [#units]	Library coverage, [#units]	Weight [kg]	Library coverage [weight-%]	Share of total weight [%]	Reason missing/Proxy [C#/P#]
Ducts, circ.	1148 [m]	100 %	6426	100 %	31.3 %	–
Ducts, rect.	23 [m]	76 %	815	85 %	4.0 %	C2/P2
Bends, circ.	467	97 %	838	97 %	4.1 %	C1/P1
Bends, rect.	10	0 %	5 86	0 %	2.9 %	C2/P2
Saddles, circ.	184	85 %	1 31	63 %	0.6 %	C2/P1
T-pieces, circ.	131	100 %	307	100 %	1.5 %	–
Reducers, circ.	120	64 %	111	44 %	0.5 %	C1&C2/P2&P1
Reducers, rect.	9	0 %	176	0 %	0.9 %	C2/P2
Flow dampers	118	100 %	600	100 %	2.9 %	–
Silencers, circ.	152	84 %	1101	68 %	5.4 %	C1/P6
Silencers, rect.	14	100 %	487	100 %	2.4 %	–
Air diffusers	173	100 %	1305	100 %	6.4 %	–
Air handling units	4	100 %	5826	100 %	28.4 %	–
Joint parts, circ.	38	0 %	19	0 %	0.1 %	C3/P3
Joint parts, rect.	8	0 %	63	0 %	0.3 %	C3/P3
End caps, circ.	89	0 %	68	0 %	0.3 %	C3/P3
End caps, rect.	1	0 %	5	0 %	0.0 %	C3/P3
External louvres	8	0 %	491	0 %	2.4 %	C3&C2/P5
Rect. boxes	98	0 %	762	0 %	3.7 %	C3&C2/P2
Extr. air valves[a]	76	0 %	37	0 %	0.2 %	C3/P4
Plenum boxes[a]	36	0 %	354	0 %	1.7 %	C3/P2
TOTAL	–	–	**20 506**	**84.5 %**	**100 %**	–

[a] *Part of extract air units.*

according to the following principles:

- Proxy P1: Proxy using the nearest dimension.
- Proxy P2: Generic galvanized steel plate from library, from calculation of surface area.
- Proxy P3: Generic steel plate.
- Proxy P4: Generic steel plate w/powder coating.
- Proxy P5: Generic aluminium plate.
- Proxy P6: Extrapolation from nearest dimension, based on weight.

The last column in Table 2 summarizes the reason for missing components/dimensions (C#) in the ventilation library and the approach used to include proxy inventories for these (P#). Developing inventories also for the components that are not directly found in the ventilation library allows us to estimate the total weight of the ventilation system for the case building, and the share covered directly by the library, and the share not covered. However, even if a component or dimension is not found directly in the library, the library can still be used to estimate proxies for a significant part of the missing components. It can do so by using the closest dimension available in the library, by calculation of surface area combined with the generic galvanized steel plates indicated in Table 1, or in one case by extrapolation from available dimensions. The joint parts and end caps listed in Table 2 could also be modelled using a generic galvanized steel plate, but since their weight and contribution is negligible, they are only modelled simplified according to their mass as a generic steel plate without prior estimation of the surface area necessary for estimating the galvanisation.

Column four and five in Table 2 summarizes the coverage of the ventilation library in terms of weight. In column four the total calculated weight of each component type is presented, while column five shows how much of this total weight that is directly covered by the library. The calculated weight of the full ventilation system is 20.5 tons, giving an estimated weight of 6.84 kg/m^2 of floor area. Close to 85 % of this is covered directly by the ventilation library. The remaining 15 % has been estimated as described above and in the last column of Table 2. The largest contributors to the total weight are the circular ductwork and the air handling units. Circular ductwork make up more than 31 % of total weight and air handling units more than 28 %. Together they make up more than 60 %, and 100 % of the inventory processes for these components are found directly in the ventilation library.

For the component types that are not fully covered by the library, three component types make up the main part of the weight. Rectangular boxes (24 %), external louvres (15.5 %) and rectangular bends (18.5 %) together make up approx. 58 % of the weight not covered directly by the library. Both boxes and louvres have mainly non-standardized dimensions and are as such specific for the case building. However, boxes can be covered with good precision with the generic galvanized steel plates inventories, while the external louvres are made from aluminium and modelled specifically for the case building.

For the rectangular bends the dimensions used in the case building are larger than the ones included in the library, and they are few in numbers. However, inventories for these have been developed based on geometrical information to calculate surface area (including flanges), and then modelled using the generic unit inventories for galvanized steel plate indicated in Table 1.

Rectangular reducers are not included in the ventilation library. Inventories for the rectangular bends have also been developed by making use of the generic unit inventories. Total weight per component is known, and the weight of rubber gaskets can be estimated from geometric parameters. By applying Equation (1) we can estimate the surface area and corresponding weight of galvanized steel plate. This enables us to model and include relatively good proxies for missing components or missing dimensions in a consistent way.

4.2. *Environmental impacts from ventilation systems*

Having developed the necessary inventories to cover the full ventilation system, the associated environmental impacts can be estimated. With all components described in terms of unit inventories the complete environmental footprint is calculated by: i) picking the component types found in the case building, ii) matching the correct dimensions for each component type from the library, and iii) specifying the quantities of each in terms of meters or number of units. The results for climate emissions for the full ventilation system of the case building are presented in Fig. 2 according to the component types listed in Table 2.

The left column in Fig. 2 contains all component types contributing more than 3 % to the total climate footprint, accounting in total for approximately 90 % of the emissions, while contributions from the remaining component types are displayed in the right column. The results from the environmental assessment show that the main contributors to the total climate footprint of the ventilation system are the air handling units and circular ducts, which contribute 28 % and 27 %, respectively. Both components are fully covered by the ventilation library. However, the third largest contributor is the external louvres which are non-standardized and building-specific components, highlighting that a generic inventory will not be able to cover every

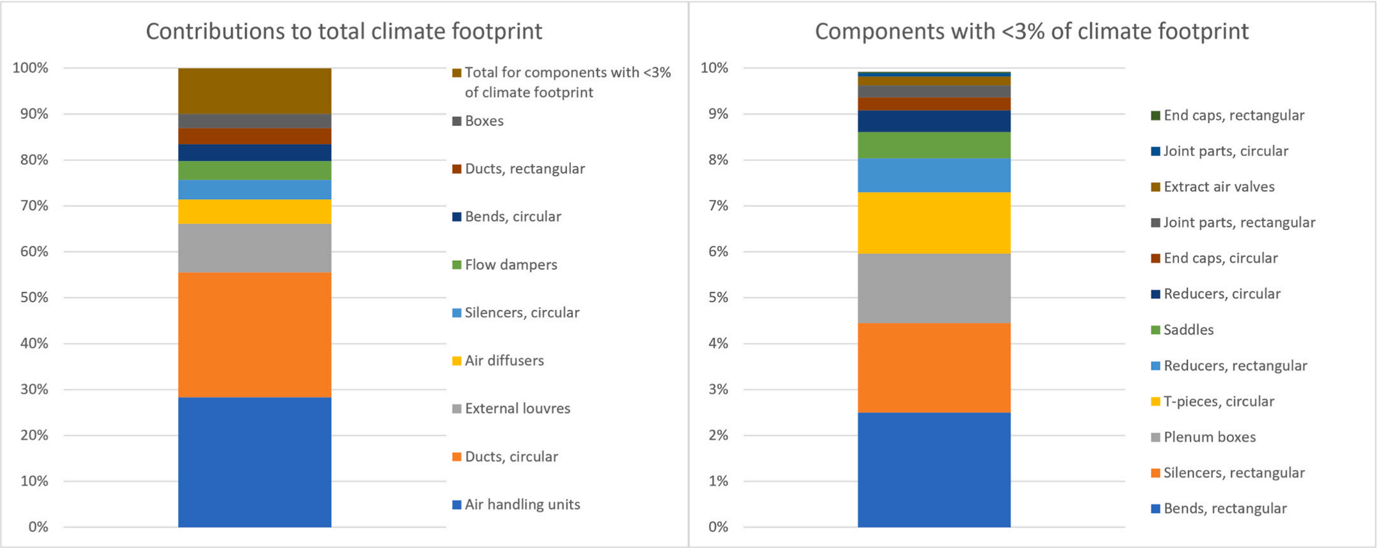

Fig. 2. Climate footprint results for the ventilation system in the case building.

Table 3
Overview of contributions to total climate footprint for the ventilation system in the case building.

Component type	Contribution	Component type	Contribution
Air handling units	28 %	Plenum boxes	1.5 %
Ducts, circular	27 %	T-pieces, circular	1.3 %
External louvres	11 %	Reducers, rectangular	0.75 %
Air diffusers	5.3 %	Saddles, circular	0.57 %
Silencers, circular	4.3 %	Reducers, circular	0.47 %
Flow dampers	4.1 %	End caps, circular	0.28 %
Bends, circular	3.7 %	Joint parts, rectangular	0.26 %
Ducts, rectangular	3.5 %	Extract air valves	0.19 %
Boxes	3.2 %	Joint parts, circular	0.08 %
Bends, rectangular	2.5 %	End caps, rectangular	0.02 %
Silencers, rectangular	2.0 %		

component and the complete footprint, and that the list of components not covered should be checked for potentially important omissions. In the case of the external louvre, one with large dimensions has been chosen to ensure low pressure drop, high resistance to rainwater intrusion and good corrosion resistance due to the high precipitation levels in the geographical location.

Table 3 presents a more detailed overview of the contributions from different component types to the total footprint presented in Fig. 2.

Most of the component types have a contribution of less than 5 %, and eight types contribute with less than 1 %. Counting only the three top contributors, two thirds of the total climate footprint is already covered. If counting only the components and dimensions covered directly by the ventilation library, and excluding all proxies developed for the case building, we find that 78.5 % of the climate footprint is covered. Of this, air handling units and circular ducts comprise roughly equal shares and in total more than 70 % of the footprint. The component types that are not included in the ventilation library, shown as the last eight entries in Table 2, accounts for 16 % of the estimated climate footprint. However, this includes the external louvres which are building specific components and account for 11 % on their own. This implies that the generic component types that are omitted from the ventilation library amount to only about 5 % of the total estimated climate footprint.

The total estimated climate footprint from the ventilation system in the case building is 68 107 kg CO_2-eq., giving an estimated 22.7 kg CO_2-eq./m^2 for the full ventilation system and 6.44 and 6.17 kg CO_2-eq./m^2 for air handling units and circular ducts, respectively. Reference values for embodied emissions for different building categories have been developed for the Norwegian Agency for Public and Financial Management [55] and used for the same purpose within the national BREEAM certification system. According to the reference values, a modern office building has embodied emissions of 230 kg CO_2-eq./m^2 for the A1-A3 phase. This reference value excludes ventilation systems and other technical installations such as sanitation, heating, electrical installations etc. It also excludes groundworks and foundations due to their case-specific large variation. Compared to the reference value, the ventilation system in the case building adds approximately 10 % to the embodied climate emissions. However, with the omission of other technical installations and groundworks, the contribution from the ventilation system to total climate footprint for the case building will be less than 10 %. A precise contribution is difficult to establish due to large variability the extent of groundworks and the general lack of verified emission profiles for technical installations, which is also the motivation behind the work presented here.

The main part of the discussion has been devoted to the climate emissions associated with production of the ventilation component. Since all inventories are modelled using the ecoinvent database and with the ReCiPe method for impact assessment modelling, results for a range of other environmental impact categories are also available. These will not be explored in detail here, but in general they replicate the main findings from the climate footprint. Air handling units and circular ducts are the main contributors for all impact categories. Air handling units contribute to total impacts with between 18.7 % and 59.3 %, for marine eutrophication and freshwater ecotoxicity, respectively. Correspondingly, circular ducts contribute to the total impacts with between 15.5 % and 38 % for freshwater ecotoxicity and marine eutrophication, respectively. Combined, the two component types account for approximately 55 %–75 % of total impacts across the environmental impact categories included in the ReCiPe method. For the climate footprint, the combined contribution to total impacts is 55.5 %, implying that these two component types are even more important for most other impact categories.

As previously noted, the component types not included in the ventilation inventory account for approximately 5 % of the climate footprint. Their share varies between 3 % and 6.1 % for the other impact categories, while the contribution from the external louvres is highest for climate related impacts. The implication of this is that the coverage of the ventilation library in terms of environmental impacts are at the lowest for climate emissions, and notably higher for most of the other environmental impact categories in the ReCiPe method.

5. Discussion

The work presented here has had as its main objectives the development and documentation of a consistent and generic inventory library for common ventilation components and dimensions and testing and validation of this for a real-life case building. Applying the ventilation library to a case building has demonstrated that it can cover the main part of the ventilation system, both in weight and in environmental impacts. More than 78 % of climate emissions were covered directly, by available library components, while even better coverage was found for other environmental impact categories. The two top contributors across all impact categories were the air handling units and the circular ducts, which were both covered fully by the library. Generic unit processes further contribute to development of proxies for missing or omitted dimensions or component types. The relatively wide coverage of available dimensions also facilitates using nearest dimension as a proxy without significantly compromising the precision of the results. From this, it seems reasonable to conclude that the ventilation library can be used to provide realistic estimates for the embodied emissions of ventilation systems.

The ventilation library is developed to represent generic and standard dimensions commonly used in ventilation systems design. However, there is usually some extent of tailor-making required for individual buildings, and thereby also use of components or dimensions that are not standard and not possible to represent directly in a generic library. As described above, this can partly be covered by generic unit processes supplied with the library, but some components will need to be modelled separately if they are to be included. For the building studied, this was the case for the external aluminium louvres which turned out to be the third most important component type. As described earlier, the louvre is a building-specific choice to withstand the wet climate, influencing both dimensions and choice of material, both of which contribute to increased embodied emissions. Increased climate adaptation might increase the need for this type of louvre construction. The conclusion from this should be that even if the library has a good representation, one should still check if important components are not represented. A first approach to this could be a simple screening to check if there are components not represented that have a significant contribution to the total weight and/or are made from a material with comparatively high emission intensity.

Taken together, the building specific louvres and the components directly available from the library account for 90 % of the total climate footprint. This indicates a potential for the ventilation library to be used on its own, and particularly if the user also makes the effort to confirm whether there are important building specific components that need to be included. To assess how well the library covers a real-life building, it was necessary to establish proxies for component types and dimensions that are not included in the library. The motivation for the library was to cover the main standard components, rather than being exhaustive. Results from the case building seem to support this. Seven component types that appear in the component list for the building, excluding the external louvres, are omitted from the ventilation library since they were regarded as having a minor contribution to total impacts. This seems to be justified by their modest share 5 % of the climate footprint.

Still, even if the coverage is promising, the process of matching the list of components with the library remains for now a manual exercise. Combining the library with BIM models could potentially make for a more automated process, but this is not straightforward and would require standardization of naming conventions and component types for different manufacturers. However, challenges would still be present in early-stage design where the freedom to optimize solutions and environmental performance is the biggest, but also where BIM models are less developed and not detailed to the level presented in this study.

Although the coverage of the library is fairly extensive it should be kept in mind that the data collection still rests on a limited set of component examples and that the modelling of LCIs inherently implies some methodological choices – both introducing some extent of uncertainty to the results. Specific components can be designed and manufactured differently by different manufacturers and also by the same manufacturer which might have several product lines to cover a variation of design options for the same component type. The library contains only examples considered to be commonly used designs, and not a variation of designs or an average material composition based on different designs and manufacturers. This implies that results from using the library should be interpreted and used accordingly. For early-stage design and evaluation of different ventilation layouts the library can give valuable insight into important aspects and differences between alternative options, identify aspects and components with high contributions, and provide a reasonable estimate of the magnitude of the associated embodied emissions. For evaluation of ventilation layouts at late design stage where the main variables have been decided, the library and results should be used with caution in cases of minor optimization of layout or for ranking of similar design alternatives where uncertainty might be of the same magnitude as the difference between design alternatives. However, for all design stages the ventilation library should provide useful estimates of associated embodied emissions. Finally, for assessment of as-built designs, manufacturer-specific EPDs or similar should be used to the extent possible, while remaining components could be estimated from the library. Ideally, a comprehensive library would include different versions of the same component so that both variation and average values would be available. With the current trend of rapidly increasing availability of EPDs, such information might be possible to represent in the years to come.

The ventilation library is so far tested on only one building. Further work should include testing on multiple buildings and building types to see if the coverage remains good for individual buildings and across building types, and to provide more examples to see the variations in environmental impacts per floor area. This could provide better estimates for including impacts from ventilation systems when data or resources are not available for performing a full assessment of the ventilation system.

A key motivation for the ventilation library development has been to fill one part of the knowledge and documentation gap for technical systems in buildings. It has been demonstrated how the ventilation library can be used to assess embodied emissions in ventilation systems for specific buildings. Going beyond assessments for specific buildings, the ventilation library could be used to assess different ventilation principles and systems, and with more empirical studies contribute to establish benchmark values for typical layouts and for different building types in terms of embodied emissions per floor area. Benchmark values could be used by building designers to assess, improve and compare their own designs, but would also be relevant for policymakers who could use such values for implementing quantitative requirements for embodied emissions. In striving to abate the negative impacts from building activity and in reaching for the global sustainability goals, knowledge of the actual impacts from ventilation and other technical systems is essential and should not be left out.

A further motivation for the library development is to provide the necessary building blocks for use in an optimization model that can propose and evaluate different ventilation system layouts to find optimal designs based on life cycle emissions. The ventilation library presented here contains the necessary building blocks for such an optimization. Smaller duct diameters reduce material, but also introduces higher pressure drops which increases the fan power and the corresponding energy use. Such an optimization model could represent an improvement compared to more commonly used design strategies that are more based on rules of thumb or approximation methods. The next step for the use of the ventilation component library would be the implementation of such an optimization model.

CRediT authorship contribution statement

H. Bergsdal: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **J. Tønnesen:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Data curation, Conceptualization. **A. Borg:** Writing – review & editing, Investigation, Data curation. **C. Solli:** Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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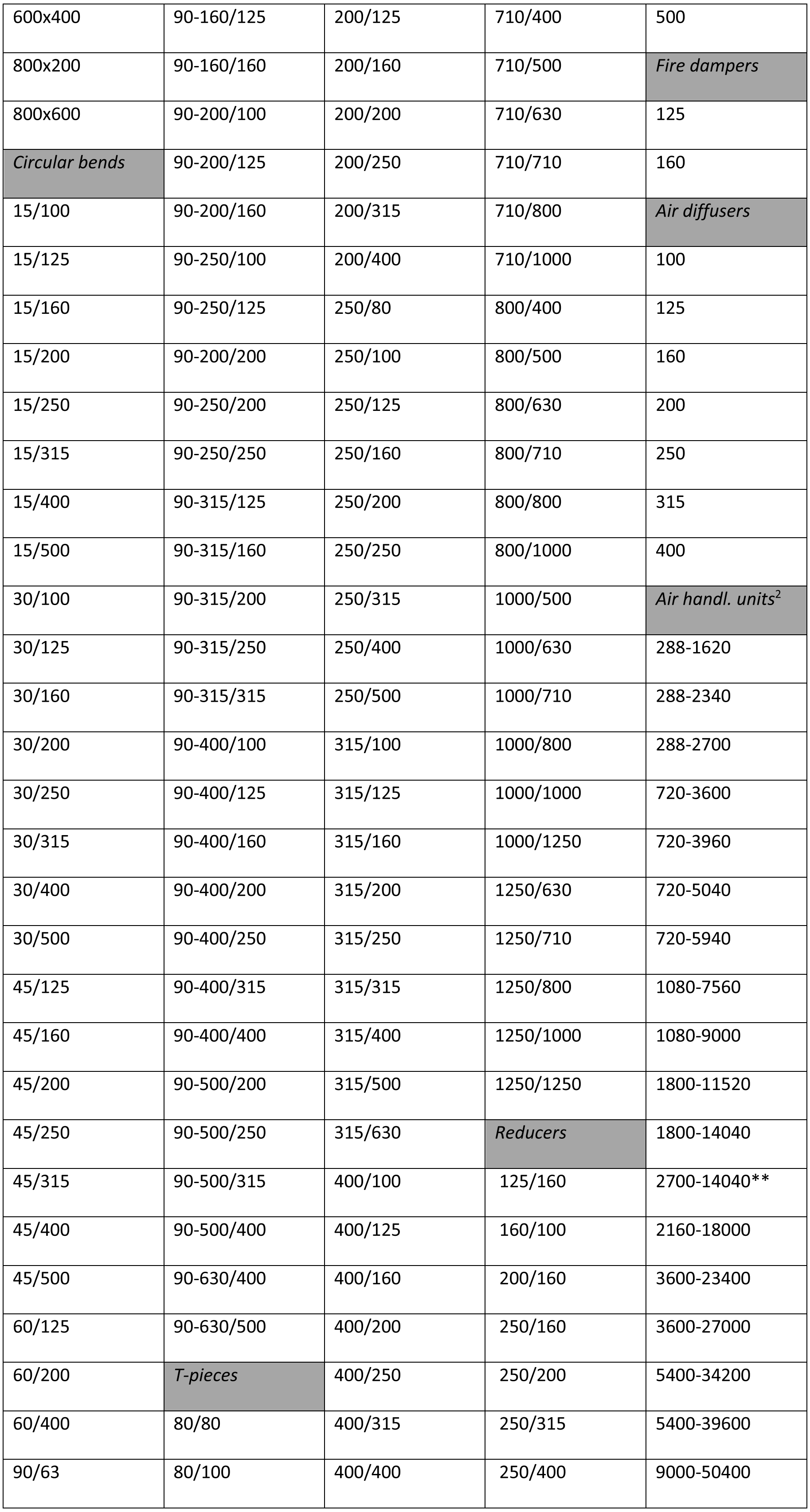
Appendix A. Inventory library component list

The naming convention for the components is as follows [units in brackets]:
Circular ducts: Diameter [mm].
Rectangular ducts: Side a x Side b [mm x mm].
Circular bends: Angle/Diameter [deg/mm].
Rectangular bends: Angle/Side a x Side b [deg/mm x mm].

Saddles: Angle – Diameter main run/Diameter branch [deg - mm/mm].
T-pieces: Diameter main run/Diameter branch [mm/mm].
Reducers: Min or max diameter [mm/mm].
Circular silencers: Diameter ingoing run - Length/Diameter outgoing run [mm – mm/mm].
Rectangular silencers: Length - Side a x Side b [mm – mm/mm].
Flow dampers: Diameter [mm].
Fire dampers: Diameter [mm].
Air diffusers: Diameter [mm].
Air handling units: Min flow rate - Max flow rate [m3/h].

Table A1
Inventory library component list.

Circular ducts	90/80	80/125	400/500	315/160
63	90/100	80/160	400/630	315/200
80	90/125	100/80	500/100	400/200
100	90/160	100/100	500/125	400/315
125	90/200	100/125	500/160	*Silencers*
160	90/250	100/160	500/200	100-300/100
200	90/315	100/200	500/250	125-300/125
250	90/400	100/250	500/315	125-600/125
315	90/500	125/80	500/400	160-300/160
400	90/630	125/100	500/500	160-600/160
500	90/710	125/125	500/630	200-300/200
630	90/800	125/160	500/800	200-600/200
710	90/1000	125/200	630/100	250-600/250
800	90/1250	125/250	630/125	315-1200/315
1000	*Rectang. bends*	125/315	630/160	315-600/315
1250	45/800x200	160/80	630/200	400-600/400
Rectangular ducts	90/1000x2000	160/100	630/250	400-900/400
1000x400	90/1400x600	160/125	630/315	*Flow dampers*
1200x500	90/400x1000	160/160	630/400	125
1200x600	90/500x1200	160/200	630/500	160
1400x600	90/600x1400	160/250	630/630	200
1600x800	*Saddles*	160/315	630/710	250
2000x1000	90-125/125	200/80	630/800	315
4000x1000	90-160/100	200/100	630/1000	400



600x400	90-160/125	200/125	710/400	500
800x200	90-160/160	200/160	710/500	*Fire dampers*
800x600	90-200/100	200/200	710/630	125
Circular bends	90-200/125	200/250	710/710	160
15/100	90-200/160	200/315	710/800	*Air diffusers*
15/125	90-250/100	200/400	710/1000	100
15/160	90-250/125	250/80	800/400	125
15/200	90-200/200	250/100	800/500	160
15/250	90-250/200	250/125	800/630	200
15/315	90-250/250	250/160	800/710	250
15/400	90-315/125	250/200	800/800	315
15/500	90-315/160	250/250	800/1000	400
30/100	90-315/200	250/315	1000/500	*Air handl. units*[2]
30/125	90-315/250	250/400	1000/630	288-1620
30/160	90-315/315	250/500	1000/710	288-2340
30/200	90-400/100	315/100	1000/800	288-2700
30/250	90-400/125	315/125	1000/1000	720-3600
30/315	90-400/160	315/160	1000/1250	720-3960
30/400	90-400/200	315/200	1250/630	720-5040
30/500	90-400/250	315/250	1250/710	720-5940
45/125	90-400/315	315/315	1250/800	1080-7560
45/160	90-400/400	315/400	1250/1000	1080-9000
45/200	90-500/200	315/500	1250/1250	1800-11520
45/250	90-500/250	315/630	*Reducers*	1800-14040
45/315	90-500/315	400/100	125/160	2700-14040**
45/400	90-500/400	400/125	160/100	2160-18000
45/500	90-630/400	400/160	200/160	3600-23400
60/125	90-630/500	400/200	250/160	3600-27000
60/200	*T-pieces*	400/250	250/200	5400-34200
60/400	80/80	400/315	250/315	5400-39600
90/63	80/100	400/400	250/400	9000-50400

1In m3/h [min/max].

Appendix B List of ecoinvent unit processes used in the ventilation components library

Table B1
List of ecoinvent unit processes used.

ecoinvent process name[2]	Generic model name/proxy	Comment
Steel mix	Steel plate	
Steel. low-alloyed {GLO}| market for		37 %
Steel. unalloyed {GLO}| market for		63 %
Sheet rolling. steel {GLO}| market for		
Energy mix	Energy	
Electricity. medium voltage {RER}| market group for		33 %
Heat. district or industrial. natural gas {RER}| market group for		33 %
Heat. district or industrial. other than natural gas {RER}| market group for		33 %
Aluminium plate	Aluminium plate	
Aluminium. wrought alloy {GLO}| market for		
Sheet rolling. aluminium {GLO}| market for		
Ventilation components factory {GLO}| market for	Infrastructure	
Zinc coat. coils {GLO}| market for	Zinc coating	Adapted thickness
Welding. arc. steel {GLO}| market for	Steel welding	
Synthetic rubber {GLO}| market for	EPDM rubber	
Sodium silicate. solid {GLO}| market for	Calcium silicate	
Vermiculite {GLO}| market for	Ceramic fireproofing	
Seal. natural rubber based {GLO}| market for	Rubber sealing	
Steel. chromium steel 18/8. hot rolled {GLO}| market for	Stainless steel	
Brass {CH}| market for brass	Brass	
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for	ABS plastic	
Cable. unspecified {GLO}| market for	Wiring cables	
Printed wiring board. through-hole mounted. unspecified. Pb containing {GLO}| market for	Printed circuit board	
Stone wool. packed {GLO}| market for stone wool. packed	Stone wool	
Glass fibre reinforced plastic. polyester resin. hand lay-up {GLO}| market for	Glass fibre	
Polyvinylchloride. bulk polymerised {GLO}| market for	PVC	
Powder coat. steel {GLO}| market for	Powder coating	
Zinc {GLO}| market for	Zinc	
Titanium dioxide {RER}| market for	Titanium dioxide	
Polyethylene. high density. granulate {GLO}| market for	Polyethylene. HDPE	
Polyester resin. unsaturated {GLO}| market for	Polyester resin	
Formaldehyde {GLO}| market for	Formaldehyde	
Phosphoric acid. industrial grade. without water. in 85 % solution state {GLO}| market for	Phosphoric acid	
Melamine {GLO}| market for	Melamine polymer	
Toluene diisocyanate {GLO}| market for	Hexane 1.6 diisocyanate. homopolymer/ Hexametyldiisocyanate	
Polymethyl methacrylate. beads {GLO}| market for	Acrylic polymer	
Aluminium. cast alloy {GLO}| market for	Aluminium	
Ferrite {GLO}| market for	Magnet	
Metal working. average for aluminium product manufacturing {RER}| processing	Metal working. generic	
Copper {GLO}| market for	Copper	
Wire drawing. copper {GLO}| market for	Wire drawing. copper	
Polycarbonate {GLO}| market for	Polymer materials	
Glass fibre reinforced plastic. polyamide. injection moulded {GLO}| market for	Polyamide	
Polypropylene. granulate {GLO}| market for	Polypropene	
Rock wool {GLO}| market for	Rock wool	
Acrylic binder. without water. in 34 % solution state {GLO}| market for	Binder	
Naphtha {RER}| market for	Dust binding oil	
Glass fibre {GLO}| market for	Glass fibre. generic	
Electronics. for control units {GLO}| market for	Electronics. generic	

1 The notation “Alloc Rec, U″ used in the naming of the ecoinvent processes and specifying the system model used, has been left out of the list in the table in order to shorten the process names since it applies to all inventories used.

Appendix C Detailed inventories

Appendix C1 – Circular ducts

Table C 1
Detailed inventories for circular ducts [per m].

Product name	Steel plate	Zinc coating	Energy	Infrastructure
	[kg]	*[m2]*	*[MJ]*	*[p]*
Duct 63	0.84	0.23	3.72	3.03E-09
Duct 80	1.02	0.28	4.55	3.71E-09
Duct 100	1.30	0.36	5.79	4.72E-09
Duct 125	1.58	0.44	7.03	5.73E-09

(*continued on next page*)

Table C 1 (*continued*)

Product name	Steel plate	Zinc coating	Energy	Infrastructure
	[kg]	*[m2]*	*[MJ]*	*[p]*
Duct 160	2.04	0.57	9.10	7.42E-09
Duct 200	2.97	0.83	13.23	1.08E-08
Duct 250	3.72	1.03	16.54	1.35E-08
Duct 315	4.89	1.12	21.77	1.78E-08
Duct 400	8.37	1.91	37.26	3.04E-08
Duct 500	10.54	2.41	46.89	3.83E-08
Duct 630	12.63	2.45	56.19	4.58E-08
Duct 710	14.57	2.82	64.84	5.29E-08
Duct 800	16.43	3.18	73.09	5.96E-08
Duct 1000	23.73	3.53	105.59	8.61E-08
Duct 1250	28.82	4.29	128.25	1.05E-07

Appendix C2 – Rectangular ducts

Table C 2
Detailed inventories for rectangular ducts [per m].

Product name	Steel plate	Zinc coating	Energy	Infrastructure
	[kg]	*[m2]*	*[MJ]*	*[p]*
Duct 1000x400	20.23	2.80	90.02	7.34E-08
Duct 1200x500	24.07	3.40	107.09	8.74E-08
Duct 1200x600	26.01	3.60	115.74	9.44E-08
Duct 1400x600	28.90	4.00	128.61	1.05E-07
Duct 1600x800	39.68	4.80	176.58	1.44E-07
Duct 2000x1000	47.35	6.00	210.71	1.72E-07
Duct 4000x1000	90.60	10.00	403.15	3.29E-07
Duct 600x400	13.45	2.00	59.85	4.88E-08
Duct 800x200	14.45	2.00	64.30	5.25E-08
Duct 800x600	20.23	2.80	90.02	7.34E-08

Appendix C3 – Circular bends

Table C 3
Detailed inventories for circular bends [per piece].

Product name	Steel plate	Zinc coating	Steel welding	EPDM rubber	Energy	Infrastructure
	[kg]	*[m2]*	*[m]*	*[kg]*	*[MJ]*	*[p]*
Bend-15 100	0.06	0.04	0.19	0.06	0.36	2.28E-10
Bend-15 125	0.09	0.05	0.19	0.07	0.54	3.43E-10
Bend-15 160	1.14	0.07	0.20	0.09	6.53	4.13E-09
Bend-15 200	0.27	0.10	0.21	0.11	1.53	9.70E-10
Bend-15 250	0.41	0.14	0.23	0.14	2.34	1.48E-09
Bend-15 315	0.74	0.24	0.32	0.18	4.23	2.67E-09
Bend-15 400	1.45	0.36	0.37	0.23	8.34	5.28E-09
Bend-15 500	1.95	0.51	0.39	0.29	11.21	7.09E-09
Bend-30 100	0.14	0.05	0.21	0.06	0.79	5.01E-10
Bend-30 125	0.21	0.07	0.23	0.07	1.19	7.53E-10
Bend-30 160	0.29	0.10	0.24	0.09	1.65	1.04E-09
Bend-30 200	0.50	0.15	0.27	0.11	2.87	1.82E-09
Bend-30 250	0.77	0.25	0.37	0.14	4.42	2.79E-09
Bend-30 315	0.90	0.36	0.41	0.18	5.16	3.26E-09
Bend-30 400	1.99	0.56	0.47	0.23	11.44	7.24E-09
Bend-30 500	2.96	0.82	0.52	0.29	17.00	1.07E-08
Bend-45 125	0.27	0.09	0.26	0.07	1.55	9.82E-10
Bend-45 160	0.40	0.14	0.29	0.09	2.28	1.44E-09
Bend-45 200	0.61	0.20	0.32	0.11	3.53	2.23E-09
Bend-45 250	0.74	0.33	0.44	0.14	4.27	2.70E-09
Bend-45 315	1.46	0.49	0.49	0.18	8.38	5.30E-09
Bend-45 400	2.93	0.76	0.57	0.23	16.84	1.06E-08
Bend-45 500	3.97	1.13	0.65	0.29	22.78	1.44E-08
Bend-60 125	0.28	0.11	0.29	0.07	1.63	1.03E-09
Bend-60 200	0.66	0.25	0.37	0.11	3.82	2.41E-09
Bend-60 400	3.77	0.95	0.68	0.23	21.66	1.37E-08

(*continued on next page*)

Table C 3 (*continued*)

Product name	Steel plate	Zinc coating	Steel welding	EPDM rubber	Energy	Infrastructure
	[kg]	*[m2]*	*[m]*	*[kg]*	*[MJ]*	*[p]*
Bend-90 100	0.24	0.10	0.32	0.06	1.37	8.66E-10
Bend-90 1000	39.12	8.03	1.97	0.57	224.53	1.42E-07
Bend-90 125	0.37	0.15	0.36	0.07	2.12	1.34E-09
Bend-90 1250	59.76	12.35	2.36	0.71	343.05	2.17E-07
Bend-90 160	0.69	0.23	0.41	0.09	3.98	2.52E-09
Bend-90 200	1.07	0.35	0.47	0.11	6.11	3.87E-09
Bend-90 250	1.37	0.56	0.63	0.14	7.87	4.97E-09
Bend-90 315	1.85	0.85	0.74	0.18	10.60	6.70E-09
Bend-90 400	5.25	1.35	0.89	0.23	30.16	1.91E-08
Bend-90 500	7.89	2.06	1.05	0.29	45.31	2.87E-08
Bend-90 63	0.17	0.05	0.26	0.04	0.96	6.09E-10
Bend-90 630	11.70	3.20	1.25	0.36	67.13	4.25E-08
Bend-90 710	15.42	4.02	1.38	0.41	88.49	5.60E-08
Bend-90 80	0.21	0.07	0.29	0.05	1.21	7.64E-10
Bend-90 800	19.01	5.24	1.66	0.46	109.14	6.90E-08

Appendix C4 – Rectangular bends

Table C 4
Detailed inventories for rectangular bends [per piece].

Product name	Steel plate	Zinc coating	Energy	Infrastructure
	[kg]	*[m2]*	*[MJ]*	*[p]*
Bend-45 800x200	12.41	1.25	71.21	4.50E-08
Bend-90 1000x2000	84.44	7.50	484.67	3.07E-07
Bend-90 1400x600	28.68	2.81	164.63	1.04E-07
Bend-90 400x1000	18.09	1.82	103.84	6.57E-08
Bend-90 500x1200	29.30	2.55	168.18	1.06E-07
Bend-90 600x1400	45.97	4.08	263.86	1.67E-07

Appendix C5 – Circular saddles

Table C 5
Detailed inventories for circular saddles [per piece].

Product name	Steel plate	Zinc coating	EPDM rubber	Energy	Infrastructure
	[kg]	*[m2]*	*[kg]*	*[MJ]*	*[p]*
Saddle-90 125/125	0.19	0.05	0.07	1.11	7.04E-10
Saddle-90 160/100	0.10	0.03	0.07	0.58	3.67E-10
Saddle-90 160/125	0.16	0.04	0.07	0.90	5.70E-10
Saddle-90 160/160	0.28	0.08	0.09	1.60	1.01E-09
Saddle-90 200/100	0.09	0.03	0.09	0.53	3.34E-10
Saddle-90 200/125	0.15	0.04	0.07	0.84	5.34E-10
Saddle −90 200/160	0.21	0.06	0.09	1.22	7.73E-10
Saddle-90 200/200	0.34	0.09	0.11	1.95	1.23E-09
Saddle-90 250/100	0.04	0.01	0.14	0.20	1.27E-10
Saddle-90 250/125	0.15	0.04	0.07	0.84	5.34E-10
Saddle-90 250/200	0.39	0.11	0.11	2.22	1.40E-09
Saddle-90 250/250	0.57	0.16	0.14	3.29	2.08E-09
Saddle-90 315/125	0.15	0.04	0.07	0.84	5.34E-10
Saddle-90 315/160	0.21	0.06	0.09	1.22	7.73E-10
Saddle-90 315/200	0.38	0.11	0.11	2.16	1.37E-09
Saddle-90 315/250	0.54	0.15	0.14	3.08	1.95E-09
Saddle-90 315/315	0.76	0.21	0.18	4.37	2.77E-09
Saddle-90 400/100	0.39	0.11	0.06	2.26	1.43E-09
Saddle-90 400/125	0.38	0.11	0.07	2.18	1.38E-09
Saddle-90 400/160	0.36	0.10	0.09	2.07	1.31E-09
Saddle-90 400/200	0.34	0.09	0.11	1.95	1.23E-09
Saddle-90 400/250	0.51	0.14	0.14	2.92	1.85E-09
Saddle-90 400/315	0.62	0.17	0.18	3.58	2.26E-09
Saddle-90 400/400	1.59	0.31	0.23	9.11	5.76E-09
Saddle-90 500/200	0.34	0.09	0.11	1.95	1.23E-09
Saddle-90 500/250	0.51	0.14	0.14	2.92	1.85E-09

(*continued on next page*)

Table C 5 (*continued*)

Product name	Steel plate	Zinc coating	EPDM rubber	Energy	Infrastructure
	[kg]	*[m2]*	*[kg]*	*[MJ]*	*[p]*
Saddle-90 500/315	0.62	0.17	0.18	3.58	2.26E-09
Saddle-90 500/400	1.40	0.27	0.23	8.02	5.07E-09
Saddle-90 630/400	1.40	0.27	0.23	8.02	5.07E-09
Saddle-90 630/500	1.51	0.42	0.07	8.68	5.49E-09

Appendix C6 – Circular T-pieces

Table C 6
Detailed inventories for circular T-pieces [per piece].

Product name	Steel plate	Zinc coating	Steel welding	EPDM rubber	Energy	Infrastructure
	[kg]	*[m2]*	*[m]*	*[kg]*	*[MJ]*	*[p]*
T-piece 100/100	0.32	0.09	0.31	0.09	1.85	1.17E-09
T-piece 100/125	3.01	0.84	0.39	0.09	17.26	1.09E-08
T-piece 100/160	3.02	0.84	0.50	0.07	17.32	1.10E-08
T-piece 100/200	3.11	0.87	0.63	0.11	17.87	1.13E-08
T-piece 100/250	3.56	0.99	0.79	0.13	20.42	1.29E-08
T-piece 100/80	0.26	0.07	0.25	0.08	1.48	9.33E-10
T-piece 1000/1000	28.80	4.29	3.14	0.86	165.30	1.05E-07
T-piece 1000/1250	38.30	5.70	3.93	0.93	219.82	1.39E-07
T-piece 1000/500	17.49	2.60	1.57	0.71	100.38	6.35E-08
T-piece 1000/630	22.23	3.31	1.98	0.75	127.62	8.07E-08
T-piece 1000/710	22.20	3.30	2.23	0.77	127.43	8.06E-08
T-piece 1000/800	23.12	3.44	2.51	0.80	132.71	8.39E-08
T-piece 125/100	0.38	0.10	0.31	0.10	2.15	1.36E-09
T-piece 125/125	0.48	0.13	0.39	0.11	2.73	1.73E-09
T-piece 125/160	3.58	1.00	0.50	0.12	20.57	1.30E-08
T-piece 125/200	3.75	1.04	0.63	0.13	21.53	1.36E-08
T-piece 125/250	3.73	1.04	0.79	0.14	21.41	1.35E-08
T-piece 125/315	4.17	1.16	0.99	0.16	23.92	1.51E-08
T-piece 125/80	0.37	0.10	0.25	0.09	2.15	1.36E-09
T-piece 1250/1000	37.31	5.55	3.14	1.00	214.14	1.35E-07
T-piece 1250/1250	42.96	6.39	3.93	1.07	246.60	1.56E-07
T-piece 1250/630	26.90	4.00	1.98	0.89	154.41	9.77E-08
T-piece 1250/710	30.71	4.57	2.23	0.92	176.27	1.11E-07
T-piece 1250/800	30.67	4.56	2.51	0.94	176.05	1.11E-07
T-piece 160/100	0.46	0.13	0.31	0.12	2.63	1.66E-09
T-piece 160/125	0.55	0.15	0.39	0.13	3.16	2.00E-09
T-piece 160/160	0.70	0.20	0.50	0.14	4.04	2.55E-09
T-piece 160/200	4.57	1.27	0.63	0.15	26.23	1.66E-08
T-piece 160/250	4.46	1.24	0.79	0.16	25.57	1.62E-08
T-piece 160/315	4.43	1.23	0.99	0.18	25.42	1.61E-08
T-piece 160/80	0.45	0.13	0.25	0.11	2.57	1.63E-09
T-piece 200/100	0.63	0.18	0.31	0.14	3.63	2.29E-09
T-piece 200/125	0.77	0.21	0.39	0.15	4.42	2.80E-09
T-piece 200/160	0.94	0.26	0.50	0.16	5.41	3.42E-09
T-piece 200/200	1.11	0.31	0.63	0.17	6.37	4.03E-09
T-piece 200/250	4.43	1.23	0.76	0.19	25.45	1.61E-08
T-piece 200/315	4.41	1.22	0.99	0.20	25.30	1.60E-08
T-piece 200/400	4.84	1.34	1.26	0.23	27.75	1.76E-08
T-piece 200/80	0.60	0.17	0.25	0.14	3.47	2.19E-09
T-piece 250/100	0.76	0.21	0.31	0.17	4.33	2.74E-09
T-piece 250/125	0.93	0.26	0.39	0.18	5.34	3.38E-09
T-piece 250/160	1.10	0.31	0.50	0.19	6.32	4.00E-09
T-piece 250/200	1.46	0.40	0.63	0.20	8.36	5.29E-09
T-piece 250/250	1.71	0.48	0.79	0.21	9.83	6.22E-09
T-piece 250/315	5.08	1.41	0.99	0.23	29.14	1.84E-08
T-piece 250/400	5.74	1.59	1.26	0.26	32.94	2.08E-08
T-piece 250/500	6.63	1.84	1.57	0.29	38.03	2.40E-08
T-piece 250/80	0.73	0.20	0.25	0.17	4.17	2.64E-09
T-piece 315/100	1.00	0.28	0.31	0.21	5.73	3.63E-09
T-piece 315/125	1.17	0.33	0.39	0.22	6.74	4.26E-09
T-piece 315/160	1.35	0.37	0.50	0.23	7.72	4.88E-09
T-piece 315/200	1.70	0.47	0.63	0.24	9.76	6.17E-09
T-piece 315/250	2.14	0.60	0.79	0.25	12.30	7.78E-09
T-piece 315/315	2.40	0.67	0.99	0.27	13.75	8.69E-09
T-piece 315/400	7.56	2.10	1.26	0.29	43.40	2.74E-08
T-piece 315/500	9.15	2.54	1.57	0.32	52.49	3.32E-08
T-piece 315/630	9.79	2.72	1.98	0.36	56.18	3.55E-08

(*continued on next page*)

Table C 6 (*continued*)

Product name	Steel plate [kg]	Zinc coating [m2]	Steel welding [m]	EPDM rubber [kg]	Energy [MJ]	Infrastructure [p]
T-piece 400/100	2.11	0.41	0.31	0.26	12.13	7.67E-09
T-piece 400/125	2.29	0.44	0.39	0.26	13.16	8.32E-09
T-piece 400/160	2.56	0.50	0.50	0.27	14.71	9.30E-09
T-piece 400/200	2.83	0.55	0.63	0.29	16.24	1.03E-08
T-piece 400/250	3.38	0.66	0.79	0.30	19.40	1.23E-08
T-piece 400/315	3.64	0.71	0.99	0.32	20.86	1.32E-08
T-piece 400/400	5.21	1.01	1.26	0.34	29.92	1.89E-08
T-piece 400/500	10.01	1.94	1.57	0.37	57.47	3.63E-08
T-piece 400/630	11.86	2.30	1.98	0.41	68.05	4.30E-08
T-piece 500/100	2.54	0.49	0.31	0.31	14.55	9.20E-09
T-piece 500/125	2.81	0.54	0.39	0.32	16.12	1.02E-08
T-piece 500/160	3.17	0.62	0.50	0.33	18.21	1.15E-08
T-piece 500/200	3.54	0.69	0.63	0.34	20.30	1.28E-08
T-piece 500/250	4.18	0.81	0.79	0.36	23.99	1.52E-08
T-piece 500/315	4.53	0.88	0.99	0.38	26.01	1.64E-08
T-piece 500/400	6.30	1.22	1.26	0.40	36.15	2.29E-08
T-piece 500/500	7.68	1.49	1.57	0.43	44.08	2.79E-08
T-piece 500/630	15.60	3.02	1.98	0.47	89.53	5.66E-08
T-piece 500/800	16.47	3.19	2.51	0.51	94.56	5.98E-08
T-piece 630/100	2.94	0.57	0.31	0.39	16.87	1.07E-08
T-piece 630/1000	21.07	4.08	3.14	0.64	120.91	7.65E-08
T-piece 630/125	3.31	0.64	0.39	0.40	18.99	1.20E-08
T-piece 630/160	3.77	0.73	0.50	0.41	21.63	1.37E-08
T-piece 630/200	4.23	0.82	0.63	0.42	24.25	1.53E-08
T-piece 630/250	5.15	1.00	0.79	0.43	29.58	1.87E-08
T-piece 630/315	5.51	1.07	0.99	0.45	31.60	2.00E-08
T-piece 630/400	7.27	1.41	1.26	0.47	41.74	2.64E-08
T-piece 630/500	8.94	1.73	1.57	0.50	51.30	3.24E-08
T-piece 630/630	10.78	2.09	1.98	0.54	61.88	3.91E-08
T-piece 630/710	19.29	3.74	2.23	0.56	110.73	7.00E-08
T-piece 630/800	19.25	3.73	2.51	0.59	110.51	6.99E-08
T-piece 710/1000	24.82	4.81	3.14	0.69	142.46	9.01E-08
T-piece 710/400	11.79	2.28	1.26	0.52	67.65	4.28E-08
T-piece 710/500	12.69	2.46	1.57	0.55	72.85	4.61E-08
T-piece 710/630	15.48	3.00	1.98	0.58	88.88	5.62E-08
T-piece 710/710	21.15	4.10	2.23	0.61	121.38	7.68E-08
T-piece 710/800	21.11	4.09	2.51	0.63	121.16	7.66E-08
T-piece 80/100	3.07	0.85	0.31	0.07	17.64	1.12E-08
T-piece 80/125	3.06	0.85	0.39	0.08	17.59	1.11E-08
T-piece 80/160	3.10	0.86	0.50	0.09	17.77	1.12E-08
T-piece 80/80	0.21	0.06	0.25	0.07	1.22	7.70E-10
T-piece 800/1000	28.57	5.54	3.14	0.74	163.98	1.04E-07
T-piece 800/400	12.69	2.46	1.26	0.57	72.82	4.61E-08
T-piece 800/500	13.59	2.63	1.57	0.60	78.02	4.93E-08
T-piece 800/630	16.39	3.18	1.98	0.64	94.05	5.95E-08
T-piece 800/710	21.10	4.09	2.23	0.66	121.10	7.66E-08
T-piece 800/800	22.01	4.27	2.51	0.68	126.33	7.99E-08

Appendix C7 – Circular reducers

Table C 7
Detailed inventories for circular reducers [per piece].

Product name	Steel plate [kg]	Zinc coating [m2]	EPDM rubber [kg]	Energy [MJ]	Infrastructure [p]
Reducer 125/160	0.19	0.05	0.08	1.06	6.72E-10
Reducer 160/100	0.19	0.05	0.07	1.10	6.93E-10
Reducer 200/160	0.24	0.07	0.10	1.37	8.68E-10
Reducer 250/160	0.40	0.11	0.12	2.31	1.46E-09
Reducer 250/200	0.39	0.11	0.13	2.25	1.42E-09
Reducer 250/315	0.55	0.15	0.16	3.14	1.99E-09
Reducer 250/400	1.06	0.21	0.19	6.07	3.84E-09
Reducer 315/160	0.57	0.16	0.14	3.28	2.07E-09
Reducer 315/200	0.56	0.16	0.15	3.21	2.03E-09
Reducer 400/200	1.17	0.23	0.17	6.70	4.24E-09
Reducer 400/315	1.09	0.20	0.20	6.26	3.96E-09

Appendix C8 – Circular fire dampers

Table C 8
Detailed inventories for circular fire dampers [per piece].

		Product name		
		Fire Damper 125	**Fire Damper 160**	
Steel plate	[kg]	0.84	0.95	
Zinc coating	[m2]	0.24	0.26	
Calcium silicate	[kg]	0.44	0.49	
Ceramic fireproofing	[kg]	0.04	0.04	
Rubber sealing	[kg]	0.01	0.01	
Thermal mechanical release mechanism*	[kg]	0.32	0.36	
Energy	[MJ]	5.35	6.01	
Infrastructure	[p]	3.38E-09	3.80E-09	
	Steel plate	**Stainless steel**	**Brass**	**PVC**
	[kg]	[kg]	[kg]	[kg]
*Thermal mechanical release mechanism [per kg]	0.35	0.54	0.02	0.08

Appendix C9 – Flow dampers

Table C 9
Detailed inventories for flow dampers [per piece].

		Product name						
		Flow damper 125	Flow damper 160	Flow damper 200	Flow damper 250	Flow damper 315	Flow damper 400	Flow damper 500
Steel plates	[kg]	2.83	3.15	3.73	4.21	5.01	7.81	9.48
Zinc coating	[m2]	0.79	0.88	1.04	1.17	1.14	1.78	2.17
Aluminium plate	[kg]	0.11	0.12	0.14	0.16	0.19	0.30	0.36
EPDM rubber	[kg]	0.05	0.09	0.11	0.14	0.18	0.23	0.29
ABS plastic	[kg]	0.02	0.02	0.02	0.03	0.03	0.05	0.06
Wiring cables	[kg]	0.10	0.11	0.13	0.14	0.17	0.26	0.32
Printed circuit board	[kg]	0.06	0.07	0.08	0.09	0.11	0.17	0.20
Energy	[MJ]	16.88	18.87	22.34	25.32	29.79	46.18	56.11
Infrastructure	[p]	1.07E-08	1.19E-08	1.41E-08	1.60E-08	1.88E-08	2.92E-08	3.55E-08

Appendix C10 – Circular silencer

Table C 10
Detailed inventories for circular silencers [per piece].

Product name	Steel plate	Zinc coating	Steel welding	EPDM rubber	Stone wool	Glass fibre	Energy	Infra-structure
Type: LKR	*[kg]*	*[m2]*	*[m]*	*[kg]*	*[kg]*	*[kg]*	*[MJ]*	*[p]*
Silencer 100–300 100	1.09	0.22	0.63	0.06	0.53	0.03	6.26	3.96E-09
Silencer 125–300 125	1.40	0.26	0.79	0.07	0.57	0.04	8.06	5.10E-09
Silencer 125–600 125	2.48	0.46	0.79	0.07	0.73	0.05	14.24	9.01E-09
Silencer 160–300 160	1.79	0.33	1.01	0.09	0.64	0.04	10.27	6.50E-09
Silencer 160–600 160	3.29	0.57	1.01	0.09	0.86	0.05	18.88	1.19E-08
Silencer 200–300 200	2.26	0.40	1.26	0.11	0.71	0.04	12.95	8.19E-09
Silencer 200–600 200	4.00	0.69	1.26	0.11	0.97	0.06	22.98	1.45E-08
Silencer 250–600 250	5.13	0.84	1.57	0.14	1.14	0.07	29.47	1.86E-08
Silencer 315–1200 315	11.92	1.89	1.98	0.18	2.14	0.13	68.40	4.33E-08
Silencer 315–600 315	7.11	1.04	1.98	0.18	1.43	0.09	40.79	2.58E-08
Silencer 400–600 400	10.00	1.31	2.51	0.23	1.86	0.12	57.40	3.63E-08
Silencer 400–900 400	12.20	1.83	2.51	0.23	2.19	0.14	70.05	4.43E-08

Appendix C11 – Rectangular silencers

Table C 11
Detailed inventories for rectangular silencers [per piece].

Product name	Steel plate	Zinc coating	Steel welding	EPDM rubber	Stone wool	Glass fibre	Energy	Infra-structure
(Type: RLYDD)	*[kg]*	*[m2]*	*[m]*	*[kg]*	*[kg]*	*[kg]*	*[MJ]*	*[p]*
Silencer 1000 1000x400	17.05	2.80	3.51	0.51	2.96	0.19	97.88	6.19E-08
Silencer 1000 1200x500	20.18	3.40	3.96	0.62	3.44	0.22	115.83	7.32E-08
Silencer 1000 1400x600	23.31	4.00	4.41	0.73	3.93	0.25	133.77	8.46E-08
Silencer 1000 1600x800	27.47	4.80	5.02	0.87	4.57	0.29	157.70	9.97E-08

Appendix C12 – Air diffusers

Table C 12
Detailed inventories for air diffuser units [per piece].

Product name	Air diffuser*	Zinc coating	Powder coating
	[kg]	*[m2]*	*[m2]*
Air diffuser 100	4.26	0.66	0.66
Air diffuser 125	4.34	0.69	0.69
Air diffuser 160	4.52	0.74	0.74
Air diffuser 200	8.50	1.36	1.36
Air diffuser 250	9.06	1.46	1.46
Air diffuser 315	11.97	1.96	1.96
Air diffuser 400	18.52	2.10	2.10

Input/sub-component	Unit	*Air diffuser composition	Sub-component composition
Diffuser plate	[kg]	0.040	Steel plate: 100 %
Diffuser frame	[kg]	0.190	Steel plate: 100 %
EPDM rubber	[kg]	0.006	
Commissioning box	[kg]	0.395	Steel plate:100 %
Commissioning box. damper and spigot details	[kg]	0.104	Steel plate: 100 %
Fixing frame	[kg]	0.250	Steel plate: 100 %
Glass fibre	[kg]	0.006	
Fastenings	[kg]	0.003	Steel plate/Aluminium plate: 50/50
PVC	[kg]	0.001	
Energy	[MJ]	5.740	
Infrastructure	[p]	3.63E-09	

Appendix C13 – Air handling units

Table C 13
Detailed inventories for air handling units [per piece].

Product type *(Min/Max flow rate)*	Air handling unit. generic[1]	Filter[2]	Electronics, generic	Energy	Infrastructure
	[kg]	*[in m3 capacity]*	*[p]*	*[MJ]*	*[p]*
288–1620	229	825	1	2841	8.31E-07
288–2340	229	925	1	2841	8.31E-07
288–2700	282	1200	1	2841	1.02E-06
720–3600	290	1400	1	2841	1.05E-06
720–3960	470	1625	1	2841	1.71E-06
720–5040	492	1975	1	2841	1.79E-06
720–5940	555	1800	1	2841	2.01E-06
1080–7560	591	3150	1	2841	2.15E-06
1080–9000	706	2900	1	2841	2.56E-06
1800–11520	746	4950	1	2841	2.71E-06
1800–14040	1013	3600	1	2841	3.68E-06
2700–14040	1063	6500	1	2841	3.86E-06
2160–18000	1356	5400	1	2841	4.92E-06
3600–23400	1436	8800	1	2841	5.21E-06
3600–27000	2135	7000	1	2841	7.75E-06
5400–34200	2297	13 500	1	2841	8.34E-06

(*continued on next page*)

Table C 13 (*continued*)

Product type *(Min/Max flow rate)*	Air handling unit. generic[1]	Filter[2]	Electronics, generic	Energy	Infrastructure
	[kg]	*[in m3 capacity]*	*[p]*	*[MJ]*	*[p]*
5400–39600	3720	10 000	1	2841	1.35E-05
9000–50400	3957	22 500	1	2841	1.44E-05

[1]Air handling unit. generic [per kg]		[2]Filter [per m3 capacity]		[3]Motor [per kg]	
All inputs in kg		*All inputs in kg*		*All inputs in kg*	
Steel plate	7.26E-01	Aluminium	3.23	Magnet	0.5
Aluminium plate	1.30E-04	Polyester resin	3.06	Aluminium	0.25
Zinc	8.30E-03	Glass fibre. generic	0.11	Metal working. generic	0.25
Titanium dioxide	3.60E-04			Copper	0.25
Polyethylene. HDPE	3.19E-03			Wire drawing. copper	0.25
Polyester resin	1.14E-03				
Formaldehyde	4.70E-07				
Phosphoric acid	2.00E-05				
Melamine polymer	2.00E-04				
Hexane 1.6 diisocyanate. homopolymer	7.50E-05				
Hexametyldiisocyanate	1.83E-07				
Acrylic polymer	1.70E-05				
Aluminium	1.23E-01				
Motor[3]	7.20E-02				
Polymer materials	1.75E-03				
Polyamide	2.60E-03				
PVC	1.62E-03				
Polypropene	4.70E-04				
Rock wool	2.56E-02				
Binder	1.20E-03				
Dust binding oil	2.00E-04				

Appendix C14 – Generic unit inventories

Table C 14
Detailed inventories for generic unit processes [per m2].

Product name	EPDM rubber	Glass wool	Aluminium plate	Steel plate	Zinc coating
	[kg]	*[kg]*	*[kg]*	*[kg]*	*[m2]*
Cellular rubber insulation mat 13 (t = 13 mm)	0.832	–	–	–	–
Insulation mat 25 (t = 25 mm)	–	0.70	0.097	–	–
Insulation mat 50 (t = 50 mm)	–	1.40	0.097	–	–
Galvanized steel plate 0.5 (t = 0.5 mm)	–	–	–	3.60	1
Galvanized steel plate 0.7 (t = 0.7 mm)	–	–	–	5.16	1
Galvanized steel plate 1.0 (t = 1. 0 mm)	–	–	–	7.50	1

Appendix D. Climate footprint per inventory

Table D1
GHG emission factors for ventilation library components.

Circular ducts			
Dimension	[kg CO_2-eq/m]	Dimension	[kg CO_2-eq/m]
63	2.61E+00	400	2.55E+01
80	3.19E+00	500	3.21E+01
100	4.06E+00	630	3.79E+01
125	4.92E+00	710	4.37E+01
160	6.37E+00	800	4.93E+01
200	9.27E+00	1000	6.98E+01
250	1.16E+01	1250	8.47E+01
315	1.49E+01		
Rectangular ducts			
Dimension	[kg CO_2-eq/m]	Dimension	[kg CO_2-eq/m]
1000x400	5.92E+01	2000x1000	1.38E+02
1200x500	7.05E+01	4000x1000	2.62E+02
1200x600	7.61E+01	600x400	3.95E+01

(*continued on next page*)

Table D1 (*continued*)

Circular ducts

Dimension	[kg CO_2-eq/m]	Dimension	[kg CO_2-eq/m]
1400x600	8.46E+01	800x200	4.23E+01
1600x800	1.15E+02	800x600	5.92E+01

Circular bends

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
15/100	4.15E-01	45/400	1.01E+01
15/125	5.63E-01	45/500	1.37E+01
15/160	7.71E-01	60/125	1.20E+00
15/200	1.24E+00	60/200	2.60E+00
15/250	1.77E+00	60/400	1.27E+01
15/315	2.96E+00	90/63	6.81E-01
15/400	5.29E+00	90/80	8.64E-01
15/500	7.07E+00	90/100	1.02E+00
30/100	6.51E-01	90/125	1.50E+00
30/125	9.15E-01	90/160	2.60E+00
30/160	1.24E+00	90/200	3.88E+00
30/200	1.98E+00	90/250	5.15E+00
30/250	2.97E+00	90/315	7.02E+00
30/315	3.60E+00	90/400	1.75E+01
30/400	7.11E+00	90/500	2.61E+01
30/500	1.04E+01	90/630	3.87E+01
45/125	1.13E+00	90/710	5.05E+01
45/160	1.60E+00	90/800	6.26E+01
45/200	2.38E+00	90/1000	1.24E+02
45/250	3.02E+00	90/1250	1.89E+02
45/315	5.38E+00		

Rectangular bends

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
45/800x200	3.68E+01	90/400x1000	5.37E+01
90/1000x2000	2.49E+02	90/500x1200	8.65E+01
90/1400x600	8.51E+01	90/600x1400	1.36E+02

Circular saddles

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
90-125/125	8.14E-01	90-315/250	2.11E+00
90-160/100	5.14E-01	90-315/315	2.93E+00
90-160/125	6.95E-01	90-400/100	1.42E+00
90-160/160	1.14E+00	90-400/125	1.41E+00
90-200/100	5.38E-01	90-400/160	1.40E+00
90-200/125	6.63E-01	90-400/200	1.40E+00
90-200/160	9.28E-01	90-400/250	2.02E+00
90-200/200	1.40E+00	90-400/315	2.48E+00
90-250/100	4.96E-01	90-400/400	5.53E+00
90-250/125	6.63E-01	90-500/200	1.40E+00
90-250/200	1.55E+00	90-500/250	2.02E+00
90-250/250	2.23E+00	90-500/315	2.48E+00
90-315/125	6.63E-01	90-500/400	4.94E+00
90-315/160	9.28E-01	90-630/400	4.94E+00
90-315/200	1.52E+00	90-630/500	5.62E+00

Circular T-pieces

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
80/80	9.10E-01	400/160	8.77E+00
80/100	1.01E+01	400/200	9.65E+00
80/125	1.01E+01	400/250	1.14E+01
80/160	1.03E+01	400/315	1.23E+01
100/80	1.09E+00	400/400	1.73E+01
100/100	1.33E+00	400/500	3.23E+01
100/125	9.98E+00	400/630	3.82E+01
100/160	9.99E+00	500/100	8.75E+00
100/200	1.04E+01	500/125	9.63E+00
100/250	1.19E+01	500/160	1.08E+01
125/80	1.50E+00	500/200	1.20E+01
125/100	1.53E+00	500/250	1.40E+01
125/125	1.89E+00	500/315	1.52E+01
125/160	1.19E+01	500/400	2.08E+01
125/200	1.25E+01	500/500	2.52E+01
125/250	1.25E+01	500/630	4.99E+01
125/315	1.40E+01	500/800	5.29E+01
160/80	1.79E+00	630/100	1.02E+01
160/100	1.85E+00	630/125	1.14E+01

(*continued on next page*)

Table D1 (*continued*)

Circular ducts

Dimension	[kg CO_2-eq/m]	Dimension	[kg CO_2-eq/m]
160/125	2.18E+00	630/160	1.28E+01
160/160	2.72E+00	630/200	1.43E+01
160/200	1.52E+01	630/250	1.73E+01
160/250	1.49E+01	630/315	1.84E+01
160/315	1.49E+01	630/400	2.40E+01
200/80	2.35E+00	630/500	2.93E+01
200/100	2.47E+00	630/630	3.52E+01
200/125	2.95E+00	630/710	6.17E+01
200/160	3.55E+00	630/800	6.17E+01
200/200	4.14E+00	630/1000	6.76E+01
200/250	1.49E+01	710/400	3.81E+01
200/315	1.49E+01	710/500	4.11E+01
200/400	1.64E+01	710/630	4.99E+01
250/80	2.82E+00	710/710	6.75E+01
250/100	2.94E+00	710/800	6.75E+01
250/125	3.54E+00	710/1000	7.93E+01
250/160	4.13E+00	800/400	4.11E+01
250/200	5.33E+00	800/500	4.40E+01
250/250	6.22E+00	800/630	5.28E+01
250/315	1.71E+01	800/710	6.75E+01
250/400	1.94E+01	800/800	7.05E+01
250/500	2.23E+01	800/1000	9.11E+01
315/100	3.82E+00	1000/500	5.53E+01
315/125	4.42E+00	1000/630	6.99E+01
315/160	5.02E+00	1000/710	6.99E+01
315/200	6.21E+00	1000/800	7.28E+01
315/250	7.70E+00	1000/1000	9.03E+01
315/315	8.60E+00	1000/1250	1.19E+02
315/400	2.53E+01	1250/630	8.44E+01
315/500	3.05E+01	1250/710	9.61E+01
315/630	3.28E+01	1250/800	9.61E+01
400/100	7.30E+00	1250/1000	1.17E+02
400/125	7.88E+00	1250/1250	1.34E+02

Circular reducers

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
125/160	8.11E-01	250/400	3.77E+00
160/100	8.12E-01	315/160	2.20E+00
200/160	1.04E+00	315/200	2.19E+00
250/160	1.61E+00	400/200	4.07E+00
250/200	1.60E+00	400/315	3.91E+00
250/315	2.19E+00		

Circular fire dampers

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
125	4.67E+00	160	5.25E+00

Flow dampers

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
125	1.58E+01	315	2.79E+01
160	1.78E+01	400	4.32E+01
200	2.10E+01	500	5.25E+01
250	2.38E+01		

Circular silencers

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
100-300/100	4.49E+00	200-600/200	1.43E+01
125-300/125	5.58E+00	250-600/250	1.82E+01
125-600/125	9.15E+00	315-1200/315	4.06E+01
160-300/160	6.95E+00	315-600/315	2.47E+01
160-600/160	1.19E+01	400-600/400	3.41E+01
200-300/200	8.59E+00	400-900/400	4.16E+01

Rectangular silencers

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
1000-1000x400	5.88E+01	1000-1400x600	8.04E+01
1000-1200x500	6.96E+01	1000-1600x800	9.49E+01

Air diffusers

Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
100	1.23E+01	250	2.65E+01

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Table D1 (*continued*)

Circular ducts			
Dimension	[kg CO_2-eq/m]	Dimension	[kg CO_2-eq/m]
125	1.27E+01	315	3.52E+01
160	1.33E+01	400	5.01E+01
200	2.48E+01		
Air handling units			
Dimension	[kg CO_2-eq/piece]	Dimension	[kg CO_2-eq/piece]
288–1620	1.19E+03	1800–11520	2.76E+03
288–2340	1.19E+03	1800–14040	3.54E+03
288–2700	1.35E+03	2700-14040**	3.71E+03
720–3600	1.38E+03	2160–18000	4.57E+03
720–3960	1.91E+03	3600–23400	4.83E+03
720–5040	1.98E+03	3600–27000	6.90E+03
720–5940	2.17E+03	5400–34200	7.42E+03
1080–7560	2.28E+03	5400–39600	1.16E+04
1080–9000	2.62E+03	9000–50400	1.24E+04

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