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FACULTY OF MECHANICAL ENGINEERING
FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AEROSPACE ENGINEERING
LETECKÝ ÚSTAV

CONCEPTIONAL DESIGN FOR UPGRADE USE OF CLEANROOM FOR AEROSPACE PARTS TESTING
KONCEPČNÍ NÁVRH NA ZLEPŠENÍ VYUŽITÍ ČISTÉHO PROSTORU PRO AERO-KOSMICKÉ ZKOUŠKY

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Specification Bachelor's Thesis

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Pursuant to Act no. 111/1998 concerning universities and the BUT study and examination rules, you have been assigned the following topic by the institute director Bachelor's Thesis:

Conceptional design for upgrade use of Cleanroom for aerospace parts testing

Concise characteristic of the task:

Space projects are technologically and financially demanding and therefore must meet rigorous standards of quality and safety. Moreover, a low product contamination during production and testing in laboratories has to be ensured. Cleanrooms ensures simulated controlled conditions for hi–tech parts testing, parameters as temperature, humidity and purity are provided by a complex technical systems in backstage. Therefore, work in the laboratory and maintenance of the technical facilities require detailed procedure specifications and personnel training.

Goals Bachelor's Thesis:

– Acquaint with cleanroom problematics, related standards and technical systems
– Present conceptual designs of cleanroom systems layout and concepts assessment based on defined criteria
– Analyse airflow circulation in clean lab and propose improvements
– Propose a concept of project realization

Recommended bibliography:

ČSN EN ISO 14644-1. Čisté prostory a příslušná řízená prostředí - Část 1: Klasifikace čistoty vzduchu podle koncentrace částic. 2019, 36 s.

ECSS-Q-ST-70-01C. Cleanliness and contamination control. European Cooperation for Space Standardization, 2008, 75 s. Dostupné také z: https://ecss.nl/standard/ecss-q-st-70-01c-cleanl-ness-and-contamination-control/

Deadline for submission Bachelor's Thesis is given by the Schedule of the Academic year 2019/20

In Brno,

L. S.

doc. Ing. Jaroslav Juračka, Ph.D. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

ABSTRACT

The thesis focuses on the problematics around designing a cleanroom. The aim is to present a conceptional design to upgrade the use of a cleanroom for aerospace parts testing. The first part of the thesis covers the introduction into the cleanroom problematics. Based on the research and the given requirements, the parameters for the cleanroom are defined. The second half presents a conceptional proposal where each one difference represents a different mindset behind it. For verification of a possibility to achieve the aimed classification, the model of the cleanroom was constructed in a SOLIDWORKS and then the airflow inside the cleanroom was simulated in an ANSYS FLUENT.

KEY WORDS

Cleanroom, clean space, airflow, classification, ISO class, design

ABSTRAKT

Tato bakalářská práce se zaobírá problematikou spojenou s návrhem čisté místnosti. Cílem práce je představit koncepční návrh na zlepšení využití čistého prostoru pro aero-kosmické zkoušky. První část práce je tvořená analýzou problematiky čistých místností. Na základě teoretického úvodu a zadaných hodnot jsou pro čistou místnost stanoveny parametry. Druhá část představuje koncepční návrhy, kde každý návrh je vytvářen z jiného hlediska. Pro ověření možnosti dosáhnout cílené třídy čistoty, byl vytvořen model čisté místnosti v SOLIDWORKS a proudění vzduchu v čisté místnosti bylo simulováno v programu ANSYS FLUENT.

KLÍČOVÁ SLOVA

Čistá místnost, čistý prostor, třída čistoty, ISO třída, návrh

ROZŠÍŘENÝ ABSTRAKT

Čistota a pořádek. Tyto dva pojmy jsou si velmi blízké a úzce propojené a jejich spojení s jakýmkoliv pracovním prostorem je zcela zřejmé. I v pracovních prostorech, které se dají považovat za nejvíce znečištěné či zanešené, jako jsou například pracoviště staveb, se nachází potřeba po dodržování určité čistoty a pořádku. Tato nutnost a potřeba po čistotě vychází z možnosti ovlivnění vykonávané práce. S rostoucí ekonomikou, průmyslem a vývojem nových technologiích se potřeba čistoty, či konkrétně po čistých prostorech, zvyšovala. V dnešní době jsou čisté místnosti a čisté prostory neoddělitelnou součástí mnoha různých odvětví v průmyslu. Každý projekt si prochází částmi jako je vývoj, konstrukce a následné jeho testování. Při těchto procesech bývá často ovlivnění vnějším činitelem nežádaným jevem. Působení vnějších podmínek znamená nestabilní průběh a možnost ovlivnění výsledku. Čisté místnosti, jak už bylo zmíněno, nachází své využití v mnoha různých odvětvích, mezi které například patří jemná mechanika, přesné strojírenství, výroba léčiv či příprava potravinových výrobků. Tato bakalářská práce se zabývá návrhem čisté místnosti, která by měla najít své využití při testovaní aero-kosmických produktů.

Rešerní část bakalářské práce se zaměřuje na problematiku čistých místností. Ze začátku jsou uvedeny definice pojmů jako je čistá místnost, čistota či čistý prostor. Následně je položeno několik základních otázek, které vznikají při navrhování čistých prostor. Tyto otázky se můžou považovat za nahlédnutí na to, jak velmi obsáhlým a komplexním tématem čisté prostory jsou. Rešerní část následně představuje normy spojené s čistými prostory. Mezi klíčové patří norma ISO 14644, která se skládá z 17 částí a podle které jsou čisté místnosti vytvářeny. Tato norma by měla každému designérovi a technikovi sloužit jako návod a měl by se těmito standardy řídit. Pro tuto bakalářskou práci jsou klíčové části ISO 14644-1 a ISO 14644-4. Díky znalostem, získaným z ISO 14644-1, je následně popsáno rozdělení čistých místností. Čistá místnost se dělí do tzv. ISO tříd, kde ISO 1 se považuje za třídu nejvyšší čistoty a ISO 8 za třídu s čistotou nejnižší. Pro každou třídu je stanoven maximální počet mikročástic, který místností může projít. Tyto mikročástice jsou ve vzduchotechnice zachycovány pomocí vzduchových filtrů. Pro potřebu čistých místností se využívají filtry HEPA a ULPA. HEPA filtr je využitelný do tříd ISO 5-8. ULPA filtr se používá pro třídy ISO 1-5. Mezi vlastnosti specifické pro čisté místnosti určitě patří počet výměn vzduchu za hodinu. Na každou třídu je potřeba určité množství výměn. Výměny zajišťují dostatečné proudění vzduchu a očištění prostoru. I proudění vzduchu v čisté místnosti je podrobně popsáno a regulováno. Ze znalostí z hydromechaniky víme, že proudění vzduchu lze rozdělit na turbulentní a laminární. Hydromechanika ve třetím ročníku bakalářského studia naznačuje, jak lze tyto druhy proudění popsat a jak se chovají. Pro tuto práci pouze postačí vědět, že kontrolované turbulentní proudění vzduchu se může nacházet ve třídách ISO 5-8. Pro třídy ISO 1-4 se musí využívat už proudění laminárního. Mezi základní vlastnosti čisté místnosti lze také zařadit pozitivní tlakový spád oproti sousedním místnostem. Tlakový spád by měl mít hodnotu mezi 5-20 Pa. Z norem vyplývá i to, že by teplota v čisté místnosti měla být ustálená a nacházet se v oblasti tělesné pohody. Teplotní výkyvy můžou znamenat nepříjemnosti nejen pro testování daných projektů, ale i pro samotné operátory. Jako poslední je v rešerní části nabídnut stručný náhled do problematiky designu čistých místností. Tato část představuje řadu doporučení a omezení, které vychází z pravidel vypsaných v normě ISO 14644-4. Tato norma například popisuje vhodné materiály pro stavbu čistých místností. Zmíněné jsou i podmínky, které čistá místnost z pohledu designu musí splňovat, zde lze například jmenovat hermetičnost, minimum rohů a ostrých hran a omyvatelnost všech částí čisté místnosti, nejen podlahy.

Praktická část následně popisuje současný stav místnosti 2.02 a představuje tři koncepční návrhy na vylepšení této místnosti. Na základě rešerní části a zadaných hodnot jsou stanoveny požadavky. Stanoveným cílem práce je představení návrhu čisté místnosti, s čímž nastala otázka na teoretické ověření dosažení zadané třídy čistoty. Pro ověření čistoty se nechalo simulovat proudění vzduchu v programu ANSYS FLUENT. Pro představení místnosti 2.02 a jejich koncepčních návrhů, byly vytvořeny modely v programu SOLIDWORKS. Následně tyto modely byly využity pro simulaci v programu ANSYS FLUENT. Pro možnost rychlého porovnání slouží půdorysový výkres každého návrhu a místnosti 2.02 vytvořený v programu CAD. Místnost 2.02 se nachází v budově C3A Leteckého ústavu Vysokého učení technického v Brně. Na této místnosti následně mají být představené vylepšení, které by pomohly získat statut čisté místnosti. Simulace ukazuje, že proudění v této místnosti by se dalo popsat jako nestabilní, objevují tendence existence samostatných vzduchových vírů. Takové vzduchové víry narušují obecnou podstatu čisté místnosti, ve které je právě kontrolovaná výměna a proudění vzduchu základní premisou. Z těchto zjištění by se dalo usuzovat, že by v této podobě místnost 2.02 z pohledu proudění vzduchu neprošla ISO normami a to i přesto, že teoretická hodnota výměn vzduchu odpovídá požadavkům z norem. První návrh lze považovat jakožto nejjednodušší řešení z pohledu proudění vzduchu a přestavby prostoru. Půdorys místnosti zůstává stejný jako je v místnosti 2.02, pouze v návrhu byly sousední místnosti 2.1 a 2.15 spojeny za účelem možného vzniku šatny. Nejdůležitějším rozdílem je počet a umístění vyústek vzduchotechniky. V tomto návrhu jsou dvě vyústky a jsou umístěny naproti sobě na užších stěnách místnosti. Tento rozdíl je zřetelný v simulaci, neboť proudění vzduchu je ustálené a má předpoklady k tomu, aby se splnily nároky, které stanovují normy na dosažení třídy ISO 8. Druhý návrh by se dal považovat za typický příklad známého rčení, že méně je někdy více. Díky svému menšímu objemu získává výhodu v tom, že se počet výměn vzduchu za hodinu radikálně zvyšuje. Díky své skromnosti v prostoru lze v simulaci i pozorovat, jak se vylepšilo chování proudění vzduchu. Ze simulací lze i vydedukovat, že při zvýšení vstupů a výstupů vzduchotechniky by šlo dosáhnout i laminárního proudění, které je podmínkou pro velmi čisté prostory, což je se z pohledu ISO klasifikace jedná o třídy ISO 1-5. Důležitější ale zůstává, že druhý návrh by mohl dosáhnout třídy ISO 8 a za dosažitelnou by se dala považovat i třída ISO 7, což potvrzuje teoretický výpočet výměn vzduchu za hodinu. Třetí design byl vytvořen s myšlenkou toho, aby mohl představit maximum prostoru bez omezení na rozpočtu. Tento návrh je ze všech objemově největší a i díky tomu přichází myšlenka na zvýšení počtu vstupů vzduchotechniky. Simulace potvrzuje předpoklady, že by i třetí návrh mohl dosáhnout ISO 8 třídy z pohledu proudění vzduchu.

Za přidanou hodnotu celé bakalářské práce lze považovat zkoumání teploty v místnosti. Idea tohoto výzkumu vznikla z podmínek, stanovených ISO 14644-4 normami, ve kterých je řečeno, že čistá místnost mimo jiné nesmí obsahovat vnitřní žaluzie. Tím, že místnost 2.02 obsahuje stěnu, která lze popsat jako vnější stěnu celé budovy, což znamená, že okna v této místnosti podléhají slunečnímu záření. Čistou místnost lze charakterizovat i jako velmi stabilní a neměnné prostředí, pod což spadá i teplota v dané čisté místnosti. Teplota je podrobněji zkoumána na návrzích místnosti 2.02 a na prvním koncepčním návrhu. Druhý a třetí design sice lze zkoumat z pohledu teploty, ale ani jeden design neobsahuje okna, na které by přímo dopadalo sluneční záření. Díky absenci tohoto problému je teplota v místnosti, která je zobrazená pomocí simulace, neměnná. Teplota v místnosti je zobrazena pomocí programu ANSYS FLUENT. Tento program nabízí různé možnosti simulování teploty, vedení, proudění a radiace tepla. V rámci simulace byla zvolena metoda Solar-Ray Tracing, která se nachází v možnostech simulace radiace. Funkce Solar-Ray Tracing dle uživatelského návodu programu má simulovat solární záření.

Pro tento úkol, tato metoda byla využita pro simulaci prostupovaného tepla skrz okna. Simulace zobrazuje výkyvy teplot uvnitř místnosti. Tyto výkyvy jsou logické a lze je považovat za správné, neboť udržet konstantní teplotu skrz celou místnost je skoro nemožné. Zobrazené teploty v simulaci odpovídají požadovanému rozmezí normy ISO 14644.

Výsledky dodané simulacemi lze požadovat za uspokojující. Důležité je ale zmínit, že tyto výsledky a návrhy jsou dílem studenta, který se s touto tématikou setkává prvně. Výsledky zjištěné skrze simulace či předložené návrhy lze považovat za teoretický základ či nastínění problematiky budoucího projektu. Hodnoty zde zjištěné by měly být prokonzultovány s expertem či přímo kvalifikovaným pracovníkem. Obecně lze konstatovat, že každý návrh má potenciál dosáhnout potřebné ISO klasifikace, přičemž každý návrh má své výhody a nevýhody a závisí na konkrétních požadavcích a představách zadavatele, aby se dalo zhodnotit, který návrh lze považovat za nejlepší.

BIBLIOGRAPHY

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DECLARATION OF AUTHETICITY

I declare that the thesis entitled, "Conceptual design for upgrade use of cleanroom for aerospace parts testing" is my own work and that all the sources that I have used or quoted have been listed and acknowledged at the end of the thesis.

In Brno on 26.06.2020 ……..……..…………………………………………..

Samuel Halamíček

ACKNOWLEDGEMENT

On this place I would like to thank my bachelor thesis supervisor, Ing. Václav Lazar, for his professional guidance and support.

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1 INTRODUCTION

Tidiness and cleanliness. Two things that are together hand in hand and its connection with the workspace is unquestionable. Even in the dirtiest workspaces such as buildings, the cleanliness always finds its way. The need for cleanliness comes from the possibility of a bad influence on the work. With the growing industry and development of new technologies, the need for cleanliness rose. And in this time the cleanroom and the clean space comes into the stage.

Today the cleanroom is a necessary part of many different branches in the industry. Every project needs to be constructed, developed, and tested. In these branches, the external conditions mean unwanted intervention into the project. The cleanroom finds its usage in precision engineering, optical industry, electrical engineering, production of drugs, and last but not least in aerospace engineering. The cleanroom for tests of aerospace parts is the one that is going to be tried to accomplish in this project.

2 THEORETICAL INTRODUCTION

The design of a cleanroom can sound on first feeling like an easy task. A room where will be done a little bit of work to fulfil some requirements from some standard and then there is a special room where is possible to do work for a potentially big reward. But which are these requirements? Which standard is the right one to follow in cleanroom design? And for what cleanroom truly stands for? For finding these answers it is necessary to gain the basic knowledge and have some theoretical background in cleanroom problematic.

2.1 WHAT CLEANROOM MEANS AND WHICH QUESTION IT BRINGS

The right thing to start with is to determine what does cleanroom and its associated words stand for.

"Cleanroom is a room within which the number concentration of airborne particles is controlled and classified, and which is designed, constructed, and operated in a manner to control the introduction, generation, and retention of particles inside the room." [1]

"Clean zone is a defined space within which the number concentration of airborne particles is controlled and classified, and which is constructed and operated in a manner to control the introduction, generation, and retention of contaminants inside the space." [1]

"Classification is a method of cleanliness against a specification for a cleanroom or clean zone." [1]

But as previous text indicated, a cleanroom is difficult and expensive work to build and design. It is necessary to answer a few main questions in logistics before investing money into the project. There is a small selection of them:

For which branch of studies will be the cleanroom used:
For each branch, there is a need for different standards. For example, with space or electronics engineering, it is necessary to guide around ISO standards. On the other hand in the pharmaceutical industry, there is going to be a need for checking and meeting with GMP norms. [2] [3] [4]

Which class or standards must be fulfilled:
Depending on projects and types of products. For each product, there is a different need for cleanliness in testing. It would be very wise to think about future projects and products and if there could be a requirement of a higher standard of the cleanroom. [2] [3] [4]

What part of the process will be done in the cleanroom:
It is important to think about how many operations will take place and how many people will be working in the cleanroom. More work means more space and that means more heat will be generated and with more people in it, it is going bounce on deciding about heating, ventilation, and air-conditioning. [2] [3] [4]

2.2 CLEANROOM STANDARDS

To achieve the status of a cleanroom it is necessary to meet with requirements given by certain standards. Every aspect around the cleanroom should be possible to find in standard, from the classification of cleanrooms to materials that should be used and more. In the real world, it is most likely to meet with the following standards:

2.2.1 ISO STANDARD 14644 CLASSIFICATION OF AIR CLEANLINESS BY PARTICLE CONCENTRATION:

International Organization for Standardization (ISO) has developed these non-governmental standards. These standards were developed from US Federal Standard 209E (FED STD 209E). [5]

The first document, ISO 14644-1, was published in 1999, followed by document ISO 14644-2 in 2000, which began the end of using Federal Standard. On 29. November 2001 was released the Notice of Cancellation for FED STD 209E and it was superseded by ISO 14644 standards. [5]

ISO 14644 standard is composed of several parts, under the general title *Classification of air cleanliness by particle concentration*: [4] [5]

- ISO 14644-1: Classification of air cleanliness by particle concentration
- ISO 14644-2: Monitoring to provide evidence of cleanroom performance related to air cleanliness by particle concentration
- ISO 14644-3: Test methods
- ISO 14644-4: Design, construction, and start-up
- ISO 14644-5: Operations)
- ISO 14644-7: Separative devices (clean air hoods, gloveboxes, isolators, mini environments)
- ISO 14644-8: Classification of air cleanliness by chemical concentration (ACC)
- ISO 14644-9: Classification of surface particle cleanliness
- ISO 14644-10: Classification of surface cleanliness by chemical concentrations
- ISO 14644-12: Specifications for monitoring air cleanliness by nanoscale particle concentration
- ISO 14644-13: Cleaning of surfaces to achieve defined levels of cleanliness in terms of particle and chemical classifications
- ISO 14644-14: Assessment of suitability for use of equipment by airborne particle concentration
- ISO 14644-15: Assessment of suitability for use of equipment and materials by airborne chemical concentration
- ISO 14644-16: Code of practice for improving energy efficiency in cleanrooms and clean air devices
- ISO 14644-17: Particle deposition rate applications

2.2.2 ISO 14698 Cleanrooms and associated controlled environments – Biocontamination control

ISO 14698 is standard which deals with problematic around biocontamination control for cleanrooms and is composed of following parts: [6]

- ISO 14698-1: General principles and methods
- ISO 14698-2: Evaluation and interpretation of biocontamination data

The first four parts of ISO 14644 standard are critical for achieving goals in this bachelor theses.

2.2.3 European Cooperation for Space Standardization – ECSS Standard

"ECSS is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities." [7] ECSS standard is a very complex structure, as it is possible to see in the picture 2.1**,** which concludes every aspect that is connected with space activity. [7]

ECSS standard is divided into branches. Parts that are relevant for the cleanroom design, quality and contamination control are: [7]

- ECSS-Q-ST-70-01C: Cleanliness and contamination control
- ECSS-Q-ST-70-50C: Particles contamination monitoring for spacecraft systems and cleanrooms
- ECSS-Q-ST-70-55C: Microbial examination of flight hardware and cleanrooms
- ECSS-Q-ST-70-58C: Bioburden control of cleanrooms
- ECSS-Q-ST-20-07C: Quality and safety assurance for space test centres

All mentioned parts fall under the Space product assurance branch.

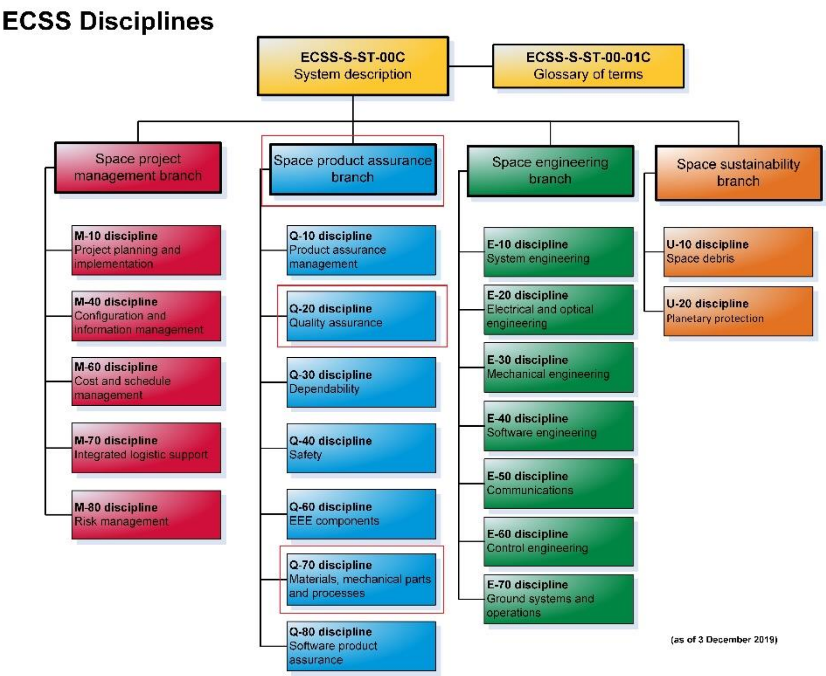

Figure 2-1 [13]

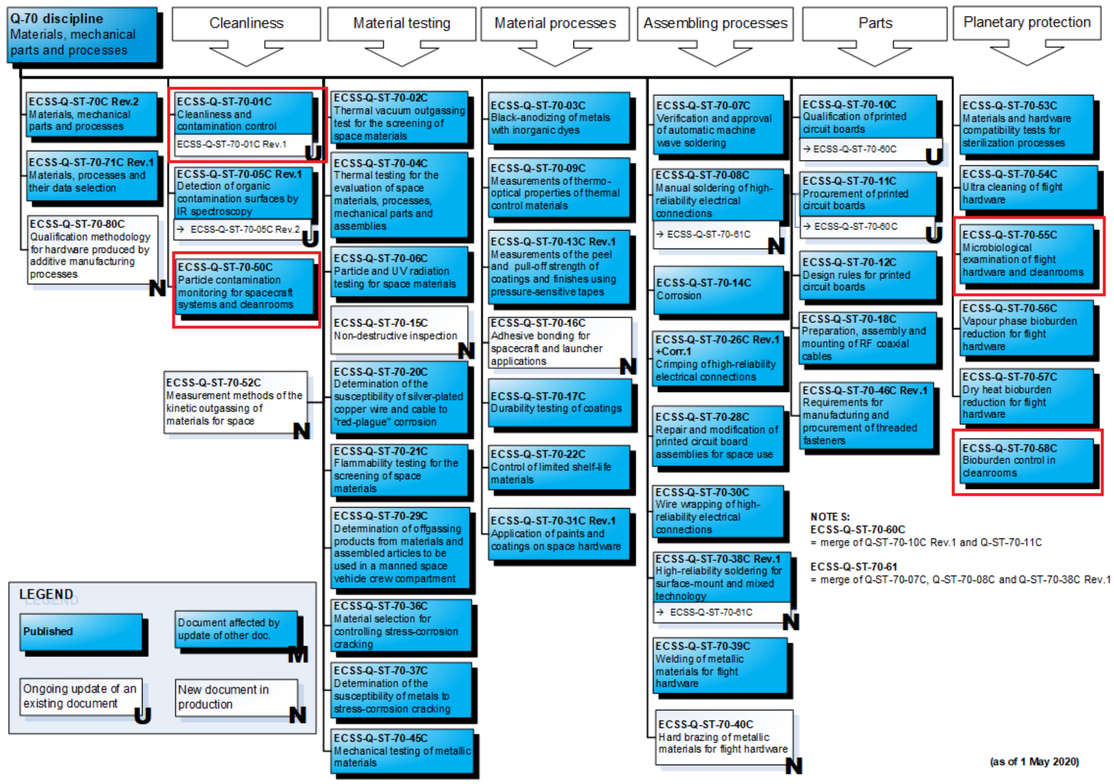

Figure 2-2 [13]

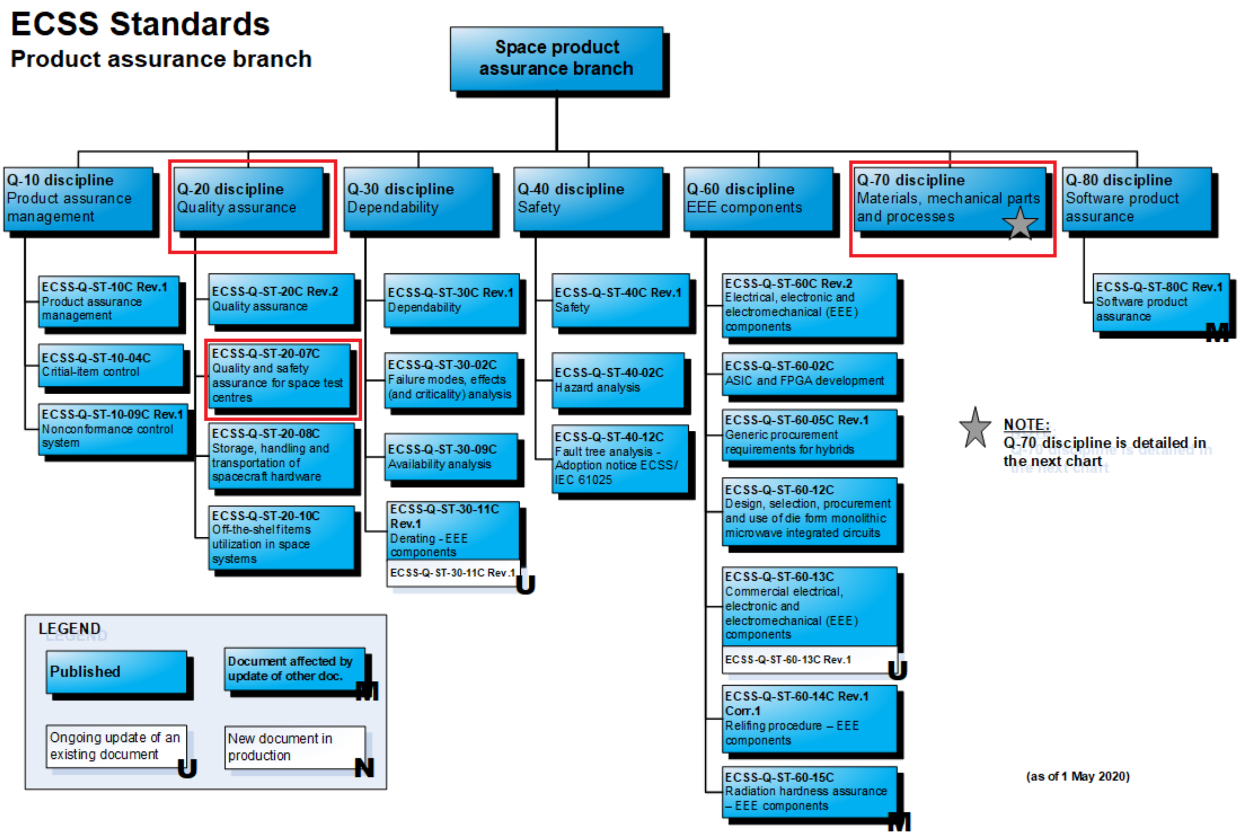

Figure 2-3 [13]

2.3 CLASSIFICATION CLASSES OF THE CLEANROOM

Cleanroom class is specified/given by parameters, which are the quantity and size of particles per volume of air. The ISO 14644-1 standard divides classes from ISO 1 to ISO 9, where ISO 1 is taken as the "cleanest" and ISO 9 as the "dirtiest" of these classes. But still, ISO 9 class is cleaner than a normal room. (For example, the air in typical office building room contains about 500,000 to 1,000,000 particles per cubic foot of air, on the other hand, the most basic class ISO 7 is not allowed to contain more than 10,000 particles per cubic foot of air.) [1] [4] [8] [9]

Only particles that have sizes ranging from 0,1µm to 5µm are measured. In each class, there is a difference from which diameter is particle taken into the measurement.

ISO class number (N)	Maximum allowable concentrations (particles/m^3) for particles equal to and larger than the considered sizes shown						FED STD 209E equivalent
	≥0.1µm	≥0.2µm	≥0.3µm	≥0.5µm	≥1µm	≥5µm	
1	10						
2	100	24	10				
3	1 000	237	102	35			Class 1
4	10 000	2 370	1 020	352	83		Class 10
5	100 000	23 700	10 200	3 520	832	29	Class 100
6	1 000 000	237 000	102 000	35 200	8 320	293	Class 1 000
7				352 000	832 000	2 930	Class 10 000
8				3 520 000	8 320 000	29 300	Class 100 000
9				35 200 000	83 200 000	293 000	

Figure 2-4 [1] [8]

In the picture 2-4, both standards (ISO STANDARD and FED STD) are included. In some companies, it is possible to still find old FED STD classes, so it is recommended to know them both. It must be mentioned that ISO 9 class is only applicable to the in-operation state. [4] [8]

With the gained knowledge about existing classes and their concentrations, it is time to check and consider which regulatory agency requirements there are for the products, that are going to be tested in the cleanroom. This next table shows examples of classification needed in different areas (branches) of manufacturing processes. [10]

Industrial Applications	**Classification**
Aerospace	ISO Class 5-8
Composite Materials	ISO Class 8
Optical	ISO Class 5-7
Electronics	**Classification**
Semiconductor	ISO Class 5
Solar	ISO Class 5-7
Wafer Board	ISO Class 5
Consumable, Pharmaceutical	**Classification**
Food Packaging	None
Pharmaceutical Compounding	ISO Class 7
Sterile Compounding	ISO Class 5
Medical Devices	**Classification**
Inplantable Devices	ISO Class 5
Device Reprocessing	ISO Class 7-8

Figure 2-5 [10]

2.4 LAYOUT AND ARRANGEMENT OF A GIVEN WORKING AREA

The main aim of a cleanroom is to achieve a certain ISO class. But for that, it is necessary to have an effective and working layout of the possible working area. Conceptional design of the working area should take into account possible energy intensity and mainly process for which is going to be the cleanroom used. With depending classification, it is important to allow enough square footage. It is critical not only for the clean zone but for airlocks which prevents migration of unwanted particles into the clean zone. [3] [8]

The layout of the cleanroom should follow this rule of thumb, that stands for the "principle with broad application that is not intended to be strictly accurate or reliable for every situation," which says that, when moving towards cleaner room there should not be skipped the "dirtier" room. (for example, when coming to ISO 6, it should from ISO 8 to ISO 7 and then to ISO 6, not from ISO 8 directly to ISO 6). [3] [8] [9]

Figure 2-6 [8]

But in the real world, it is not always necessary to make all the classes/airlocks before the wished classification of the clean zone. It is possible with the appropriate air changes per hour. The number of airlocks needed is based on several conditions like the size of the cleanroom, the number of people working inside, the equipment inside, location of the clean zone in the building, a process taking inside the cleanroom, etc. [8]

A single access should be used in the most critical spaces. The single access makes prevention before cross-contamination which can be very sensitive in some biopharmaceutical processes. [3] [8] [9]

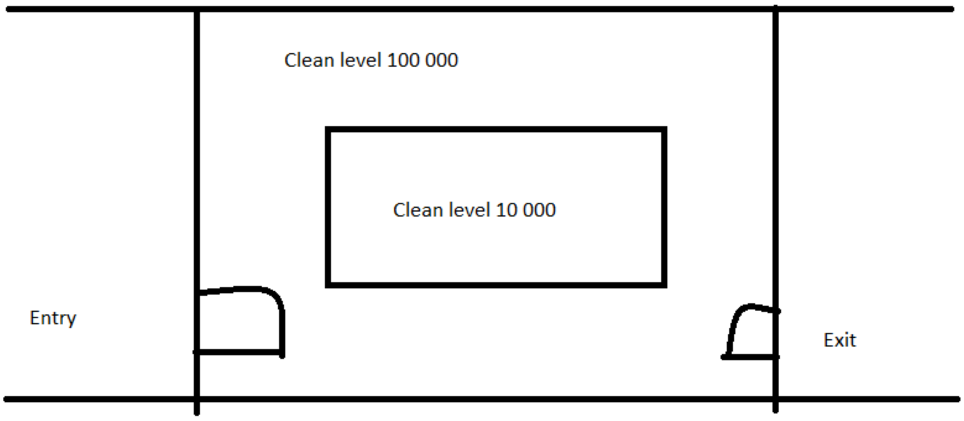

Figure 2-7

2.4.1 **Usage of smaller working space**

For tests and work with smaller components, it is not needed to use and upgrade the whole room to the required class. It is possible to build or to buy a cleanroom cabin, cabinet, or a workstation. The stipulation is that the smaller working space must be placed inside already existing clean space. This solution is for example used in spaces, where the higher classification cannot be achieved by rebuild because of lack of space or the rebuild would be too expensive. The usage of this principle can be found in the cleanroom at the Institute of Physical Engineering at the Brno University of Technology, where is placed laminar flow cabinet from Czech company Labox s.r.o. (Figure 2-10). [3] [4]

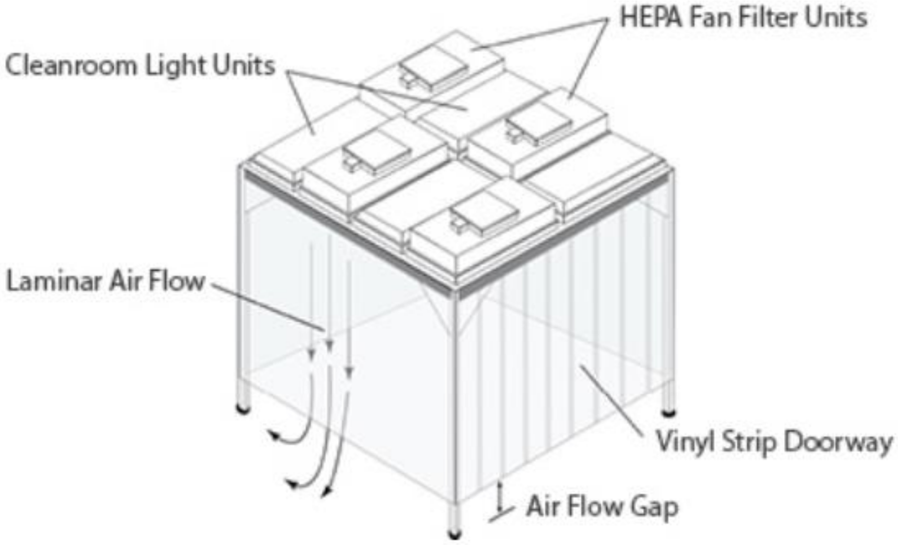

Figure 2-8 [14]

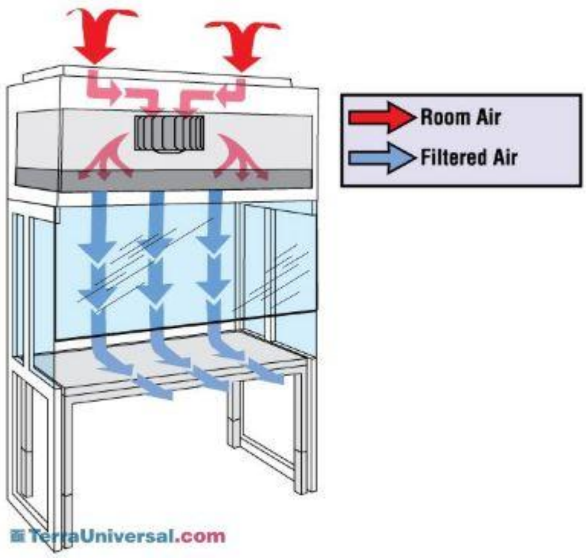

Figure 2-9 [15]

Figure 2-10

2.5 HEATING, VENTILATION, AIR CONDITIONING - HVAC SYSTEM IN CLEAN SPACE

The HVAC system creates, as one of many operations, for example, a pressure differential between a clean space and non-clean space. The pressure differential is crucial for the cleanroom because thanks to the differential the environment in the cleanroom is stable. To define a controlled environment the HVAC System must fulfil these requirements: [9]

2.5.1 AIR CHANGES PER HOUR

Air must flow through filters to achieve cleanliness. The more often the air goes through a filter, the more particles are intercepted in filters. [8] [9] [10]

The increased air supply is provided to eliminate the settling of the particulate and de-escalate produced contamination and to let particulates pass through air filters more often. [8] [9] [10]

Required air changes per hour (ACH)	
ISO Class	Average number of air changes per hour
ISO 5	240-360 air changes per hour (unidirectional airflow)
ISO 6	90-180 air changes per hour
ISO 7	30-60 air changes per hour
ISO 8	10-25 air changes per hour
Conventional building	*2-4 air changes per hour*

Figure 2-11

This table should be used only as an example. Many outside aspects must be taken into consideration to achieve the required conditions in a specific cleanroom.

2.5.2 AIR FILTERS

Air filters are used for taking out contaminants from the air. Unclean air enters the filter through the upstream side as "clean" air exits through the downstream side. Air-filters are described and divided by their efficiency, airflow resistance, and particular holding capacity. The efficiency of air filters must be accomplished with minimal space pressurization even for big atmospheric dust load. Economical usefulness of air filter is defined by previously mentioned efficiency of air filters with long service life and minimal energy cost. HEPA and ULPA filters are the most commonly used filters in the cleanroom industry. High efficiency air filters are closely described in European Standard EN 1822. [9]

High-efficiency particulate air - HEPA Filter

HEPA Filter is usable until ISO Class 5 included. By European standard EN 1822 HEPA filter must remove minimal 99.95% of particles, which passes through the filter, with a diameter equal to 0.3 μm. [4] [9] [11]

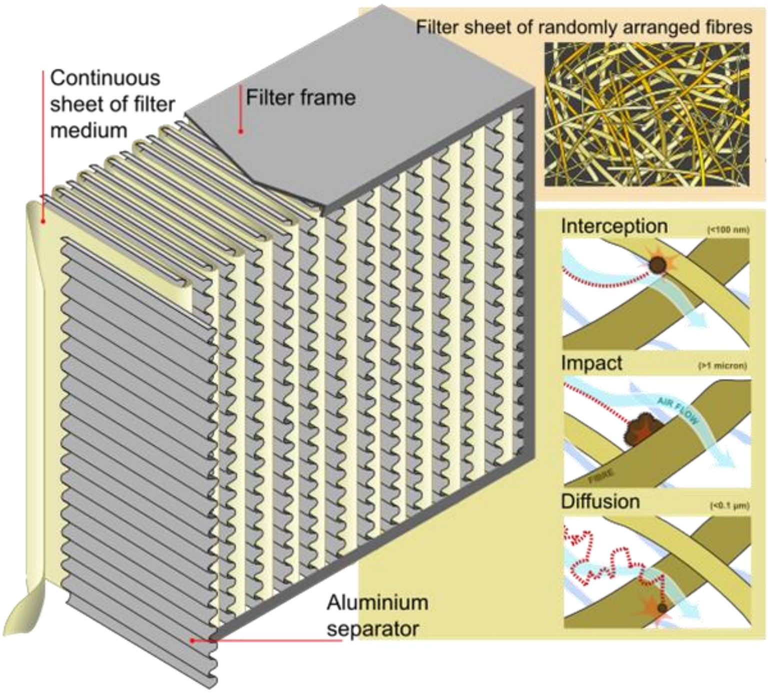

Figure 2-12 [16]

Ultra-low penetration air - ULPA Filter

ULPA filter by the definition of the European Standard EN 1822 provides a minimum of 99.999% efficiency removing airborne particles with a minimum size of 100 nanometres. ULPA Filter provides ISO Class 3. [4] [11]

Filter Group	Filter class	Efficiency (%)	Penetration (%)
ELPA Filter	E 10	≥ 85	≤ 15
	E 11	≥ 95	≤ 5
	E 12	≥ 99.5	≤ 0.5
HEPA Filter	H 13	≥ 99.95	≤ 0.05
	H 14	≥ 99.995	≤ 0.005
ULPA Filter	U 15	≥ 99.999 5	≤ 0.000 5
	U 16	≥ 99.999 95	≤ 0.000 05
	U 17	≥ 99.999 995	≤ 0.000 005

Figure 2-13

2.5.3 AIRFLOW PATTERNS

Choose of right airflow principle is one of the critical decisions in cleanroom design. Space cleanliness classification is the primary variable in the determination of the airflow pattern. The aim is to take away all the small particles which are produced by operators, materials, work equipment from the clean space. Airflow should avoid possible creating static zones with not enough air change per hour. Airflow patterns can be divided as unidirectional and non-unidirectional. Mixed airflow is made by a combination of unidirectional and non-unidirectional patterns. [3] [4]

Unidirectional airflow

Unidirectional or so-called laminar, airflow pattern is used in cleanrooms ISO 5 and cleaner. Unidirectional airflow can be either horizontal or vertical (Figure 2-14 and 2-15). For securing straightness of the airstream, filtered air supply, and air return must be in both cases opposite to each other. Zones with high requirements should be placed near to the air supply. Thanks to unidirectional airflow, particles that are formed on one workplace are taken so quickly that they can’t migrate to the adjacent workplace. [3] [4]

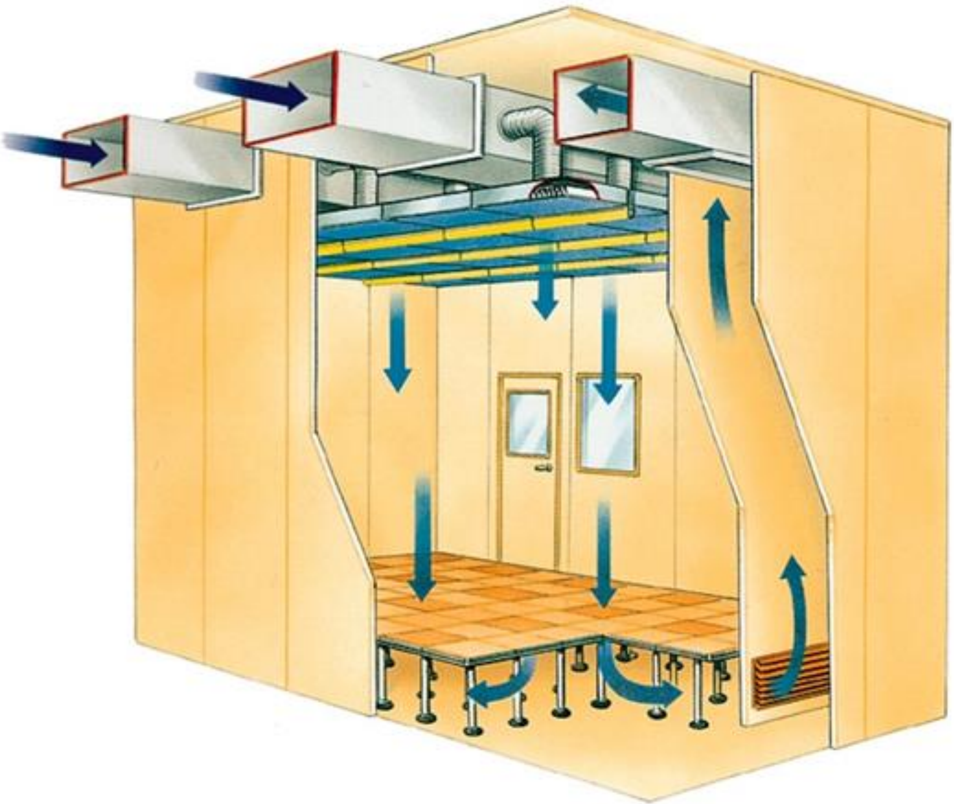

Figure 2-14 [17]

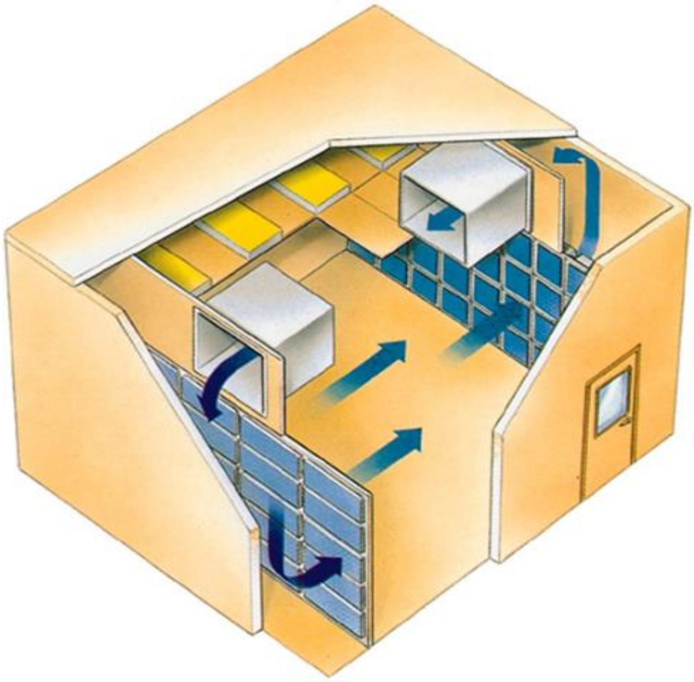

Figure 2-15 [17]

Non-unidirectional airflow

Non-Unidirectional or so-called turbulent, airflow pattern is used in cleanrooms ISO 6 and less clean zones. [9] [12]

ISO 14644-4: "Air flows from filter outlets located in multiple positions distributed across the inlet plane and is returned through remote locations. Filter outlets may be distributed at equal intervals throughout the cleanroom or clean zone or grouped over the process cores. The location of filter outlets is important for cleanroom performance. While return air locations in non-unidirectional airflow systems are not as critical as those in unidirectional applications, care should be taken to distribute the returns, as is done with the supplies, to minimize dead zones within the cleanroom." [3]

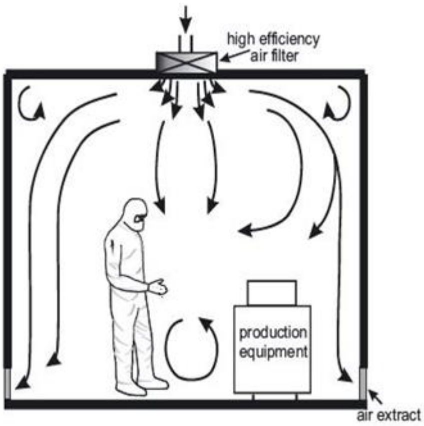

Figure 2-16 [12]

Mixed airflow

Mixed airflow combines non-unidirectional and unidirectional airflow patterns in one room. Airflow may be parallel in one part but in the other parts can flow turbulently. [3] [12]

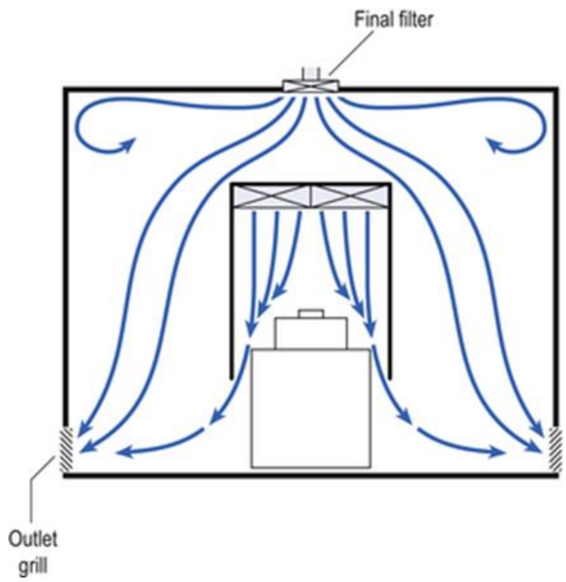

Figure 2-17 [18]

ISO Class	Type of airflow
ISO 1	unidirectional airflow
ISO 2	unidirectional airflow
ISO 3	unidirectional airflow
ISO 4	unidirectional airflow
ISO 5	unidirectional/mixed airflow
ISO 6	non-unidirectional/mixed airflow
ISO 7	non-unidirectional/mixed airflow
ISO 8	non-unidirectional/mixed airflow

Figure 2-18

2.5.4 PRESSURE DIFFERENTIAL

Pressure differential creates the integrity of a cleanroom environment. A cleanroom is in most cases positively pressurized concerning the other areas. Pressure differential secures that contamination cannot come less clean zones or from areas with no clean classification. [3]

The ISO 1644-4 Standard recommends pressure differential between adjacent cleanrooms or zones of different cleanliness levels in the range between 5Pa to 20Pa. It is recommended to have differential pressure 10Pa between two cleanrooms and 15Pa between a cleanroom and an uncertified space. This pressure differential allows doors to be opened and avoids unintended cross-flows due to turbulence. [3] [4]

2.6 CLEANROOM CONSTRUCTION AND MATERIALS

A cleanroom is a very complex piece of work. Every aspect, or a certain part in this kind of work has its recommendations and obligations.

With a cleanroom, the project designer meets obligations, which are there to help fulfil predetermined conditions or to reduce possible contamination. For example, from the construction point of view, it is recommended to have rounded corners. This recommendation is there to ensure that, in these spots will dust gather as least as possible. [3] [10]

The same idea as for construction goes for materials used in a cleanroom. Wisely used material will not only help in achieving elected cleanliness but can also reduce energy and overall costs. [3]

2.6.1 CONSTRUCTION RECOMMENDATIONS AND REQUIREMENTS

A cleanroom can be described also as a very stable and consistent area, where the conditions are remaining the same all the time. A designer should follow tips and must meet the requirements which are there to avoid any possible inconsistency.

Human is the main polluter. His movement and heat-producing disturb the airflow pattern. With this gain knowledge, workplaces and workstations should be placed into the cleanroom in such a way, which will minimize the needed movement of people working in it. A workplace should not be placed close to the entry and exit of a cleanroom. [3]

Cleanrooms with high cleanliness class are not situated to perimeter walls because of potential heat losses etc. [3]

Every entry and exit of materials or workers in normal usage should go through airlocks or gowning room. [3]

It is not possible to have open two or more doors of an airlock. To secure this requirement it is possible to use light or sound signalization or some form of blocking the door. [3] [4]

With glazing, it is recommended to use double glazing with an airtight seal. Glazing should be of the non-opening type. Blinds or shutters should be fitted outside of the clean zone or inside of double glazing. Glazing frames should be smooth. [3]

Doors should avoid many horizontal surfaces as possible. Doors should not have thresholds. [3]

Ceiling and its attachment should be sealed to avoid possible contamination from ceiling void or income of air bearing particles. Attention should be given to the position of components like sprinklers and lights which should not disturb the intended airflow. [3]

Walls should be resistant to impact and abrasion. Walls should not have any sharp edges and corners should be rounded which will lead to effective cleaning and non-accumulation of unwanted particles. [3]

The floor should be smooth, without porous, conductive it is needed, resistant against slipping, abrasion. The floor should be easy to clean and resistant to chemicals from those which are used in cleaning and disinfection products to fluids, which could be spilled during the manufacturing process. In hand could come special adhesive pads for removing unwanted particles from boots. [3]

In summary, it can be said that cleanroom from the construction point of view should accomplish these construction requirements: [3]

- Hermeticity
- no possibility of contamination from outside
- no sharp edges, niches which would be difficult to clean
- smooth, solid and durable surface
- resistance against humidity, mold
- stability to cleaning disinfection products or other

2.6.2 CHOOSING OF MATERIAL

With the gain knowledge about specialities and requirements in construction and design, it is time to look at materials, which can fit these requirements. [3]

The ISO 14644-4 Standard gives a list of typical surface materials: [3]

- For walls and ceiling:
  Sheets of stainless steel, anodized aluminium, polymer sheets or coating
- For floors:
  polymer coating or sheets, tiles with appropriate sealed joints

Still, it is not possible to say which material is the best and which material is the worst. A designer needs to take into consideration potential chemical, thermal and mechanical stresses that come during operation (production, cleaning, etc). Every cleanroom is special and needs an individual solution.

3 MOTIVATION AND AIM OF THE THESIS

The aim of this bachelor theses is to present the conceptional proposals of the cleanroom construction at IAE BUT. The cleanroom would bring new possibilities of research and development and raise the competitiveness of the Institute of Aerospace engineering.

The clean space shall be situated in a room 2.02 (of BUT building C3A). The proposals may include adjacent rooms 2.01 and 2.15. The utilization of the cleanroom should be for tests of aerospace parts and should include two worktables (1500x800x750) and one locker (750x400x1800). The cleanroom should be equipped with a computer and a vacuum chamber. One operator at least must able to fit into the cleanroom with respect for possible tests and experiments.

Based on the literature review and ISO 14644 the cleanroom for testing of aerospace parts should have the minimum classification of ISO 8. For ISO 8 class is acceptable to use non-unidirectional airflow with a velocity around 10-20 air changes per hour, where the air is cleaned by HEPA filters located before inlet vents. The pressure differential between the cleanroom and the gowning room is around 5 to 20 Pa. The temperature should stay at a fine level which is around 19 to 23°C.

4 THE PRACTICAL PART OF THE THESIS

The purpose of a practical part is to present different solutions for the problem of creating the cleanroom. The practical part contains the current status of a room 2.02 and 3 conceptional design of the cleanroom.

Each design is represented by CAD drawing, by the SOLIDWORKS 3D model and by simulations in ANSYS FLUENT. Models and drawings show the different approaches to every design. The airflow is the fundamental basis of every cleanroom and that is why it is displayed and examined in the ANSYS FLUENT simulations. For two of the designs, the temperature was simulated because of the possible influence of the sun heat.

4.1 CURRENT STATUS OF A ROOM 2.02

At the start, it is necessary to introduce the current status of space which should be transformed into the cleanroom. The placement of the room is already established in the previous part. Room 2.02 is to the student knowledge being used as a test room but the fact that it is not a standardized cleanroom is restrictive.

The length of the room 2.02 is 6.65 meters and the width is 3 meters. Room 2.15 is a small room that should become a gowning room for room 2.02. Room 2.01 is to the student knowledge only used as a storeroom.

The room height is 3.5 meters, but the room height is reduced to 3 meters thanks to the fake ceiling. In the ceiling are placed 3 squared swirl diffusers 600x24. In Figure 4-4 it is possible to see a vent that can be open by a handle situated next to the vent. This vent is the only air outlet of the room and it is assumed to work only on the pressure differential between room 2.02 and room 2.15.

The HVAC technical documentation says that the power from a single swirl diffuser is 400m^3/h. From the power, it is possible to calculate the value of velocity inlet for the ANSYS FLUENT Simulation, which is 4.5 m/s. The value of the pressure outlet is 15 Pa.

In figure 4-2 and the 3D model, it is possible to see outside windows. The sun heat potentially means a big problem for the stability of temperature in the cleanroom. In room 2.02 as displayed in figure 4-5 this problem solved with inside sunblind. But as it is known from the theoretical introduction the inside sunblind is not allowed in the cleanroom. And that is why the sunblind is not included in the 3D model and not in the simulation. The simulation should show how much can the sun heat affect the temperature and its stability in the room.

The function of the Solar system loading in ANSYS FLUENT can simulate the sun heat coming through the windows. For the inlets, the temperature is set to 20°C.

Mesh		
Patch conforming method	Body sizing - Element size	Mesh Statistics - Elements
Tetrahedrons	0,15 m	167094

Figure 4-1

Setup of	General	Models			Boundary conditions				
ANSYS	Gravity	Viscous model	Energy	Solar loading	type of inlet	Velocity magnitude	Temperature	type of outlet	Pressure difference
FLUENT	On	K-Epsilon	On	On	Velocity	4.5 m/s	20°C	Pressure	15 Pa

Figure 4-2

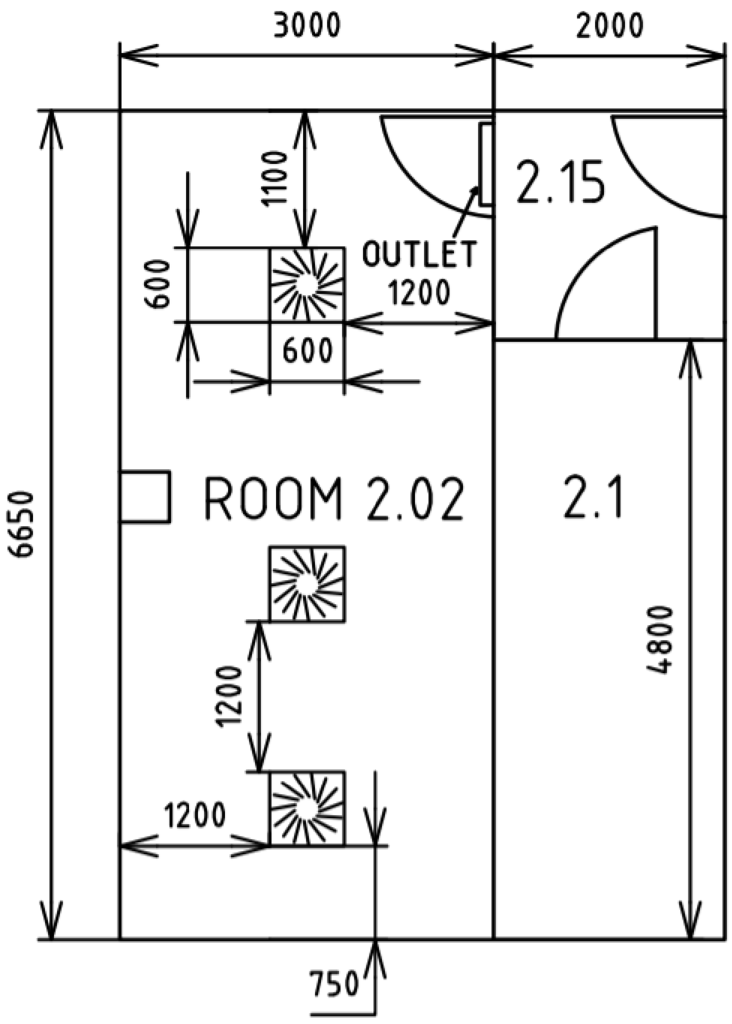

Figure 4-3

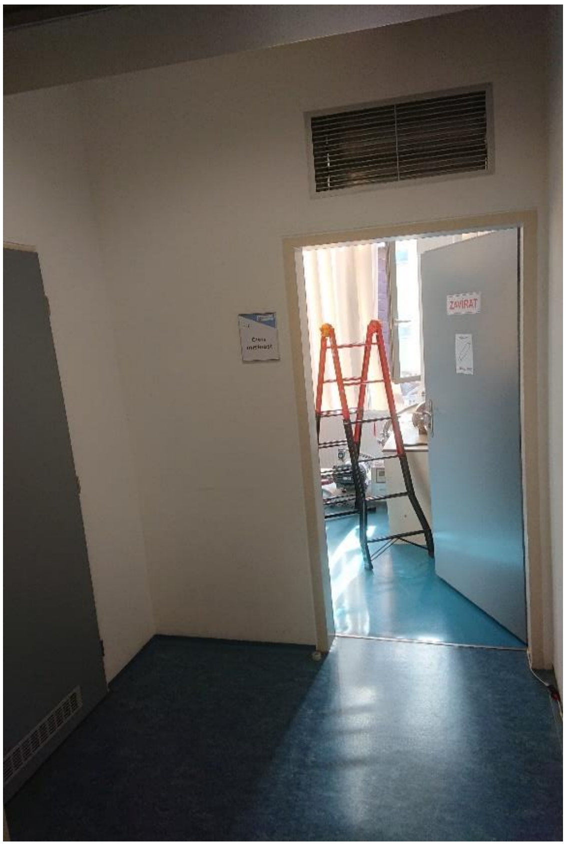

Figure 4-4

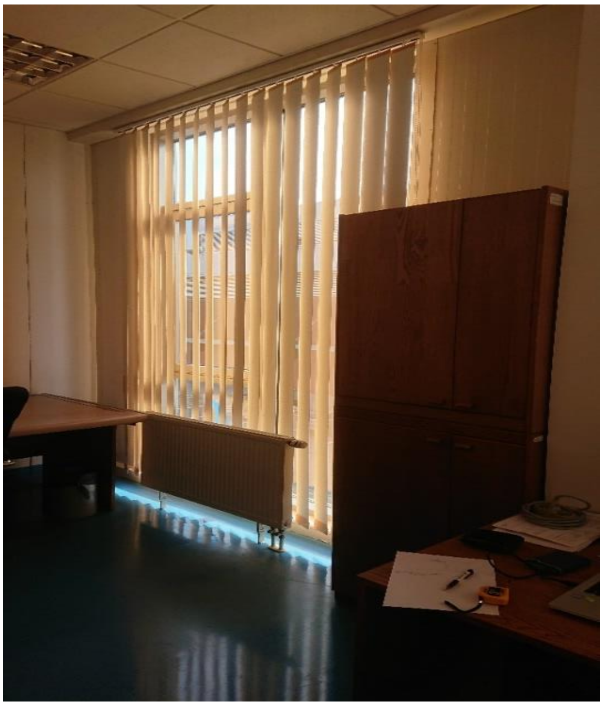

Figure 4-5

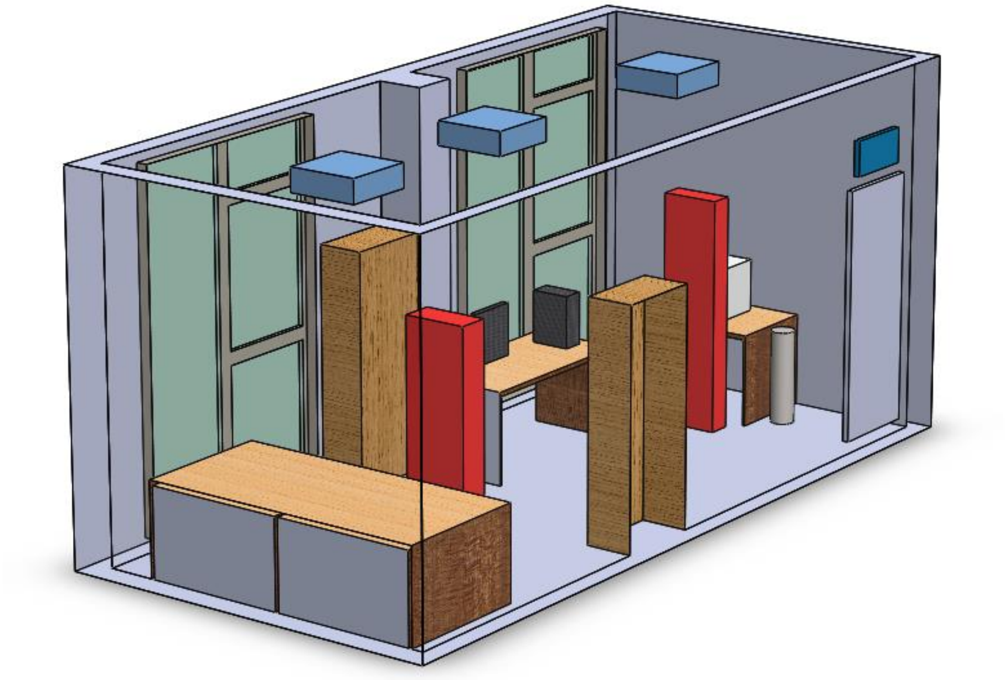

Figure 4-6

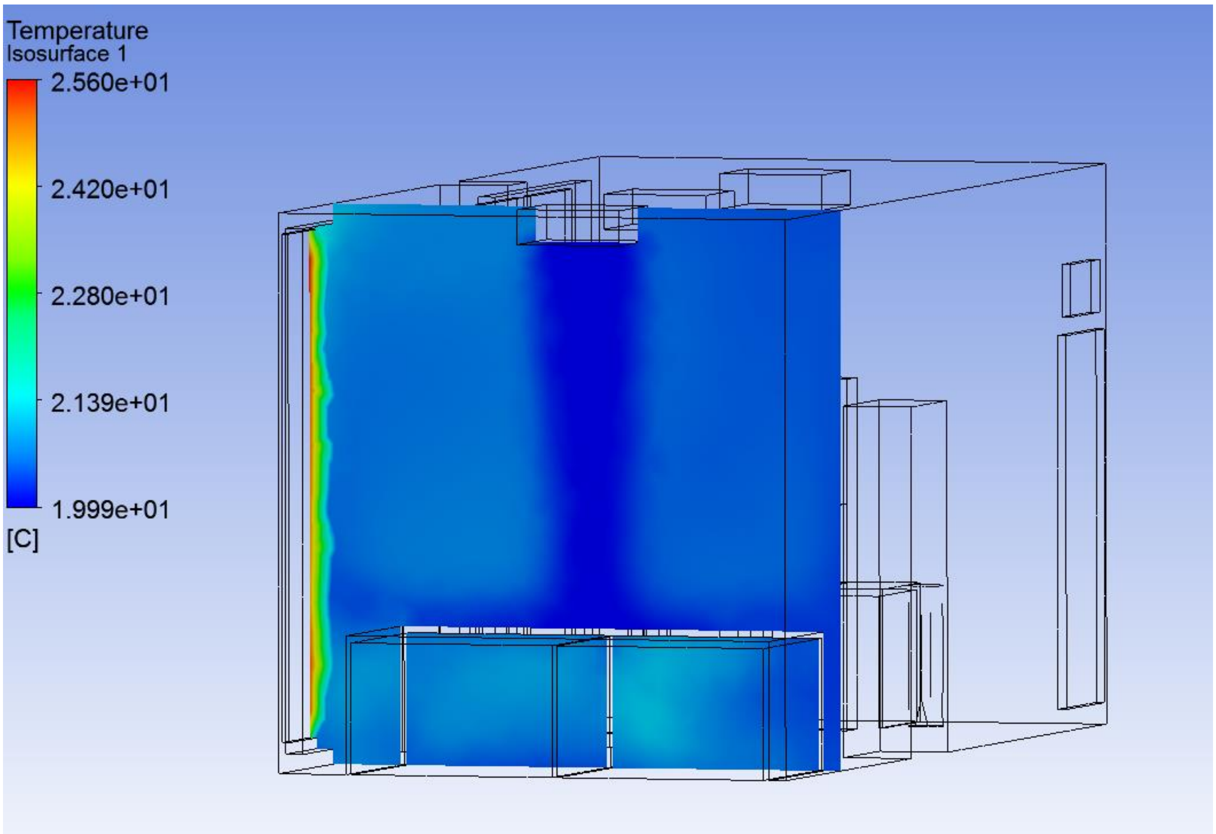

Figure 4-7

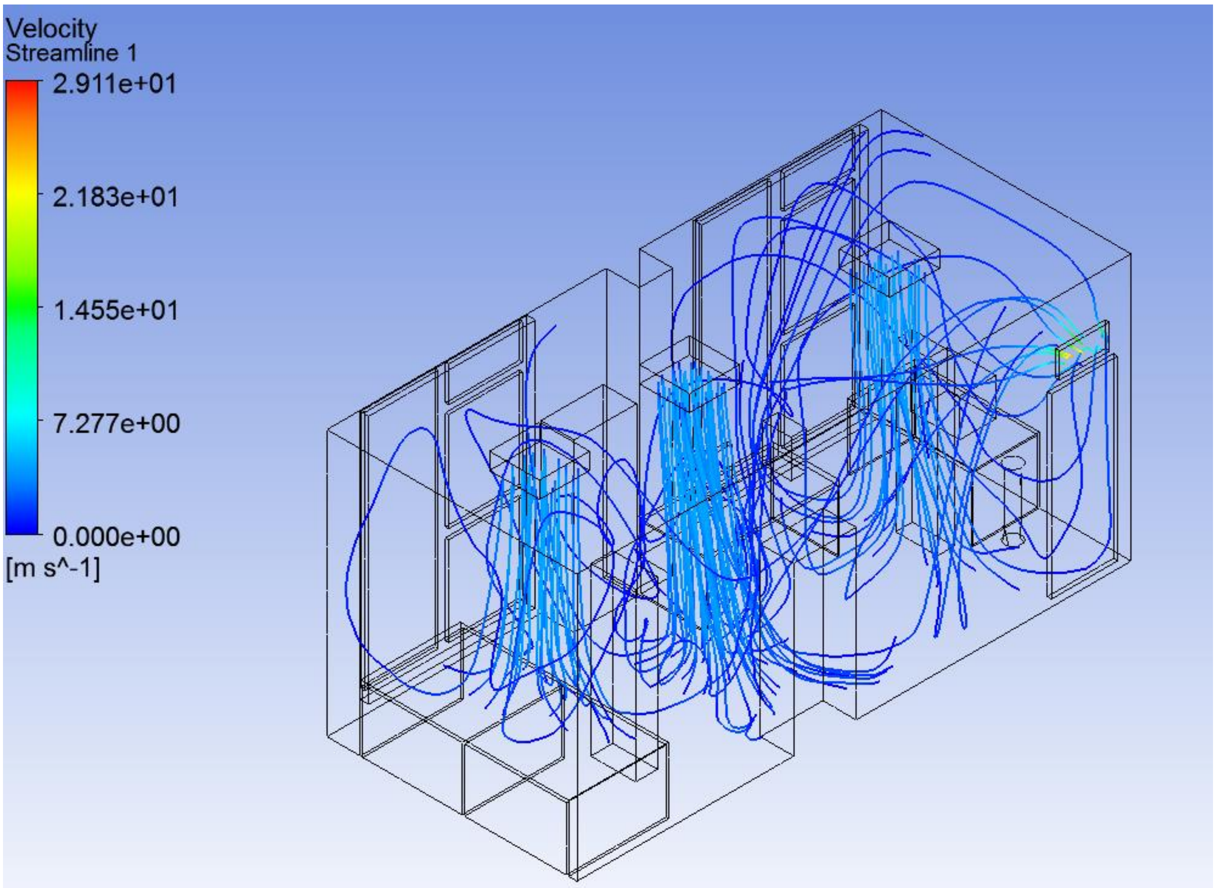

Figure 4-8

4.2 CONCEPTIONAL DESIGN 1 – THE CHEAPEST ONE

As the title hints, the intention behind this design was to create the cleanroom in the easiest way that is possible. That means minimal rebuild with the possible cost of worse ISO classification.

The cubic capacity of the first design stays the same as the cubic capacity of room 2.02. Room 2.1 and room 2.15 are united into the one bigger gowning room.

The position and the number of squared swirl diffusers stay the same as in room 2.02. The biggest and the main differences as it is possible to see in figure 4-12 are the 300x150 wall grilles that are placed at the downside of the 2 shorter walls. These wall grilles should enhance the airflow and ensure the ISO 8 classification from the air quality point of view.

The velocity inlet for the ANSYS Simulation is 4.5 m/s, which is the same as in room 2.02. The value of velocity is in harmony with requirements for an ISO 8 classification. The wall grilles are set as the pressure outlets with value 15 Pa for a better comparison of the results.

The problem of sun heat appears in this model too. As was mentioned earlier sunblind is not allowed inside of the cleanroom. The windows should not be openable.

The function of the Solar system loading in ANSYS FLUENT can simulate the sun heat coming through the windows. For the inlets, the temperature is set to 20°C.

Mesh		
Patch conforming method	Body sizing - Element size	Mesh Statistics - Elements
Tetrahedrons	0,15 m	167628

Figure 4-9

Setup of	General	Models			Boundary conditions				
ANSYS	Gravity	Viscous model	Energy	Solar loading	type of inlet	Velocity magnitude	Temperature	type of outlet	Pressure difference
FLUENT	On	K-Epsilon	On	On	Velocity	4.5 m/s	20°C	Pressure	15 Pa

Figure 4-10

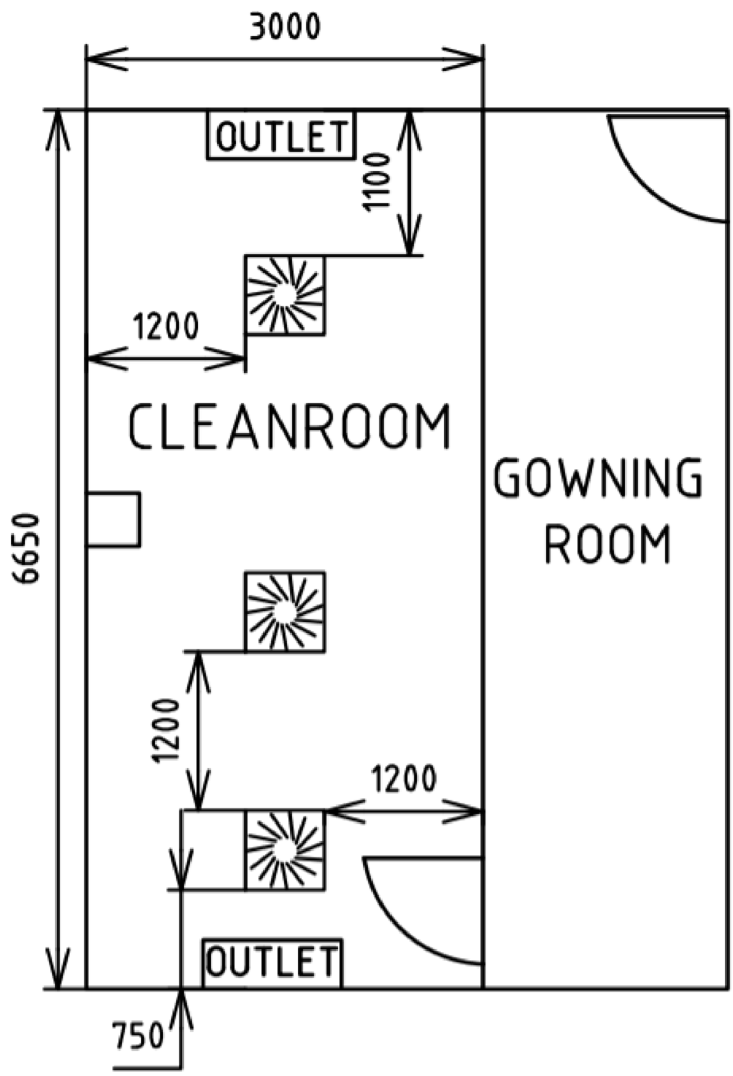

Figure 4-11

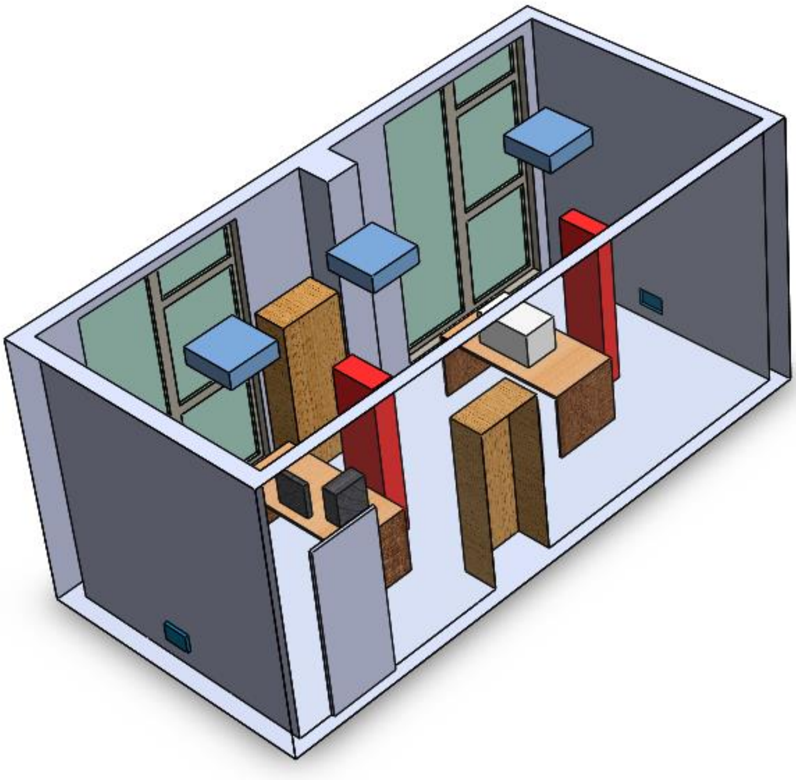

Figure 4-12

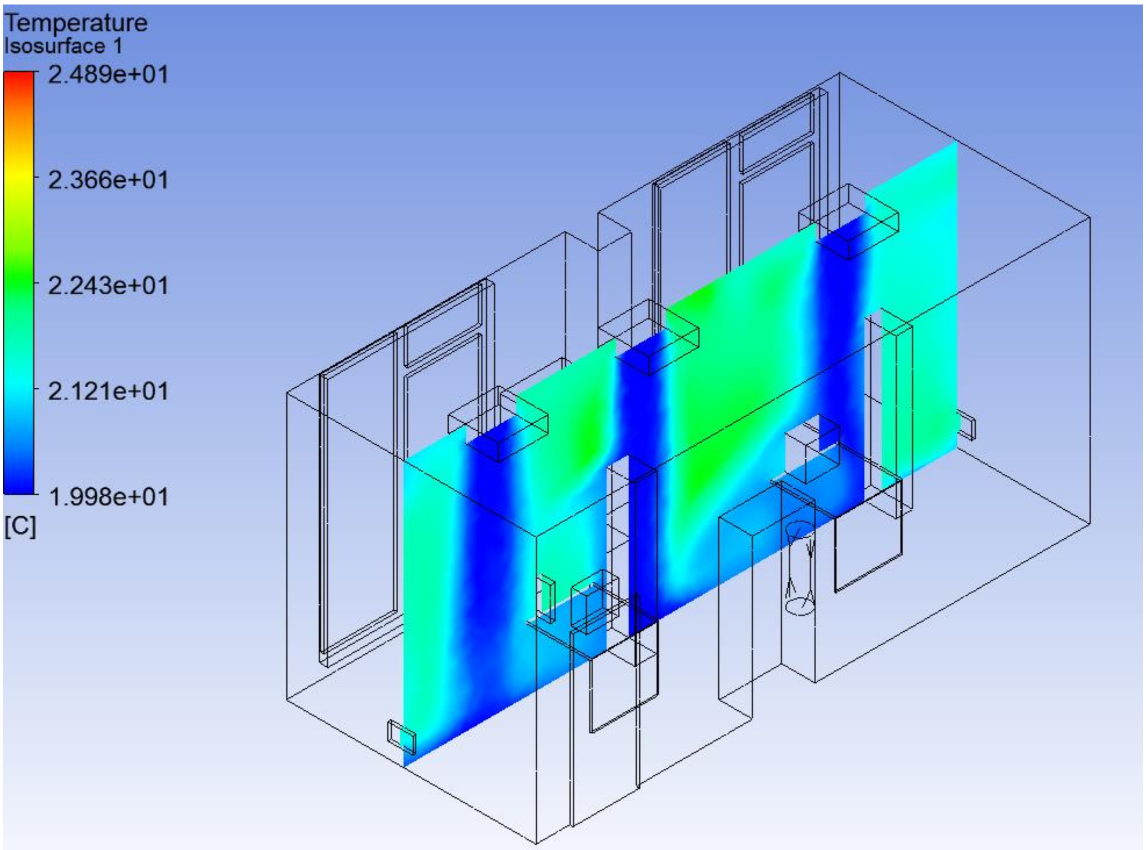

Figure 4-13

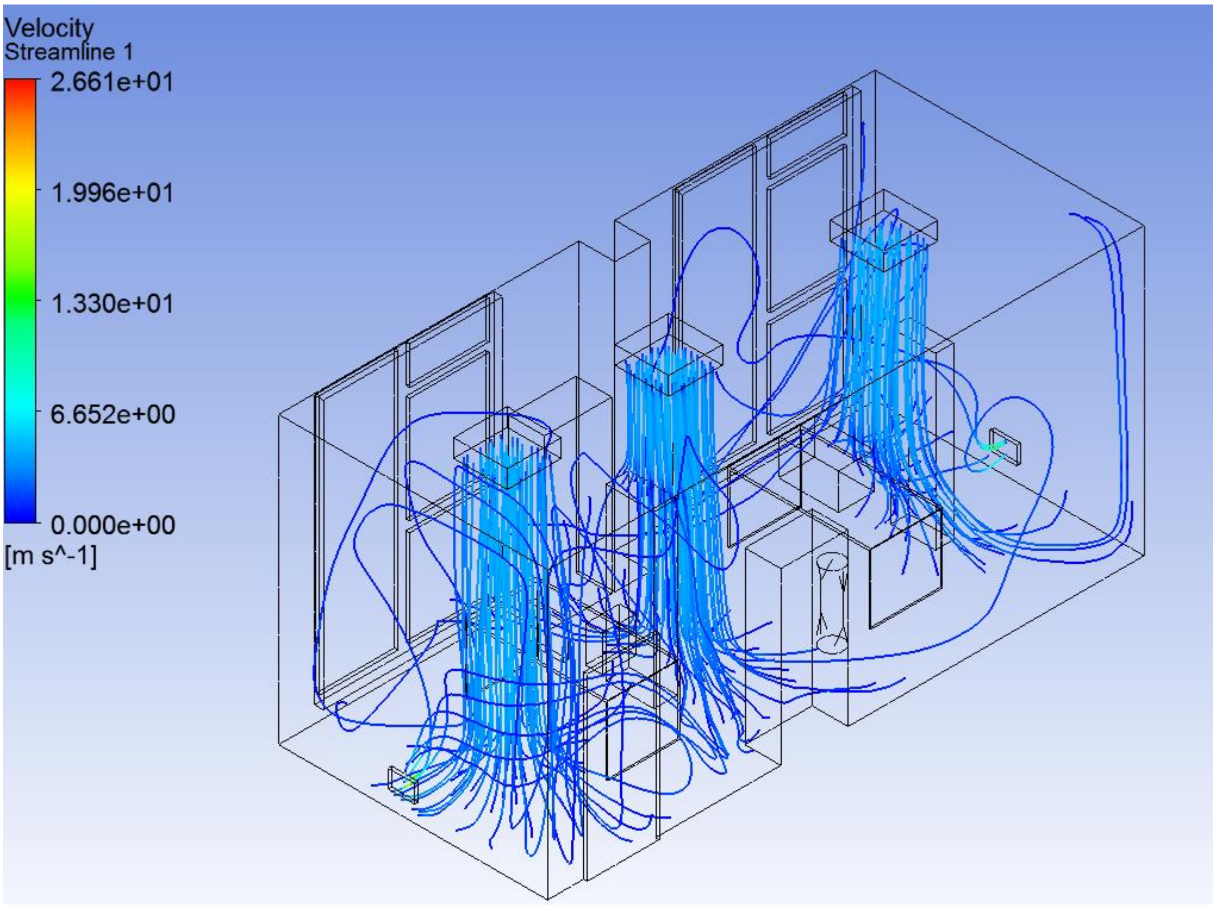

Figure 4-14

4.3 CONCEPTIONAL DESIGN 2 – THE CLEANEST ONE

For the second design came an idea of the cleanroom with as high ISO classification as possible and in which the conditions would not be affected by external factors (for example the sun heat in design 1).

As is possible to see in figure 4-17 this design presents a small cleanroom, which is practically inside of room 2.02. The length is 4.8 meters and the width is 1.8 meters. The remained space from room 2.02 should be used as the gowning room or possibly as a low ISO class cleanroom for establishing a high ISO class of the second cleanroom design.

The position of the air diffusers remains the same as in the first design. The number of air diffusers inside the cleanroom is reduced to 2. From the SOLIDWORKS model, it is possible to see that air diffusers are positioned directly over the tables. The wall grilles are placed at the downside of the right wall. This position should secure good air circulation and even possibly unidirectional airflow.

For the ANSYS FLUENT Simulation, the value of velocity inlet is 4.5 m/s. The wall grilles are set as the pressure outlets with value 15 Pa. These values secure possible comparison between the designs and it corresponds with the requirements for an ISO 8 classification.

The problem of the solar heat in this design is solved by the added wall. For an explanation, the 3D model does not include any windows because they are not relevant for the simulation, but of course, it is still possible to build unopenable windows into the walls. Windows are even recommended for minimalizing the movement into and inside the cleanroom.

The function of Solar system loading is not applied because of the absence of the solar heat. The temperature for the inlets is set to 20°C.

Mesh		
Patch conforming method	Body sizing - Element size	Mesh Statistics - Elements
Tetrahedrons	0,15 m	73326

Figure 4-15

Setup of	General	Models			Boundary conditions				
ANSYS	Gravity	Viscous model	Energy	Solar loading	type of inlet	Velocity magnitude	Temperature	type of outlet	Pressure difference
FLUENT	On	K-Epsilon	On	Off	Velocity	4.5 m/s	20°C	Pressure	15 Pa

Figure 4-16

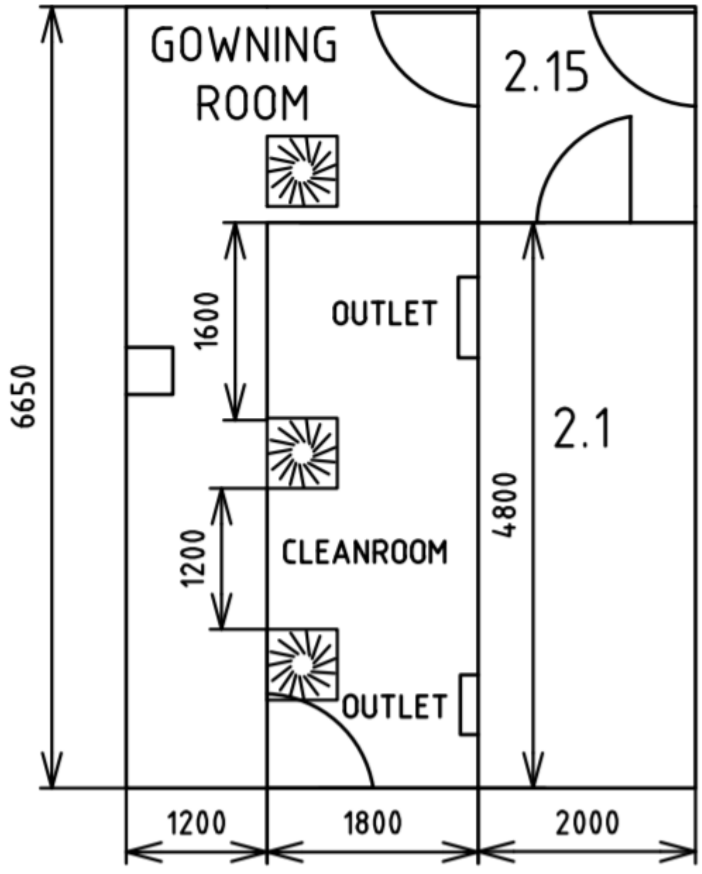

Figure 4-17

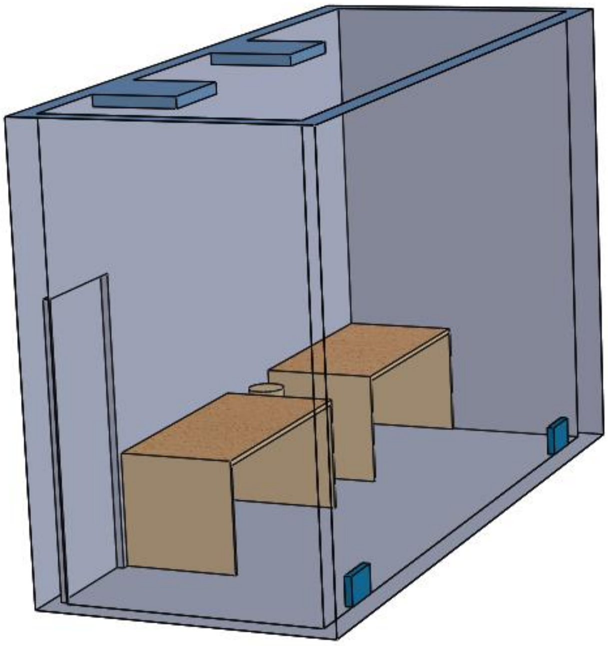

Figure 4-18

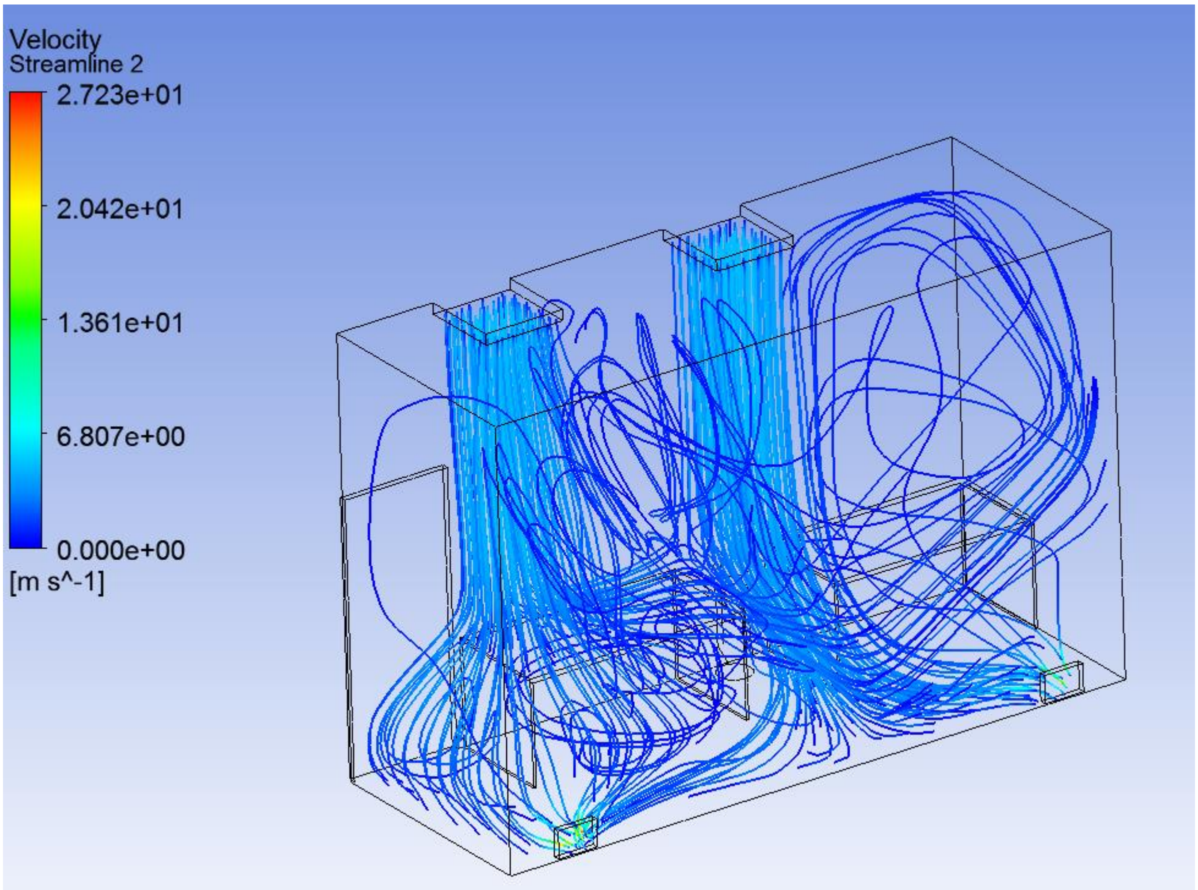

Figure 4-19

4.4 CONCEPTIONAL DESIGN 3 – THE BIGGEST ONE

The third design presents a cleanroom that can be constructed when there are no limits. As the title says, the cleanroom is the biggest one of the 3 designs and probably it would cost the most.

The cleanroom is created by connecting room 2.02 and room 2.01. The length is 4.8 meters and the width is 5 meters. As the gowning room is used the room 2.15 which is extended into the room 2.02.

The number of air diffusers in the cleanroom rise to 4. The air diffusers are in squared position for good air circulation and for securing of not creating independent air vortexes. In the cleanroom are placed 2 wall grilles opposite to each other.

For the ANSYS FLUENT Simulation, the value of velocity inlet is 4.5 m/s. The wall grilles are set as the pressure outlets with value 15 Pa. These values secure possible comparison between the designs and it corresponds with the requirements for an ISO 8 classification.

The problem of the solar heat is not included in this design. It is assumed that the problem is solved for example by outside sunblind or by erasing the windows. Each operation can be possibly very expensive but this design operates with perfect conditions and no budget limits.

The function of Solar system loading is not applied because of the absence of the solar heat. The temperature for the inlets is set to 20°C.

Mesh		
Patch conforming method	Body sizing - Element size	Mesh Statistics - Elements
Tetrahedrons	0,15 m	184340

Figure 4-20

Setup of ANSYS FLUENT	General	Models			Boundary conditions				
	Gravity	Viscous model	Energy	Solar loading	type of inlet	Velocity magnitude	Temperature	type of outlet	Pressure difference
	On	K-Epsilon	On	Off	Velocity	4.5 m/s	20°C	Pressure	15 Pa

Figure 4-21

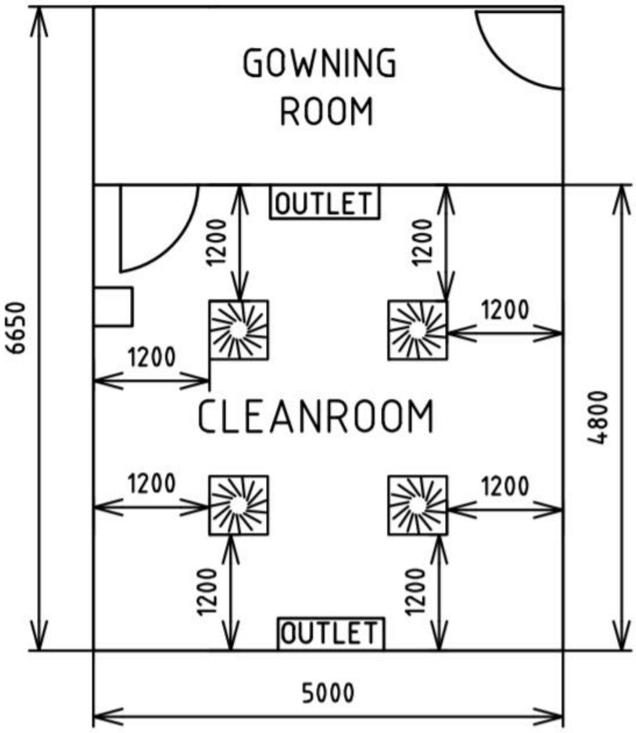

Figure 4-22

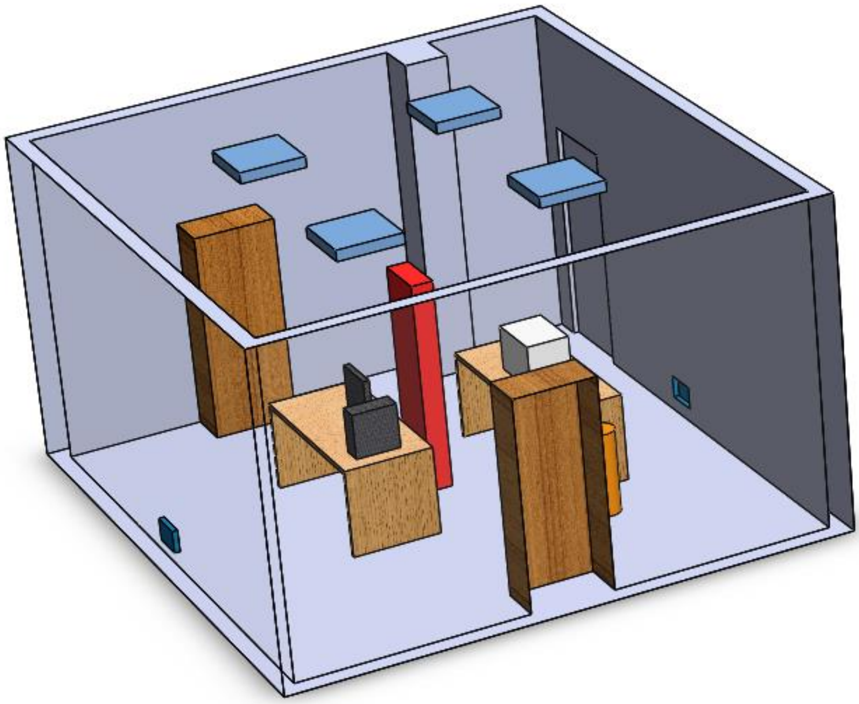

Figure 4-23

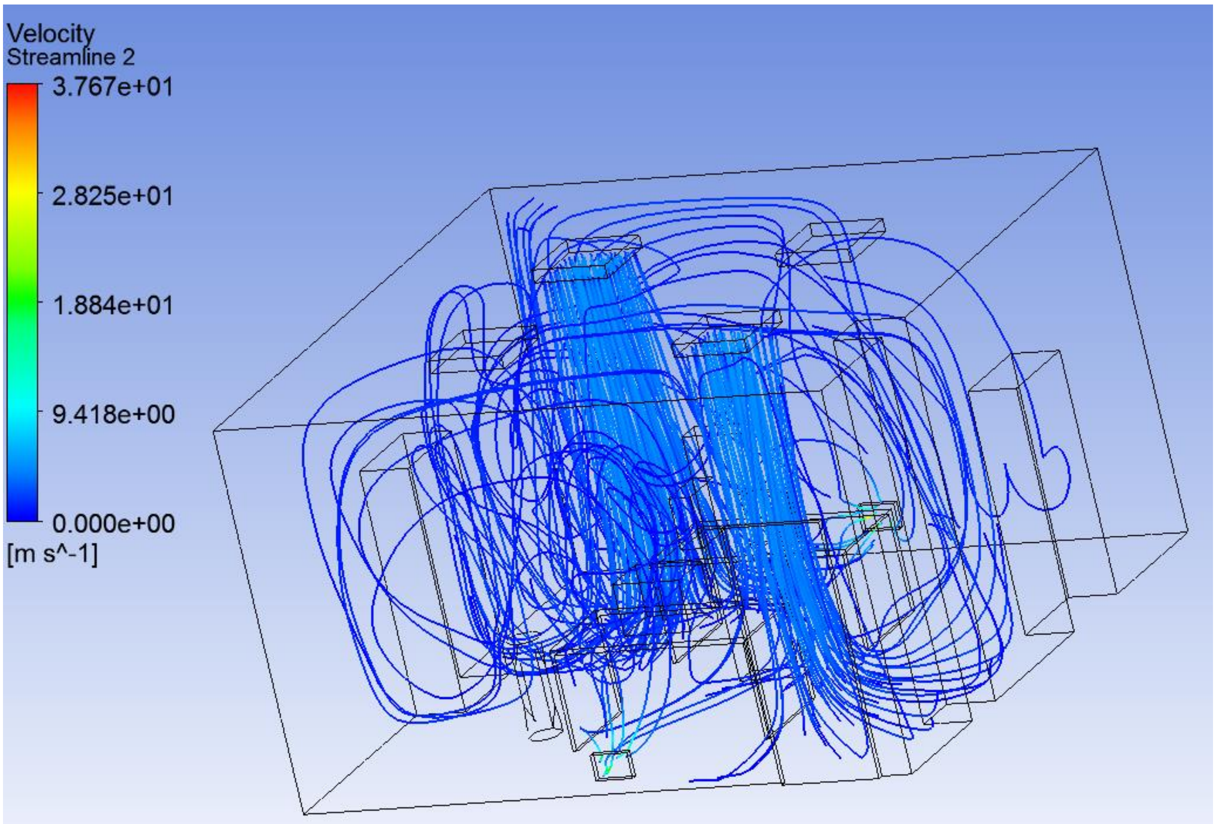

Figure 4-24

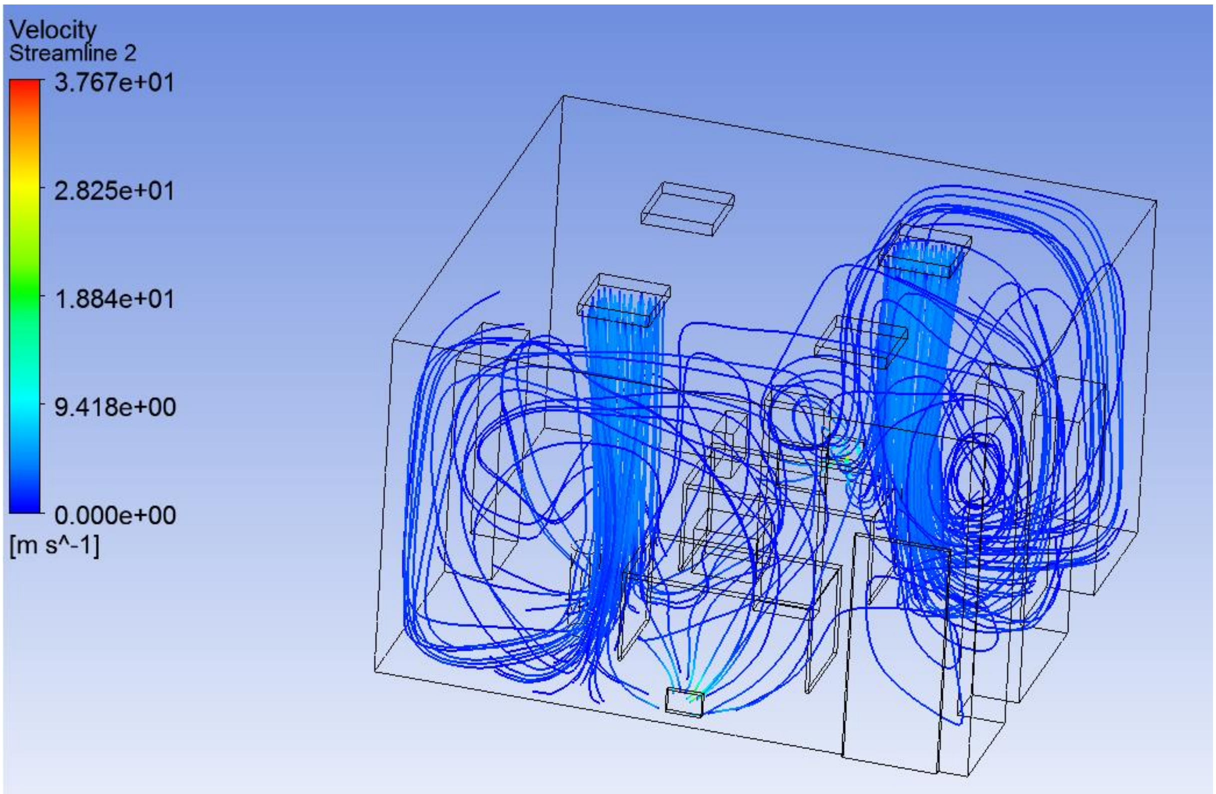

Figure 4-25

5 DISCUSSION

5.1 ANALYSIS OF THE AIRFLOW

As it was mentioned the airflow and the air changes are the primary aspect of every cleanroom. The air changes can be theoretically calculated from input parameters. Sufficient power does not equate with good airflow. That is why for every design was created a simulation in the ANSYS FLUENT.

The airflow in room 2.02 can be described as unsteady with the potential of creating uncontrolled vortexes. The air changes per hour would meet the requirement of ISO 8 classification, but vortexes are not allowed and are in a collision with what clean space means and that is a controlled environment. The position of the outlet stops the possibility of good and frequent recirculation of the air. From the airflow point of view, room 2.02 is not a cleanroom and it would not pass the ISO 8 classification.

Design 1 shows that the problem can be resolved with good placing and a sufficient number of outlets. The airflow goes through the whole cleanroom and it ends up in the outlets as it should. From the airflow point of view, this design should pass ISO 8 classification.

Design 2 is smaller and that is why the airflow is more impactful. The position of the tables is perfect because the airflow goes and cleans it right away. The small size of the cleanroom allows for quick air exchange in the cleanroom. This design would pass the ISO 8 classification with the potential of achieving the ISO 7 classification.

Design 3 presents a good airflow. The risen number of inlet vents leads to an increase in air changes per hour. The cubic capacity of design 3 is the biggest one. The airflow looks good enough for passing the ISO 8 classification.

Design 2 is the best from the air changes per hour and airflow point of view.

	Velocity inlet (m/s)	Number of inlets	Flow area of inlet (m^2)	Cubic capacity (m^3)	Power of inlet (m^3/h)	air changes per hour	Number of outlets	Airflow
Room 2.02	4,5	3	0,031	64	500	23	1	Not good
Design 1	4,5	3	0,031	64	500	23	2	Good
Design 2	4,5	2	0,031	27,5	500	36	2	Perfect
Design 3	4,5	4	0,031	77	500	26	2	Good

Figure 5-1

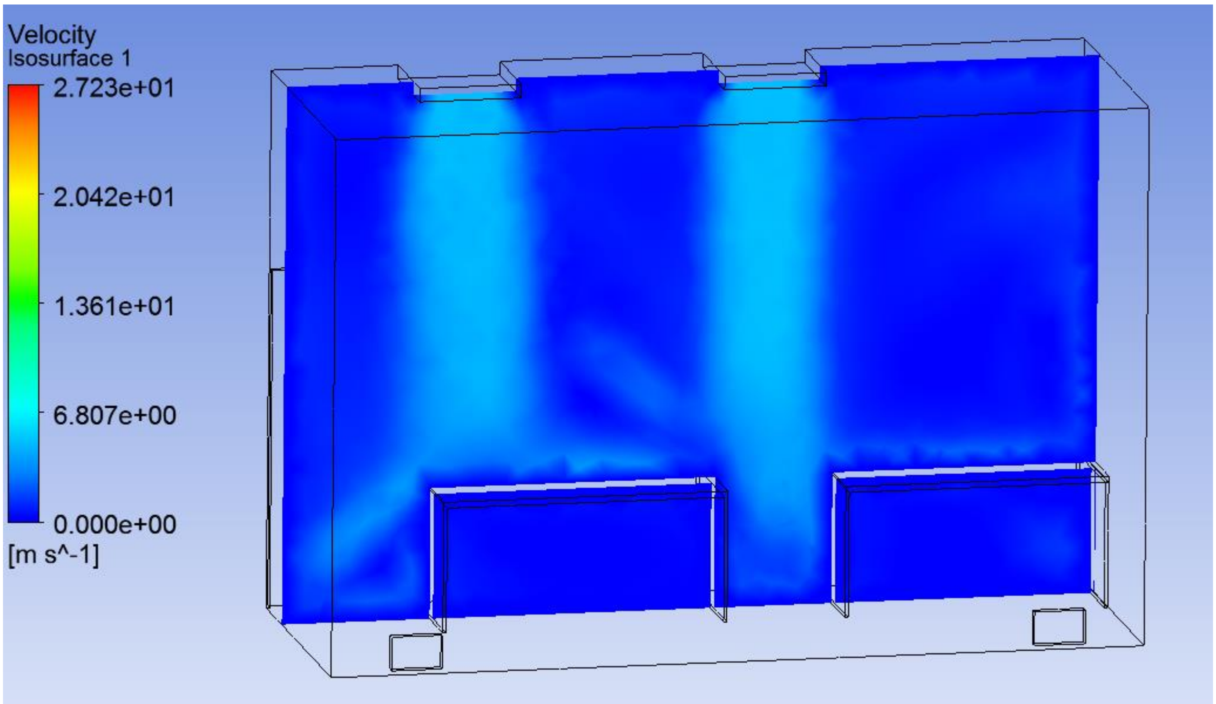

Figure 5-2

5.2 THE TEMPERATURE

With the look at room 2.02, it came to a question if the sun heat can make dramatic changes in the temperature of the clean space.

The instability of the temperature can be seen in the ANSYS FLUENT Simulations of room 2.02 and design 1. The sun heat is simulated with the function called Solar-Ray Tracing.

The simulations show some deflection of the temperature, but they are not great and the temperature in the room stays between the required 19°C to 23°C. It should be mentioned that the supplier of the HVAC System commits himself with the stability of the temperature. It was proven that the sun heat must be taken into account and it should not be overlooked in the future reconstruction of the cleanroom.

In the second and third design, the temperature does not change, because of the absence of outside windows. The temperature in the whole cleanroom stays the same as is the temperature of an ingoing air.

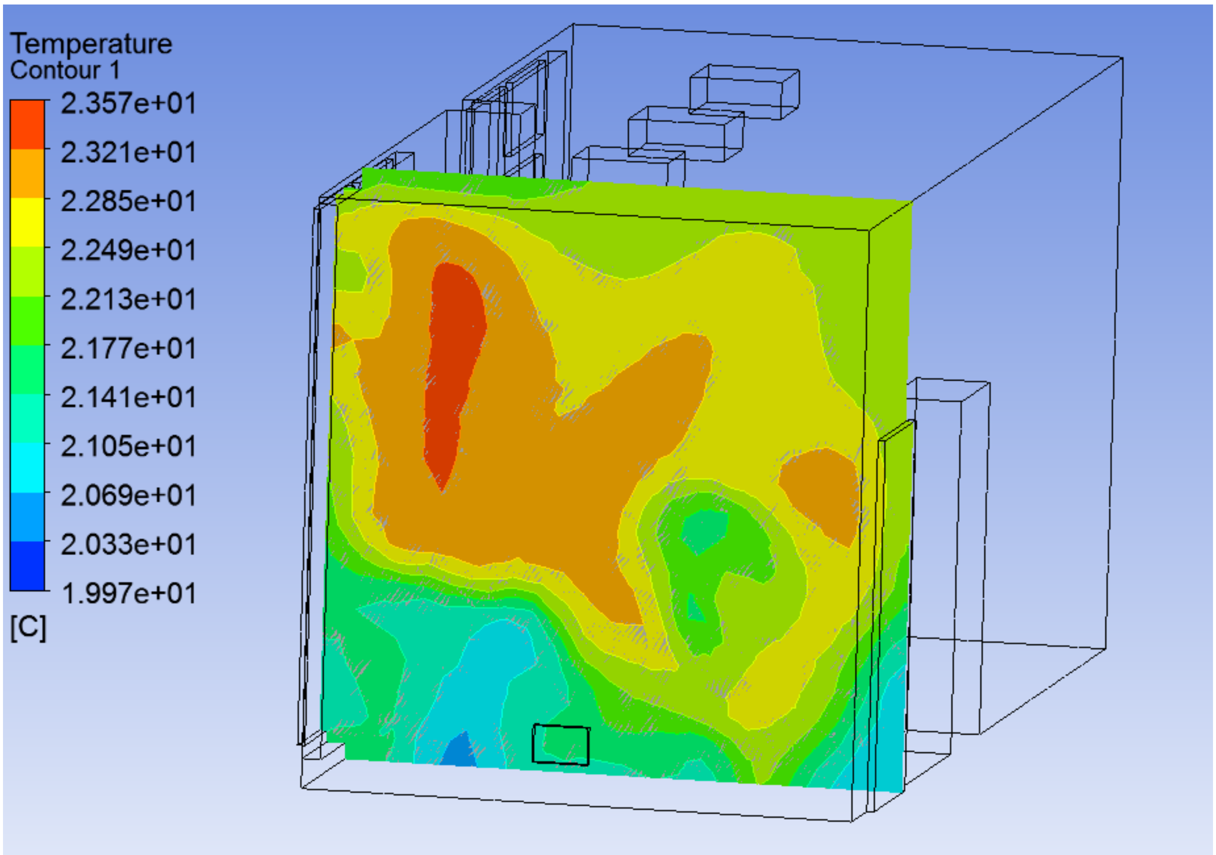

Figure 5-3

5.3 THE REALIZATION OF THE PROJECT

The realization of the cleanroom project must be in hand with the requirements of the ISO 14644 standards. For example, In Annex C of part 4 is written approval of an installation which recommended to be used as a guide for the future contracting authority. Values presented in this bachelor theses should be taken as a possibility of what can be achieved not as the final values. The values must be discussed with an expert around the HVAC System.

5.4 RESULTS

The practical part presented the current status of room 2.02 and 3 possible designs that deal with a problem of uncontrolled airflow. Room 2.02 can become a cleanroom but it needs improvements not only in the branch of the HVAC System. Every design has its pros and cons but from the airflow point of view, every single one should pass the required ISO 8 classification. For me, design 2 is the one that I most prefer because it can pass through higher classification and it does not deal with the sun heat problem.

6 CONCLUSION

The aim of this bachelor theses was fulfilled. The research part introduced cleanroom problematics, which is very complex. The research presents standards, where the ISO 14644 Standard can be taken as the most important and as the one which will be followed. The standard is composed of many parts where parts 1 and 4 are the most useful to the theses. The ISO 14644-1 discusses the problematics of air cleanliness and sets up the classification of a cleanroom. The ISO 14644-4 deals with the complexity and problems of designing the cleanroom.

Based on this research part the values for the practical part were established. The practical part presented the current status of room 2.02 and its possible rebuilds. As the aim was to present the conceptual proposals of the cleanroom, the question of verifying the classification has risen. And as the research part suggest the airflow is the critical part of every cleanroom. That is why the airflow is simulated in ANSYS FLUENT. The simulation showed that room 2.02 could not be described as a cleanroom because of the uncontrollable vortexes inside the room. The vortexes are the consequence of poor placement and the insufficient number of outlets. In terms of the airflow, room 2.02 would not pass the ISO 8 classification, even that the HVAC System is powerful enough to secure enough air changes per hour. The conceptual proposals were each one taken from another perspective but with the same aim of passing the ISO 8 classification. For that aim airflow was simulated in each design. Design 1 presents how much difference can the placement of outlets be. The base of design 1 as room 2.02 but the airflow looks more stable and controlled. Design 2 can be described as a typical example of less is sometimes more. Because of the smaller cubic capacity, the airflow could be unidirectional and the number of air changes per hour has risen, which could lead to higher ISO classification. Design 3 presents the maximum space possible, with that, comes a need for an extra number of inlets. From the perspective of an airflow, every design would pass through the requirements of the ISO 8 classification.

As an extra value or above requirements can be described the temperature simulation. From the research part, it is known that the cleanroom is a very stable space that concludes the temperature stability. And the temperature stability can be questioned in room 2.02 because of the windows which divide the outdoor and indoor environment. The instability can occur in the cleanroom even more because as the ISO 14644-4 says, the indoor sunblind is banned in a clean space. For the resolution of this problem, the temperature is simulated in ANSYS FLUENT by the radiation function of Solar-Ray Tracing. This function should simulate the solar radiation coming through the windows. This function was used in simulations connected with room 2.02 and design 1. This problem does not occur in design 2 and 3 because they do not include outside windows. The simulation shows that the inside temperature is a bit unstable but is within the allowable range.

The bachelor theses can be described as a very successful one. The theses presented not only one but three conceptional proposals of the cleanroom with the conclusion of accomplished work. On top of that, it hints into the problematics of temperature stability. My tip for next time would be to create the cleanroom in the ANSYS program and not in the SOLIDWORKS because from the little what I saw, the ANSYS brings more complexity into the inlet and outlet problematics. When it comes to temperature stability, I would probably suggest to find an expert on the ANSYS program or try another simulation program. There is not enough support and from what I have researched, the ANSYS mainly deals with problematics around the mechanical parts and to connect the task of airflow and temperature was very problematic.

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