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3d Thermal Climate Monitoring in Factory Buildings

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Abstract

Guaranteeing defined conditions, such as the temperature levels inside the factory's building shell, is often important to produce high-quality products. Heating, ventilation and air conditioning (HVAC) equipment, as part of the technical building services, is energy intensive and accounts for a major share of the factory's energy demand. For an effective utilisation, the HVAC system control has to compensate time dependent variations of building-internal loads and demands as well as changing weather conditions that can cause local temperature differences. In this paper, a computational fluid dynamic model, coupled with a wireless sensor network, is presented that allows the estimation of the temperature and air flows at every position in the factory building, in real-time. This can then be used to improve control strategies of HVAC systems towards a more energy efficient and demand oriented climate conditioning within factory building shells.

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1. Introduction

Factories are places where manufacturing and value creation take place. Value creation processes demand for infra-structural (energy and resource supply, emission and waste disposal as well as product sales) and ultra-structural (steering, operating and maintaining as well as manufacturing execution) elements and actions [1]. This socio-technological system serves humans by providing the desired boundary conditions and environment to produce goods, which themselves provide an additional value for society [2]. Manufacturing equipment or transformation processes demand human workforce, energy supply, operational resources, information supply as well as supply, transport and disposal of fixtures, raw materials, goods and waste. Some of these supplies for example cannot be immediately provided, but have to be converted or generated and distributed to other places of the factory. These peripheral systems are subsumed as the technical building services (TBS). After process heat generation, with approximately 64,7% of the total energy throughput, the most energy intense technical building services consists of indirect energy demands such as space heating, ventilation and air conditioning (HVAC) and lighting, as depicted in Figure 1.

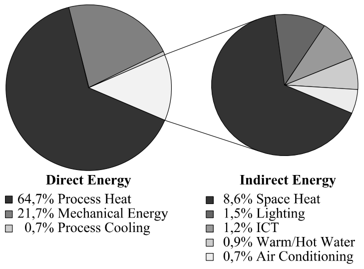

Fig. 1. The proportion of indirect energy demand to the total effective energy demands of the German industry from 2008-2012, based to [3].

The German industry demanded in average between 2008 and 2012 about 55.4 TWh/a of final energy for space heating and 4.9 TWh/a for space cooling. This corresponds to 9.4% of the total final energy demand, utilised just for purposes to

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provide proper environmental conditions to workforce and technical equipment in factories [3]. The sum of indirect energy makes up 12.9% of the total effective energy utilised in industry. Indirect energy is demanded in order to provide environmental conditions as room temperature, humidity, air purity levels and compensation of heat emission, as well as proper illumination of workspace through lighting and provision of communication infrastructure through ICT. The degree of the energetic linkage between the value adding processes and the peripheral processes can be defined as the energetic adjacency and clustered in four peripheral orders [4]. Space heating and air conditioning are commonly utilised as fourth order peripheral equipment – central installations supplying large areas within the factory building with tempered and conditioned air without direct feedback of local demands. Moreover, the heat and conditioned air is provided according to the principle of indiscriminate all-round distribution with often only singular sensor feedback from a local sensor. This results into often ineffective distribution of space heat and conditioned air and only vague feedback on a true fulfilment of target values [5]. Partially unknown or fluctuating external and internal loads lead to not well controlled environmental conditions. To counter this informational gap, this paper presents an approach that provides real-time information about the actual temperature conditions and air flows within the total factory building. Based on this informational added value, heat and conditioned air can be inserted and controlled de-centrally. The objective is to realise de-central supply of locally conditioned air in harmony with the local requirements and fluctuating internal loads.

2. Current Approaches on indoor climate sensing within buildings

2.1. Thermal climate conditions within factory buildings

The indoor climate is influenced by thermal emissions resulting from internal loads from machines and equipment and external loads from direct radiation through translucid surfaces (e.g. windows) as well as from the outside temperature on the outside walls and into internal loads from the heating and ventilation system. Internal loads from machines and equipment result from the utilisation of effective energy for direct value creation or for supportive services. Effective energy types utilised in such machines and equipment is process electricity, process heat, mechanical energy as well as light, which are all eventually converted into losses (anergy) and wasted energy (exergy). Waste energy has still a thermodynamic potential to perform work and is theoretically recoverable. In case of highly fluctuating and statistically appearing exergy emissions, an efficient recovery is not possible and the energy will result into effecting the local heat distribution.

External emissions have seasonal dependencies, with fluctuation over the daytime. The transmission impact is depended upon the relative temperature difference of outside and inside wall surfaces and the thermal conductivity of the wall structure (λ is a matter constant).

The internal heat flow load from the heating and ventilation is induced by heat exchangers (through radiation and convection). The standardised heat flows are calculated considering the following parameters:

- Inner and outer standardized temperature
- Constructional and technical parameters (e.g. envelope surface A and λ)
- Volume flow, specific heat capacity and density of air from outside

It is to be remarked, that European standards for calculating the standard heat flow do not take inner loads and solar thermal radiation into consideration [6][7], which is actually the essential functional element for the design of low energy buildings.

Especially in production environments, the minimum and maximum temperature conditions at workspaces are strictly defined by technical regulations for working places (e.g. in Germany by the ASR A3.5 for room temperatures). Therefore, the conditional requirements are not the same all over the factory building, but moreover with local requirements dependent on the type and the burden of manual labour as well as on the technical requirements for production and quality assurance processes [8].

2.2. Measurement approaches

In order to provide the demanded heat input, the ventilation shafts distribute heat flows directly from the central heating or cooling entity to the outlet within the factory building. Alternatively local heaters are placed in the building supplied by hot water cycles (or in some cases directly by gas or electricity). These ventilation outlets and heaters are regulated by singular thermostats or by single temperature sensors. The placement of thermostats is usually near the device (as it regulates the flow rate of the hot water cycle). Temperature sensors are placed at representative locations of the most sensitive area to be supplied. In fact, this can lead to two problems:

- Heat input flows are controlled by singular measurements regarding only local extracts of the actual area or space to be controlled, leading to locally over or under heated areas.
- A once representative position of singular temperature sensors can change to sub-optimal control results as soon as layouts are changes, production lines are moved or altered or constructional changes are applied.

To measure temperature, optical surface thermometers for inner walls and object surfaces as well as aerial thermometers for temperature in space are available. These sensors only measure the temperature on a specific point. Often, one is interested to know the temperature on places where measuring is impractical or even infeasible, like at head-height at a work station. Linear interpolation of nearby measurements for these locations is unlikely to produce an accurate estimate, as heat is predominantly transported by airflows, both naturally occurring and enforced by ventilation systems. For an accurate interpolation of temperature at unmeasured locations, information of the current air flow has to be properly incorporated.

The actual air flows induced through local temperature and pressure differences or induced by active ventilation can hardly be measured throughout an entire factory building. Sensing techniques capable of measuring the speed and direction of low speed air flows are only a few, e.g. ultrasonic anemometry, three-dimensional (3d) hot wire anemometry. These techniques only measure flow on a single point, so capturing global air patterns would require many of these sensors, which would make such an approach expensive and bulky. Optical techniques like particle image velocimetry are likewise expensive and require tracer particles to be inserted into the factory building.

A linear interpolation between measured points only applies for a dense field of taken temperature samples to produce a fair image of the energy distribution, but is not capable of assessing the actual air exchange (flows) within the building, which would be necessary to utilise control of heat flows adapted to the specific local requirements within the factory building. Alternatively, simulation approaches offer ways to analytically derive 3d maps of the temperature and air flow, yet with restrictions.

2.3. Simulation approaches

Instead of measuring, one could opt for calculating the governing indoor climate instead by using a suitable model.
The spatial and temporal dynamics of indoor climate are governed by 3d fluid dynamics. More specifically, it is known that the indoor airflow and temperature distributions adhere to some basic laws of physics, i.e. conservation of energy, conservation of momentum and conservation of mass (laws of conservation).

These laws can be written as a coupled set of nonlinear partial differential equations, known as the Navier Stokes equations. There is no general analytical solution to these equations [9], so they have to be solved numerically. This is done by so called Computational Fluid Dynamics (CFD).

The most common way of numerically solving the Navier-Stokes equations is by means of finite volume methods [10]. In this approach, the domain under study (factory building) is spatially and temporally discretised. This means that it is virtually divided into small interconnected volumes, each with a temperature, pressure and 3d flow velocity. For each of the volumes, all conservation laws must be met. By means of this discretisation and some additional assumptions (see [10] for details), the Navier-Stokes equations can be written as systems of coupled linear equations:

$$A_u(u^k, v^k, w^k, P^k)u^k = b_T(u^{k-1}, q_v^{k-1}, e_v^{k-1}) \tag{1a}$$
$$A_v(u^k, v^k, w^k, P^k)v^k = b_v(v^{k-1}, q_v^{k-1}, e_v^{k-1}) \tag{1b}$$
$$A_w(u^k, v^k, w^k, P^k, T^k)w^k = b_w(w^{k-1}, q_w^{k-1}, e_w^{k-1}) \tag{1c}$$
$$A_T(u^k, v^k, w^k)T^k = b_T(T^{k-1}, q_T^{k-1}, e_T^{k-1}) \tag{1d}$$
$$A_C(u^k, v^k, w^k)\vec{v}^k = 0 \tag{1e}$$

These sets of equations define the discretised, three-dimensional climate at time instance k, given by temperature vector T, pressure vector P and flow velocity vector $\vec{v} = (u \quad v \quad w)$, with u, v, w the x-, y- and z-components of the velocity respectively. Note that these climate vectors are each N long, with N the number of cells into which the factory building was discretised. The first three equations represent the momentum equations in x-, y- and z-directions. The fourth equation represents the energy equation and the last the continuity equation. The various matrices A are square and sparse, with 7 non-zero elements per row (assuming first-order upwind discretisation on a rectangular mesh). The right hand side vectors b are the known boundary conditions: the climate at the previous time instance, the source terms q (e.g. fans in the momentum equations and heaters/AC's in the energy equation) and the exogenous influence (e.g. the outside temperature). Note that the momentum equations are non-linear and all equations are mutually coupled. It therefore requires an iterative numerical procedure to solve the full set of equations.

The SIMPLE algorithm [10] is a well-known method to solve the equations and is show in algorithm 1. It is an iterative algorithm that sequentially builds and solves the equations, based on the most recent iterants for T, u, v, w and P. It does so for the momentum equations and the energy equation. The continuity equation is not explicitly solved. Instead, a correction on the pressure field is calculated, which will steer the individual flows $\hat{u}, \hat{v}, \widehat{w}$ that jointly do not meet continuity, toward a set of flows u, v, w that do. After solving an equation, the iterant is updated with the new solution with a relaxation factor $0 < \alpha < 1$ that is applied for numerical stability. After all equations have been solved and the iterants T, u, v, w, P have been updated, a convergence check tests if the iterants jointly fulfil the conservation laws. Only if this is true, the solution has been found. In case not, another iteration run is performed.

```
Given        $u^{k-1}, v^{k-1}, w^{k-1}, T^{k-1}, P^{k-1},$
             $q_u^{k-1}, q_v^{k-1}, q_w^{k-1}, q_T^{k-1}, e_u^{k-1}, e_v^{k-1}, e_w^{k-1}, e_T^{k-1}, \alpha, \alpha_P$
While not converged
   Setup & solve        $A_u(u, v, w, P)\hat{u}^* = b_u(u^{k-1}, q_u^{k-1}, e_u^{k-1})$
   Update $\hat{u}$             $\hat{u} := (1-\alpha)\hat{u} + \alpha\hat{u}^*$
   Setup & solve        $A_v(u, v, w, P)\hat{v}^* = b_v(v^{k-1}, q_v^{k-1}, e_v^{k-1})$
   Update $\hat{v}$             $\hat{v} := (1-\alpha)\hat{v} + \alpha\hat{v}^*$
   Setup & solve        $A_w(T, u, v, w, P)\widehat{w}^* = b_w(w^{k-1}, q_w^{k-1}, e_w^{k-1})$
   Update $\widehat{w}$             $\widehat{w} := (1-\alpha)\widehat{w} + \alpha\widehat{w}^*$
   Setup & solve        $A_P(\hat{u}, \hat{v}, \widehat{w})P' = b_P(\hat{u}, \hat{v}, \widehat{w})$
   Update $P$             $P := P + \alpha_P P'$
   Correct              $(u, v, w) = f\big((\hat{u}, \hat{v}, \widehat{w}), P'\big)$
   Setup & solve        $A_T(u, v, w)T^* = b_T\big(T^{k-1}, q_T^{k-1}, e_T^{k-1}\big)$
   Update $T$             $T := (1-\alpha)T + \alpha T^*$
   Check for convergence
end
$(u^k \; v^k \; w^k \; T^k \; P^k) = (u \; v \; w \; T \; P)$
```

Algorithm 1: The SIMPLE method for solving the Navier-Stokes equations

To accurately model three-dimensional fluid dynamics, a high resolution spatial discretisation is generally necessary. This means that the number of cells N can be very large, even in the order of millions. For both numerical stability and accuracy, the temporal discretisation then has to be relatively small, too. Additionally, other equations often need to be added to account for e.g. turbulent effects. As a result, CFD is a computationally intensive procedure that is difficult to parallelise. Even with today's developments in (cloud) computing power, it is unlikely that an accurate model of a large open space, (like a factory building), will run in real-time in the near future.

Even if highly accurate CFD calculations can be run, it is practically impossible to flawlessly recreate the indoor thermal climate as there will always be things that are not (fully) captured in the model, e.g. unknown material parameters, drafts through unintentional building shell leaks, unexpected thermal emissions by a malfunctioning machine, etc.

2.4. Data assimilation

Neither measuring nor modelling are practically able to monitor the 3d thermal climate in real-time. However, the combination of the two methods is promising, as a model is able to capture complicated air flows and measurements can be used to compensate for the gap between model and reality.

Combining models and measurements is a field known as data assimilation. Perhaps the most famous algorithm that fuses a model with measurements is the Kalman filter [11]. This technique is still widely used today as it efficiently enables the fusion of a linear model with noisy sensor data in a least squares optimal way.

Over the years, many variants of the Kalman filter and other data assimilation techniques have appeared that are equipped to deal with non-linear and discontinuous problems [12]. The Ensemble Kalman filter (EnKf) [13] is often used in combination with fluid dynamic problems, as it treats the CFD model as a black box and can deal with the non-linearity involved.

The EnKf performs numerous simulations with the CFD model with slightly different starting states. It thereby estimates a probability density function (pdf) of the current indoor climate by comparing the various model results to the actual acquired measurements.

The EnKf is a powerful modular data assimilation tool, but requires numerous model evaluations to estimate the indoor climate at a certain time instance. With the computational complexity that is involved in the CFD model, this approach is unfit for real-time 3d indoor climate monitoring.

3. Real-time 3d indoor climate monitoring

3.1. Wireless temperature sensing

For the temperature measurement within the factory building a hard-wired sensor network has no practical feasibility, as distances for sensor signals are too far and the effort for cable installations are too high. Therefore, a wireless sensor network was the matter of choice. The following requirements for the research prototype nodes were stated:

- Maximum signal distance from node to node of 30 meters
- Fairly high signal strength to withstand most EMC problems induced by motors and drives found in the application area
- Self programmable sensor nodes to implement own routines
- Standard battery life time in operation of two years or longer
- Established communication standard for coexistence with existing communication standards in place.

The objective of the selection of suitable nodes was not to utilise the most energy saving network, but moreover, a stable basis for testing the general applicability of the sensor network within a factory environment, which has not been done before.

Hence, a node platform with the ZigBee communication standard was chosen, equipped with an integrated SMD temperature sensor and interface for additional sensor extensions. Supplied by two AA standard batteries, with no external antenna but the master node), 38 sensor nodes were placed on strategically selected locations.

It is targeted to find locations to realise a possible wide coverage, while receiving a highly granular distribution, with lowest possible overlap and still considering technical restrictions. Such restrictions are the protection from possible damage by transport systems, overhead cranes and other moved masses as well as liquids and dust. Figure 2 shows the sensor node placement resolved in the virtual factory building model by coloured and numbered dots

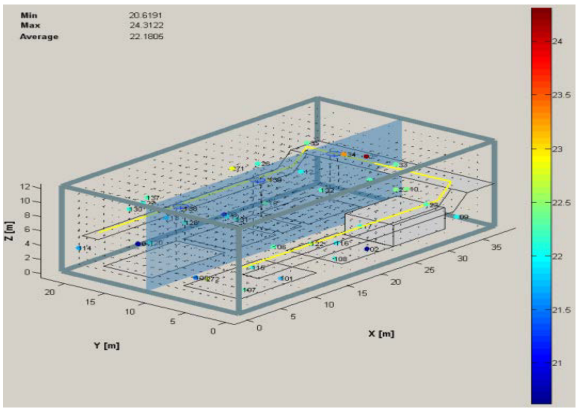

Fig. 2. Sensor placement resolved in the virtual 3d factory building model, indicating the actual temperature by colour code and their unique ID

The sensor placement strategy resulted in to nine sensors on ceiling height (10 m) in an evenly distributed grid to ensure to capture local temperature differences inducing upwind above heat emitting machines or solar radiation heated surfaces. Three sensors were placed directly in the output downstream of the circulation fans to capture the actual performance of the heat exchangers (the actual volume flow is known from temporary anemometers readings in correlation with settings of the ventilation control). On medium height (6 m), seven sensors were placed in one meter distance from walls and on top of the climate chamber (cube within building model). Major restrictions for sensor placement are overhead cranes, which prevents the optimal grid-structured placement. 15 sensor nodes were place on working height and on one meter above relevant heat emitting machines, as well as close to doors, to capture temperature drops based on opening doors or wall openings to neighbouring building structures. Seven further nodes were placed on floor level to capture the blow down temperature of the ceiling fans, under the constraints of the hall way and machine layout that represent obstacles for an optimal radial distribution of the downwind.

3.2. Virtual modelling of the factory and energy flows

The implemented proprietary CFD simulation software was written in Matlab with a solver along the lines of Algorithm 1. This was done with the following goals in mind:

1. To create a model that provides qualitatively correct information in real-time
2. To have full understanding of the solver and full access to it to make alterations.

The first point means that the model should be able to predict the main air flow pattern in the factory building; the global direction and whereabouts of the most significant air movements, whereat, quantitative errors are allowed. The speed-up is achieved by using coarse discretisation, by omitting certain parts of the modelled geometry and physics that are relatively insignificant and by adding empirical relations for wall-air heat transfer, which otherwise would need high resolution discretisation. By tuning the resolution, the model is made to perform just faster than real-time.

The second point is needed for the development and implementation of an efficient data assimilation algorithm as described in the next section.

3.3. Real-time data assimilation

The main idea of the data assimilation algorithm is to avoid the need for multiple model evaluations, as these are computationally expensive and difficult to complete in real-time. Instead, the CFD solver is altered to perform the data assimilation during the normal simulation.

Looking at Algorithm 1, it can be observed that a large, non-linear problem is solved by means of many consecutive linearisations of smaller linear sub-problems. From this, the idea arose to, instead of running an Ensemble Kalman filter on the large original problem, to embed a regular linear Kalman filter in the solver.

In order to use a regular Kalman filter, a state space model of the relevant dynamics is needed [11][12], which is of slightly different form than Equations 1a-e. This conversion can be done in a fairly straightforward manner for those skilled in the art. Moreover, as the proposed monitoring system only uses temperature sensors, only the energy equation in Equation 1d, which is in fact already linear, needs to be converted to state space form. With the energy equation rewritten to its state space form, the Kalman filter can be inserted into the CFD solver of Algorithm 1. Instead of the step that sets up and solves the energy equation, the energy equation is converted into its state space form and a new temperature field is obtained by applying a Kalman filter to that state space model and the available temperature measurements. The resulting estimated temperature field is used to update the iterant for T under relaxation, as before.

Recalculating the state covariance, an important part of the Kalman filtering procedure [11] can be done after the solver has converged. With this procedure, a data assimilation method is developed that needs only one (adapted) model evaluation. Due to the replacement of solving a system of equalities by a Kalman filter, the evaluation time of this new method is longer than a regular model evaluation, but since just one is needed, it was found to still meet the real-time requirements in our case study.

4. Case study application in the lab factory environment

4.1. Description of the lab factory environment

Die Lernfabrik is a research platform of the Institute of Machine Tools and Production Technology used as an application environment for research projects. The research platform is a suitable environment for prototypes, as it provides a real factory building with diverse production machines, machine-near peripheries as well as central peripheries providing technical building services, interacting in the same way as in industrial environments, but without the technical and organisational restrictions of a commercial factory site. The size and equipment of the application environment can be compared to an SME from the metal processing sector. Heat emitting entities (internal loads) range from conventional metal cutting machines to CNC-machining centres, but also climate chambers with specific demands on constant humidity and temperature levels for precision measurement, but also robot systems for handling purposes, an injection moulding machine with drying and tempering equipment as well as peripheral equipment for coolant treatment.

5. Discussion of Results

Figure 3 shows a screenshot of the developed monitoring tool frontend. In the top left image, the 3d factory layout is shown. The other three images show the temperature and flow distributions on various cross sections in the factory building. The cross section on the bottom left corresponds with the blue plane in the 3d image. The top right and bottom right correspond to the green plane (horizontal) and the red plane respectively. With the tool, other cross sections can be selected for visualisation, thereby providing insight in the three dimensional climate distribution in the factory building.

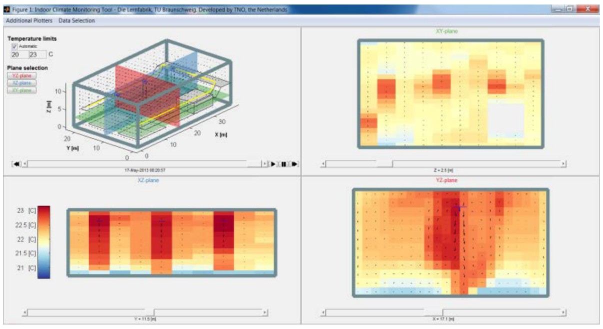

Fig. 3. Temperature maps and air flows in three planes in within the modelled factory building of the lab factory.

We found that the tool was able to estimate the indoor climate in real-time, with a time step of one minute, running on a consumer notebook with an Intel Core I7-3720QM at 2.6 GHz with 8 GB memory, using only one core.

Figures 4a and 4b show the red cross-section in more detail. In Figure 5a, only the three temperature measurements that are available in that plane are depicted.

Fig. 4a. Three temperature measurements on cross-section of factory building (22 meters wide, 12 meters high). The central ceiling fan is pointing down.

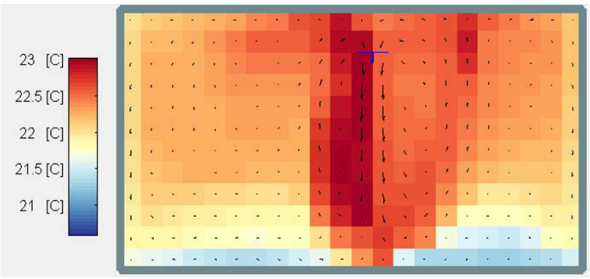

Fig. 4b. Estimated flow and temperature distributions on the cross section. It can be seen that the fan was active, by the circulation effect.

The blue line indicates a fan that is mounted near the ceiling and capable of blowing (optionally heated) air down towards the floor. The standard operation is circulation of internal air; optionally air from the outside can be inserted. Figure 5b shows the result of the fusion of the measurement with the coarse 3d indoor climate model. This information is processed by the thermal climate model, calculating a temperature field driven by forced advection, corrected with the available measurements.

6. Critical Review and Outlook

The presented methodology gives detailed insight into the thermal energy flows of factory buildings. However, increasing the level of transparency is just a first step towards improvement. Real energy savings can be achieved – based on the 3d monitoring - by applying 3d indoor climate control and (when updating the design of the system) better dimensioning of e.g. HVAC components. Also simpler measures might be derived e.g. when identifying negative effects of door or window operation or alternative zoning/layout of the factory.

The 3d indoor climate monitoring system was set up as a prototype at this point with known limitations. For instance, the proprietary CFD model does not contain turbulence equations, which are relevant on this scale. An improvement of the monitoring system itself could be achieved by improving the model or adding more sensors (or both) – however, this has to be balanced with respect to potential energy savings that might be achieved. The Matlab implemented model is not as good or as fast as commercially (or open source) available software. When coupling with other software, the model quality can be greatly enhanced while remaining real-time.

The calculations were qualitatively verified, but have not yet been quantitatively validated yet. Such validation requires additional measuring points at undesirable locations, that should be there long enough for various flow fields to occur. This proved infeasible in the current situation, but will be part of future work.

Besides that, future work will focus on extending the methodology to other conditions like emissions (e.g. CO_2, particles, solvents) as well as relative humidity, which broadens the fields of application and enfolds even more energy saving opportunities (e.g. air filtration systems).

7. Acknowledgements

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