WHITEPAPER

5 forces that drive energy efficiency in pre-engineered modular cleanroom design

Introduction

5 interrelated forces that drive energy efficiency in modular and pre-engineered cleanroom design

Cleanrooms consume large amounts of energy compared with the energy consumption in non-classified rooms, like commercial buildings. Literature survey (A. Fedotov) and experience in the field show that cleanrooms use up to 25,3 times more energy (1,25kW/m² vs. 0,06kW/m²) than other rooms that are not being used as cleanroom application.

The energy consumption of HVAC usually amounts to 50-75% of the entire electric consumption in a cleanroom (N. Lenegan), due to the high airflow rates needed to realize a particular cleanliness class in your cleanroom.

In our vision, the energy consumption of a cleanroom directly relates to the design of that cleanroom. In the very near future, different determining factors of energy consumption must be taken into account for achieving an optimized cleanroom design.

The energy footprint for example: high energy consumption leads to a high CO_2 footprint, but also the economic factor, telling us the importance of manufacturing cost-efficiently, has to be considered. Furthermore, we are aware of markets where cleanroom technology is not even available due to high Life Cycle Costs.

Note: We rather talk about Life Cycle Cost instead of Total Cost of Ownership due to the fact that, at design phase, we already bear in mind the demolition of the cleanroom and the materials that will be used. Nevertheless, the TCO will at all times be an important component of LCC.

By understanding those determining factors that lead to high energy usage, we examined and brought together 5 aspects that help you drive reduced energy consumption and lower the energy footprint in modular pre-engineered cleanroom design.

In this whitepaper, you will learn 5 important forces that are inherent to the design of energy efficient cleanrooms:

1. Air Tightness (AT)
2. Demand Controlled Filtration (DCF)
3. Air Change Effectiveness (ACE)
4. Computational Fluid Dynamics (CFD)
5. Continuous Particle Monitoring

Force 1

Air Tightness (AT)

What we can state is that the air in a cleanroom is quite costly, if not one of the most high-priced types of air. Back in the days, very little attention used to be paid to the air tightness of a cleanroom, whereas these days, the air tightness is considered more profoundly while designing a cleanroom in order to minimize air leakage and optimize cleanroom efficiency.

VCCN's Guideline 10 (VCCN Richtlijn 10) is a well-described guideline when focusing on the air tightness of a cleanroom from a design approach. Before the development of Guideline 10, air tightness was an indefinable variable when designing a cleanroom. In practice, one could hardly speak of a consistent approach. The passive house standard has been applied several times, but there was little relevance for this building standard to cleanroom applications.

This guideline brings uniformity in the design of air tightness of cleanrooms and it describes the classification of the cleanroom shell's air permeability (the walls, the ceiling and the floor). The guideline can therefore be put forward as a point of discussion at design phase to be part of the URS.

We have been using the terms 'air tightness' and 'air permeability' when pointing out this first force that drives reduced energy consumption. Both terms are often used mixed up as synonyms, rather are they opposites. Whereas the air tightness in VCCN's Guideline 10 refers to the degree of restriction of uncontrolled airflow through the cleanroom shell, the air permeability refers to the rate of airflow through the building shell when there is a different air pressure on either surface of the shell.

C = the air permeability coefficient: $\dfrac{\text{Liter}}{(s \,.\, Pa^{1/n})}$

Classification by leakage class

Table 1 below provides an overview of the leakage classification, ranging from class L00 up to class L5. Now, what does this mean? Guideline 10 defines several leakage classes, classified by the maximum amount of air leakage per m² building shell surface. So, each leakage class defines a maximum leak factor.

Applying this leak factor in following formula results in a maximum permissible amount of uncontrolled airflow per m² at various pressure differences:

Qvl = f . ΔP0.65

Qvl = leakage per m²: l/(s . m²)

f = leak factor (nondimensional quantity)

ΔP = pressure difference [Pa]

Leakage classification	Leak factor [f]	Maximum thresholds
L00	0,243000	$Qv_l = 0{,}243000\ \Delta P_s^{0{,}65}$
L0	0,081000	$Qv_l = 0{,}\ 081000\ \Delta P_s^{0{,}65}$
L1	0,027000	$Qv_l = 0{,}\ 027000\ \Delta P_s^{0{,}65}$
L2	0,009000	$Qv_l = 0{,}\ 009000\ \Delta P_s^{0{,}65}$
L3	0,003000	$Qv_l = 0{,}\ 003000\ \Delta P_s^{0{,}65}$
L4	0,001000	$Qv_l = 0{,}\ 001000\ \Delta P_s^{0{,}65}$
L5	0,000333	$Qv_l = 0{,}\ 000333\ \Delta P_s^{0{,}65}$

Table 1: Overview of leakage classes, classified by the maximum amount of uncontrolled airflow per m² building shell surface (source: VCCN)

A small comparison shows us that this way of classifying is of the utmost importance within cleanroom design. Let's say that a leakage class of at least L3 should be defined in cleanroom design. Applying the formula above for leakage class L3 means that we arrive at an air leakage of 0,0381 l/sm² with a pressure difference of 50Pa. Leakage class L1 however, also with 50Pa pressure difference, arrives at an air leakage of 0,3433 l /s m², which is nearly ten times more.

As a conclusion of this first force, we can state that there is a strong relationship between the volume of the cleanroom and the potentially feasible leak-tightness factor. The smaller the room, the more difficult it is to obtain a high leak-tightness factor. Not necessarily from an architectural point of view, rather from the limitations of a regulation technology point of view. Nevertheless, new regulation technology algorithms beyond VAV (Variable Air Volume) regulation allow designers to engineer the highest leak-tightness (smallest leak factor) even with very small cleanroom dimensions, e.g. 50m³.

Surprisingly, we can observe every day in cleanroom environments that leakages are created deliberately and specifically for cleanrooms with smaller dimensions to allow the pressure regulation in the cleanroom as a result of a failing up-to-date control system.

Pre-engineering cleanrooms from a modular point of view leads to fewer air leakages since design engineers have 'pre-thought' everything in advance, in contrast to having to improvise on the construction site, resulting in a lot of trial and error.

Force 2
Demand Controlled Filtration

In our vision, from a pre-engineered and modular cleanroom point of view, dynamically controlled ventilation flow rates have a tremendous impact on energy consumption in cleanrooms.

In practice, we noticed that for ISO7 cleanrooms a rate of 25 air changes is frequently used. Now, supposing that we have a particle counting system, we would see that it is not always necessary to have this rate of 25 air changes. For example, when there is little contamination in the room (low demand for filtration) and with a continuous particle monitoring system, an air change rate of 10 is tolerable.

Nevertheless, a higher air change rate would undoubtedly be required when there is much more contamination in the room, e.g. due to process environments or cleanroom users who don't keep in mind their cleanroom dress code. And this degree of filtration controllability in various circumstances is exactly what DCF is about.

By looking at a PAL, we see that the pre-defined recovery time is an important value in cleanroom design. If we apply DCF when entering the PAL, the ventilation flow can temporarily be increased in order to drastically reduce the recovery time, saving time for the cleanroom user.

The formula used for Demand Controlled Filtration is following:

$$N = -2{,}3 \cdot 1/t \cdot \log_{10}(C/C1)$$

N = decay rate of particles = air change rate at the measuring location
t = time of decay
C = airborne concentration of particles after a given decay time
C1 = initial airborne concentration of particles

The formula above learns that the recovery time depends on the air change rate. The time value often used in GMP environments is 15 minutes.

C = 3520
C1 = 352.000
N = - 2,3 . 1/15 . log10 (3520/352.000) = 0,306 AC/min. = 18,36 AC/hour

This shows that if we reduce the time of decay to 5 minutes, an air change rate of 55 will be needed. The conclusion here is quite obvious that a dynamic regulation of the air change rate has a positive effect on the recovery time, and not only by entering a PAL, but to all zones inside a cleanroom area. The modular interpretation of cleanroom engineering allows us to configure the necessary building blocks with dynamically controlled ventilation flow rates.

Force 3

Air Change Effectiveness

An important, often underestimated value in traditional cleanroom design is the Air Change Effectiveness, the third force that we will clarify in this whitepaper. ACE indexes have been measured in a variety of cleanrooms and reported extensively, for example by Whyte et al (2014).

An essential design parameter is the effect of an air diffuser on the airflow. When designing a non-unidirectional airflow (non-UDAF) cleanroom, designers have to decide how much filtered air should be supplied in order to achieve a required cleanroom classification as specified in ISO 14644-1 (2015), Annex 1 (cGMP). In practice, the decision of the air change rate in a classified room used to be rather standardized, based on experience and assumptions, and hardly on an analytical model.

On the other side, we noticed increasing air change rates in case of higher cleanroom classifications. Recently, different questions came up: To what degree are the air changes effective? How well is the air distributed in a cleanroom? What mostly happened is that professionals have been thinking about the volume of air that needs to be blown into the cleanroom, but not about the distribution of the air in that room. By focusing on those questions, the ACE has become a decisive topic in modular cleanroom design.

The ACE can sometimes be confused with the ventilation effectiveness, which describes the ability of an air distribution system to eliminate internally generated pollutants from a room. It is common practice for cleanroom facilities to use ventilation systems with high airflow rates to control indoor contaminants. Unfortunately, those ventilation systems are often over-designed and unavoidably energy intensive (Khoo, 2012). Other literature surveys show that Eulerian and Lagrangian numerical methods (Hu and Tung, 2002), as well as Computational Fluid Dynamics (Zhao and Wu, 2005) have been applied to examine airflow fields in non-UDAF cleanrooms. Both publications indicate that many cleanrooms have excessive airflow rates, leading to an immense Total Cost of Ownership (high capital cost, running cost and energy cost).

Poor air mixing is not only related to the correct positioning of the air inlet points and type of air diffusers. In many cases, determining the location and quantity of wall return points is even more important. A correct positioning of the wall return air grills allows an increase of ACE and this with a lower air supply rate, resulting in a more energy efficient cleanroom.

The measured air change rate at a location is obtained by measuring the decay rate of test particles at a location.

Following formula, relating to the formula that has been mentioned when describing the force ‘Demand Controlled Filtration’, can be applied:

$$N = - \frac{1}{t} \quad \text{in} \quad \frac{C}{C1}$$

N = decay rate of particles = air change rate at the measuring location
t = time of decay
C = airborne concentration of particles after a given decay time
C1 = initial airborne concentration of particles

If the cleanroom is perfectly mixed, the ACE index will have the value of 1 at all locations. In the situation that the ACE index gives a higher value than 1, more clean HEPA filtered air than average will reach the test location and the cleanliness classification will be better.

The advantage of pre-engineered modular cleanroom design compared to conventional cleanroom design, is the easiness to make design adjustments without major modifications. Think about process machines that might be positioned otherwise over a certain period of time and thereby heavily influence the airflow and its effectiveness. How this third force, the ACE, shows a strong relationship with ‘Computational Fluid Dynamics (CFD)’, will be clarified in the next part of this whitepaper.

Force 4

Computational Fluid Dynamics

When learning about forces that drive energy efficiency in modular pre-engineered cleanroom design, we must point out Computational Fluid Dynamics, which is directly linked to Digital Twins. The topic Digital Twins refers to the creation of a digital environment at the design phase. The basis of Digital Twins are actually simulation scenarios in which a digital environment is used to examine how an event would turn out in reality. I herewith refer to what has been said above about changing setups in cleanrooms where for example process machines might be changed from one location to another location over a certain period of time.

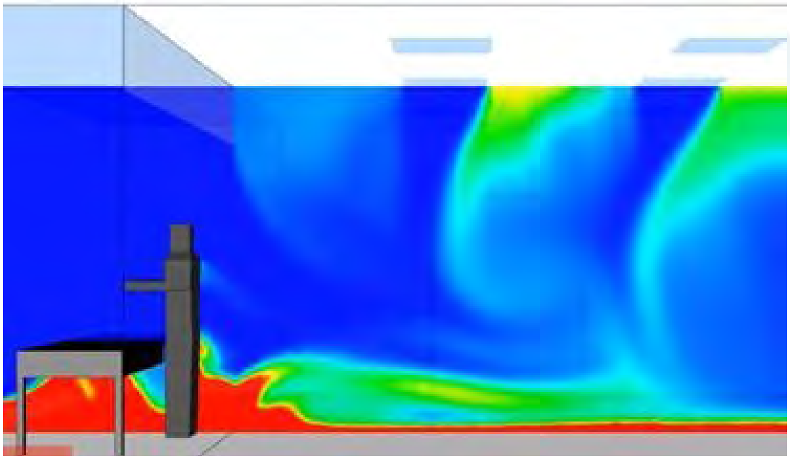
In our vision, real-time simulation and Artificial Intelligence can be perfectly used to enhance the design of the cleanroom or process by providing the opportunity to evaluate a wide range of alternative designs. Such evaluation of alternative designs prior to physically building the cleanroom leads to optimized airflow management and therefore energy management. Computational Fluid Dynamics (CFD) software is used to model and to predict fluid airflows, which is critical in order to optimize energy efficiency. This dynamic simulation is typically used to optimize the thermal performance of the cleanroom under various conditions. Furthermore, CFD is also used to analyse complex 3D cooling flows and to conjugate heat transfers in the airflow of the cleanroom. With CFD as part of Digital Twin, airflows can be simulated optimally within these changing setups in a cleanroom. An efficient airflow (not too low, but certainly not too high) will be a clear derivative within Digital Twins.

With the emergence of the Internet of Things (IoT), the potential for a transformational journey has been created. A transformational journey in which a simulation model of the cleanroom is tied through the internet, to sensors capturing data and to actuators controlling its operation. The result is a so-called digital twin of the physical product or process that can be used to analyse and diagnose its operation, and to optimize its performance and maintenance real time.

The simulation-based digital twin concept incorporates the physical process, the simulation models and the connections that facilitate communications between the two.

The applications of digital twins are numerous:

- Energy savings through perfect CFD simulation in order to achieve the required cleanroom classification with minimal air change rates.
- The lowest energy consumption through identifying the ideal period of maintenance (predictive maintenance)
- Industry 4.0 ready cleanroom design to capture data in order to transform data into wisdom through machine learning



Force 5
Continous Particle Monitoring

As a result of rising energy prices, we notice that many cGMP and non-cGMP companies are considering installing a continuous particle counter in their cleanroom. Since continuous particle counting within cGMP is only a requirement in Grade B and Grade A environments, it didn't happen often in other cleanroom environments until today. Companies are finding that the investment cost of an online particle counting system pays for itself very quickly and opt for this interesting investment. A shift in the cleanroom world that is fully in line with our patented VIX concept and which we therefore completely approve.

The predetermined Air Change Rates needed to achieve a certain classification are usually drawn up from rules of thumb and assumptions. As can be seen in the table below, it has been established that the air in an ISO6 environment must be purged no less than 50 times per hour. From our expertise, we experience that these values have been built in with far too much certainty. A major flaw, for example, is that it does not consider variable factors per specific cleanroom, such as the number of operators and their clothing protocols, the contamination of machines, or the processes taking place in the cleanroom. This often creates an overkill in terms of air changes, which will result in unnecessarily high energy consumption. By integrating a continuous particle counter, real-time integer data on contamination inside the cleanroom can be extracted. Based on this data, it can be determined how many air changes are needed to achieve certain cleanliness classifications.

Continuous monitoring of a critical environment requires constant particle sampling. In this method, data is collected continuously so that events are not being missed. Sampling intervals can be of any duration, but shorter intervals give better temporal resolution. Short intervals also provide huge amounts of data that can feed the system. Typical time intervals range from one to 15 minutes.

Continuous particle counting not only gives insight into whether we are doing things right, but also whether we have the cleaning and disinfection procedure under control. In practice, if we see high values, this often means that there is something wrong with the clothing procedures of the people inside the cleanroom. Large particles (>1µm) often originate from the clothing of operators inside the cleanroom.

Another important factor in this is the ACE, or the local Air Change Effectiveness. It is determined by good mixing of the pulse air on one hand and the number of take-back points at floor level on the other. At ABN Cleanroom Technology, we always aim to have an ACE of around 1, which means that the required pulse flow rate is minimal.

By using artificial intelligence, we can perform pattern detection. For instance, we could uncover the differences between cleanroom conditions before and after cleaning processes. Or check which clothes and clothing procedures are the least polluting. By collecting and comparing all this data, we get a profound insight into the co-relation of different physical parameters. Moreover, we can always give operators and technicians immediate feedback when established procedures are not followed. By using sensors and sensor points, we can always check whether the agreed changing procedures in the Personnel Airlock are being followed correctly. All these solutions can be easily integrated into your 21 CFR Part 11 workflow.

The platform that allows the above-mentioned is GMPconnect. A CFR21 Part 11 compliant cloud platform that collects and maintains integer online data. This data allows us to maintain our risk-based management vision. From our own experience, we can state that a continuous particle counter is a good investment. The savings it delivers in terms of energy consumption alone pay for themselves in no time at all. Moreover, it always gives cleanroom users the most accurate insights into the processes in their cleanroom, from which an enormous amount of valuable information can also be extracted.

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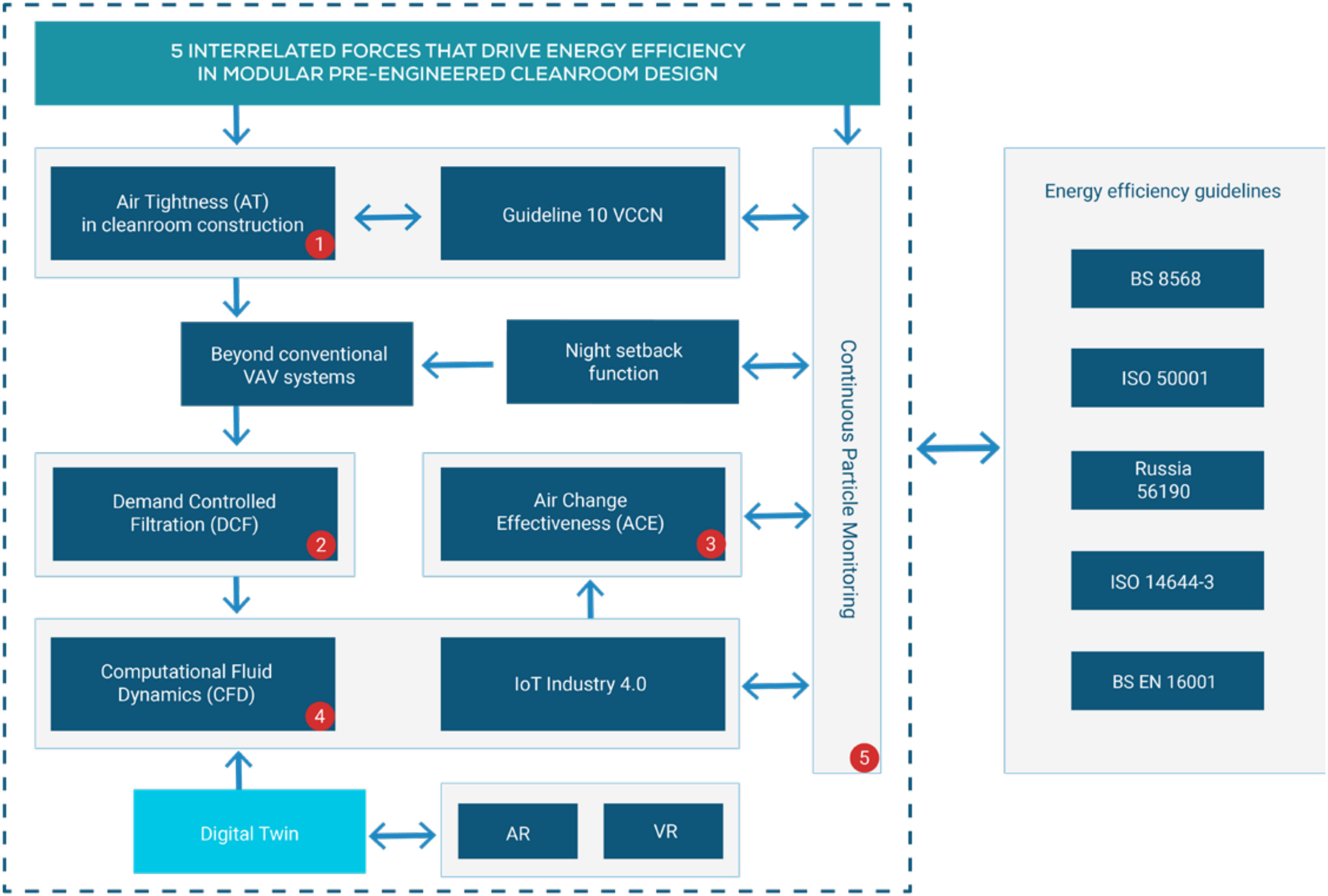
5 INTERRELATED FORCES THAT DRIVE ENERGY EFFICIENCY
IN MODULAR PRE-ENGINEERED CLEANROOM DESIGN
Air Tightness (AT)
in cleanroom construction
1
Guideline 10 VCCN
Beyond conventional
VAV systems
Night setback
function
Demand Controlled
Filtration (DCF)
2
Air Change
Effectiveness (ACE)
3
Computational Fluid
Dynamics (CFD)
4
IoT Industry 4.0
Digital Twin
AR
VR
Continuous Particle Monitoring
5
Energy efficiency guidelines
BS 8568
ISO 50001
Russia
56190
ISO 14644-3
BS EN 16001

Want to know more?

Jo Nelissen MSc is the founder and CEO of ABN Cleanroom Technology and holds a Master Degree in Mechanical Engineering & Asset Management. He focuses on innovative concepts in pre-engineered cleanroom design. Furthermore, he specializes in asset management in modular & pre-engineered cleanroom design.

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