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Learning Spaces for Engineering Education: Approaches and Design Guidelines

TESI DI LAUREA MAGISTRALE IN
MANAGEMENT ENGINEERING – INGERNERIA GESTIONALE

Author: **Haya Mahmoud**

Student ID: 10694512
Advisor: Monica Rossi
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Abstract

With the advancements of technology and the increasing demand of specialized competences from students and engineering graduates, the topic of Learning Spaces (LS) for Engineering Education (EE) has been raised a lot, to prepare engineering students for working life and universities to respond to the changing industrial environment. It's not clear what the relationship between the physical place, student's perception of learning and how a teacher carries the teaching processes. The paper intends to fill the gap between learning activities in higher education and the learning environment itself. First, the thesis offers a snapshot of the current educational spaces; Learning Factories (LF), Makerspaces (MS), Hackerspaces (HS) and Fablabs (FL) in terms of physical Architectural Design (AD) from origin to identify emergence of design guidelines if any, as well as the pedagogical approaches (PA) practiced within these spaces. Second, the thesis sweeps the literature for design aspects and success criteria for LS design to find best practices. Third, the paper makes passes over the dimensions: drawing together research from LS, PA and AD to identify connections and gaps through a systematic literature review (SLR). Fourth, a visual Learning Space Analysis (LSA) of entities and institutions that directly attempt to model their LS is done by setting some research recommendations with the aim to find structural commonalities between the categories and across. The paper conceptualizes a LS as a product and attempts to adapt Product Development Process (PDP) to a LS to construct a preliminary Learning Space Design Guidelines (LSDG).

Keywords: higher education, engineering education, pedagogy, learning spaces, space design.

Sintesi

Con i progressi della tecnologia e la crescente richiesta di competenze specialistiche da parte di studenti e laureati in ingegneria, il tema degli Spazi di Apprendimento (LS) per la Formazione in Ingegneria (EE) è stato sollevato molto, per capire come gli studenti di ingegneria si stanno preparando alla vita lavorativa e come le università stanno rispondendo al cambiamento dell'ambiente industriale. La relazione tra il luogo fisico e la percezione dell'apprendimento da parte dello studente e il modo in cui un insegnante trasporta i proventi dell'insegnamento non è una preoccupazione primaria anche se l'idea di un campus è cambiata in gran parte. Il documento intende colmare il divario tra le attività di apprendimento nell'istruzione superiore e l'ambiente di apprendimento. In primo luogo, la tesi offre un'istantanea degli spazi educativi attuali; Learning Factories (LF), Makerspaces (MS), Hackerspaces (HS) e Fablabs (FL) in termini di progettazione architettonica fisica (AD) dall'origine per identificare l'emergere di eventuali linee guida di progettazione, nonché gli approcci pedagogici (PA) praticati all'interno di questi spazi. In secondo luogo, la tesi esamina la letteratura per aspetti e criteri di successo per la progettazione LS per trovare le migliori pratiche. In terzo luogo, il documento supera le dimensioni: riunendo la ricerca di LS, PA e AD per identificare connessioni e lacune attraverso una revisione sistematica della letteratura (SLR). In quarto luogo, un'analisi visiva di entità e istituzioni che tentano direttamente di modellare il loro LS viene eseguita impostando alcune raccomandazioni di ricerca con l'obiettivo di trovare comunanze strutturali tra le categorie e trasversalmente. Il documento si conclude con una linea guida di progettazione configurabile per lo specifico spazio di apprendimento.

Parole chiave: istruzione superiore, istruzione ingegneristica, pedagogia, spazi di apprendimento, progettazione dello spazio.

Contents

Executive Summary

The paper's context touches the context of **Learning Spaces** (LS) for **Engineering Education** (EE) in the theoretical streams of **Pedagogical approaches** (PA) and application of **Architectural Design** (AD). It analyses the different spaces and PAs being applied within them apparent in publications, then it explores these spaces from their design aspects to demonstrate best practices. The main methodology used is a **Systematic Literature Review** (SLR). The paper chooses the EE and LS context due to the advancements of technology and the increasing demand of specialized competences from engineering graduates and students. Raising the topic of EE immediately raises many questions: How are engineering students being prepared for working life? How are universities responding to the changing industrial environment? What skills are most in demand? What opportunities do collaborations with universities hold for businesses and manufacturing firms? How are LSs adjusting to these needs? These needs push industries to reach out to universities for collaborations and exchange of knowledge and expertise.

The paper fills the gap in two phases: First, systematically evaluating the literature to explore the interplay between LSs in higher education, the **PA** employed in these spaces and their **physical design aspects**. 182 papers have been analysed and a conceptual framework encompassing the typologies of LS, pedagogical practices, and architectural layout. Second, A snapshot of the current education spaces in terms of design and physical layouts, where the aim is to find structural commonalities between the categories and across.

The paper will be structured as follows: the second section explains the different LSs at universities in present day, their historical development and emergence of **design guidelines** if any, the different **PAs** within **EE** and best practices for designing educational spaces by capturing some work of entities and institutions that directly attempt to model their LSs. The third section explains the research methodology which is a thorough SLR that passes over the three dimensions explained above which are: EE, PA, and AD, drawing together conclusions from publications and different sources. The fourth section displays the results of the SLR to identify connections and gaps. The fifth section utilizes a visual (LSA) to select spaces applying the previously mentioned best practices and the selected success criteria. Finally, the paper models the PDP approach for products to LS to produce LSDG.

1 Introduction

With the increasing demands of the market, a call for a high level of expertise is pushing universities to develop competences that extend beyond the walls of lecture halls, practical exams and even theoretical case studies (Nelson, 2021). Universities are shaping and reshaping their educational modules and curricula internally through innovation in novel teaching methodologies and **PAs**, and externally through collaborations with small scale and medium enterprises (SMEs), start-ups and other institutions to bring as much as possible from the post-graduate life into the university experience (Fourtané, 2022). For the engineering department, the challenges of the twenty-first century are particularly more difficult, with the rise of the fifth industrial revolution (European Commission, 2021), one of its main pillars include up-skilling and re-skilling workers within a European Skills Agenda. This revolution goes beyond producing goods and services in a profit-centric model, it complements the combination of internet and technologies that are emerging by leveraging sustainability, resilience, and human-centric design. This agenda highlights the importance of having the right skills for jobs by supporting vocational education and training (VET), the European universities initiative and upskilling scientists, increasing the number of sciences, technology, engineering, and math (STEM) graduates and fostering entrepreneurial skills (European Commission, 2021). Following this agenda, universities are constantly developing their educational landscape in flagship initiatives (European Commission, 2021) lead by the European council that concluded in May 2021. Some would say an EE 5.0 is tangent to I5.0 (Díaz Lantada, 2020). European universities are considered as transnational alliances amongst them that offer curricula that are student-centered and approaches that are challenge-based on which students, academics and external partners cooperate to tackle issues faced by Europe. In this context, universities need not only rethink EE but also the required outputs of the entirety of university experiences, where skills must prevail degrees (Gürdür Broo et al., 2022). EE cannot be considered as a holistic concept of theories and practices, but one must regard the envelop in which it takes place. Advances in **PA** lead to better outcomes and quality results. However, the effect of the LS on the outcome in terms of design and design aspects remains crucial and overlooked. This is where the contribution of this paper sets in, by studying the current practices and proposing solutions and approaches for LS design and development.

Figure 1, Industry 5.0 pillars, source: (European Commission, 2021)

1.1. The first dimension: The Space

This chapter discusses LS for EE. To clarify terms at the outset, LS indicate the physical places such as classrooms, workshops, laboratories, or libraries that constitute a university campus (Marmot, 2006). But this definition is rather traditional and doesn't include internet educational platforms, workplaces and most recently hybrid formats of learning (Salinas-Navarro et al., 2019). This chapter lays out the context of the LS in which the study further investigates. In the recent years, more concrete and spaces have emerged from different fields and for different motives around the world. However, all of them have the common objective of increasing competences within the frameworks of EE and STEM Education. The origin, development and historical steps of these spaces are explained to track the emergence of design guidelines for the physical AD of these spaces.

1.1.1. Learning Factories

A widely accepted definition established by (Lamancusa et al., 1997) is "... a facility that supports product realization within a new practice based, engineering curriculum." The definition implies a dynamic **participatory experience** of process and product realization. It explains the integration of industrial production environment and learning environments. In this context, real industrial problems are transmitted into dedicated classrooms, the overall objective remains **problem-based learning** and **experimental experiences**. While the different factors that enable LFs may vary; scope, implementation, size, location, and governance are still fundamental. Furthermore, LFs are not duplicates of industrial factories but are designed to serve best and suit the intended experiential learning processes (Jorgensen et al., 1995). To date, there are 14 LFs listed in the directory (International Association of Learning Factories, 2022b).

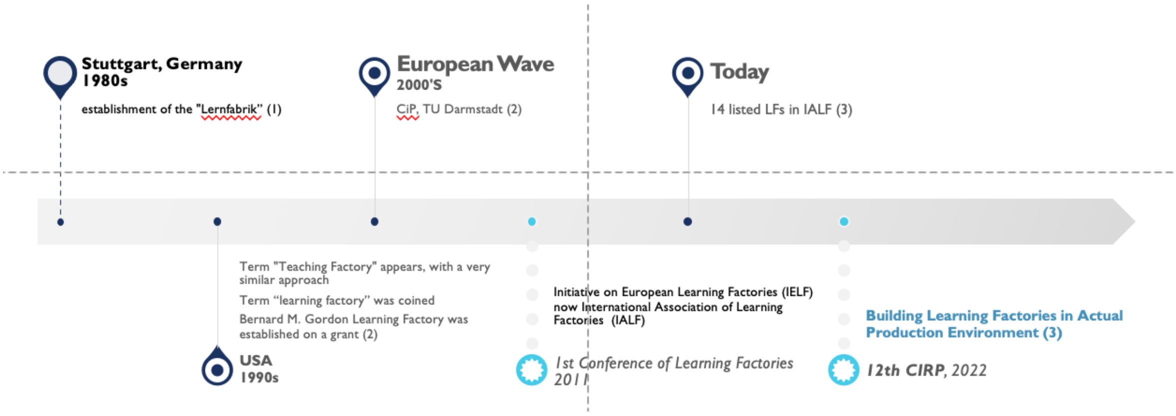

Figure 2. LFs historical development

Examining the emergence and historical development of LFs allows to see if any design guidelines were laid down during their creation. The concept originated in Germany with the term Lernfabrik in the 1980s (Abele, Metternich, & Tisch, 2019). A similar concept originated in the US named "Teaching Factory" that had a similar approach but in the field of medicine. Nowadays, the two terms are used interchangeably by defining the context. Later, the term was coined to pave the way for the initiative on European Learning Factories (IELF). It was renamed the International Association of Learning Factories (IALF) (International Association of Learning Factories, 2022). This association held a Conference on Learning Factories (CLF) yearly with a list of topics to submit papers on. A review of the topics of each year's conference was made. These topics can be used as an indicator of the general trends and maturity level of LFs as a LS. A scan of the topics of the CLF over the last 12 conferences shows a dominance of lean and manufacturing related topics across the years. For the sake of the dimensions being investigated for this paper, only the years with papers related to EE, PA and/or design aspects were listed. Table 1 shows a quick review of these topics and their relation to the dimensions understudy:

No.	Year	Conference, Location	Topics related to Education OR learning OR Design
1st	2011	Darmstadt, Germany	Learning and competency-building as a competitive factor, Leaders as teachers.
5th	2015	Bochum, Germany	New learning factory concepts
6th	2016	Gjøvik, Norway	Research based innovation and learning.
8th	2018	Patras, Greece	Advanced Engineering Education.
9th	2019	Braunschweig, Germany	Learning approaches and evaluation.
10th	2020	Online-Conference (organized by TU Graz)	Interdisciplinary education in learning factories.
12th	2022	Fusionololis 2, Singapore	Building Learning Factories in Actual Production Environment

Table 1, Cross referencing CLF topics with research dimensions

From the table, the learning dimension holds a strong hold on the objectives and goals of these conference from the direction of the conferences. The third dimension, which is design, isn't taken into consideration until 2022. The proposed topic "Building LFs in Actual

Production Environments" indicates a general direction to start integrating LFs in an existing environment.

1.1.2. Hackerspaces

The origin of the hackerspace network starts with an encounter between Euro-American hackers at a summer camp and the publication of the "hackerspace design patterns" which is a blueprint for new computer clubs, delivered by German hackerspace members at the influential Chaos Communication Congress (CCC) gathering in 2007. The concept originated in Germany (1990) under the Chaos Computer Club (CCC, 2022) recognized as the most influential hacker collective in Europe. The idea travelled to the US as the HS movement with a prototype in DC to seed community involvement, fostering local programmers and showing a different face for hackers whose name originated with association to a negative notion (Borland, 2007). There are 2442 hackerspaces listed, 887 active and 369 planned worldwide (*HackerspaceWiki*, 2022). The term indicates spaces within the community were programmers -also referred to as hackers- can meet to share ideas and infrastructure within the computer field in a physical space (*HackerspaceWiki*, 2021). These spaces contain projects with technical aspects and challenges presented which are accompanied by an exchange of knowledge. The literature emphasizes the important role of hackerspaces and hardware start-ups in experimenting with novel manufacturing and entrepreneurship models, which results in a wide variety of increasing knowledge levels in the field of manufacturing modelling across genres and disciplines (Jones et al., 2014). Halskov et al. (2012) examines the ramifications of hacking for academics, as well as how the DIY movement may influence civic involvement and educational change. The word Hackademia refers to a framework that uses a participant-observer research paradigm and participatory research methodologies to provide a semi-structured educational experience applied within HS (Halskov et al., 2012).

A guide to HS design was published with distinct patters ranging from infrastructure or sustainability to communication within the members and the importance of collaborations to establish governance, and location selection (Jens & Pylon, 2007). The guide explores some minor aspects of physical spatial dimension such as the presence of a strong infrastructure such as services and having experienced personnel in building structures for renovations or newly constructed spaces, presence of smaller separate rooms for meetings, a kitchen, sofas, comfortable chairs, sound system experience, a projector, gaming consoles, bathroom with a shower, and a washing machine for guests. These features might seem basic; however, they echo the communal aspect of these spaces that is often overlooked. Eric Michaud -the cofounder of the previously mentioned prototype- outlines 7 steps to start a HS successfully (Eric Michaud, 2012). He approaches HS as a **design-for-needs** with the hackers that populate the space as main stakeholders. They could be computer hackers, hardware, food, metalwork etc. Next a detailed list of needs is set; power source running water, ventilation, concrete floor, natural light, darkroom for photography, AC room for servers, physical work hack area, soundproof room. Next, the geographical location is determined based on accessibility, presence of safe car parks. After selection, an open vote democratic approach is taken for renovations from painting to installations.

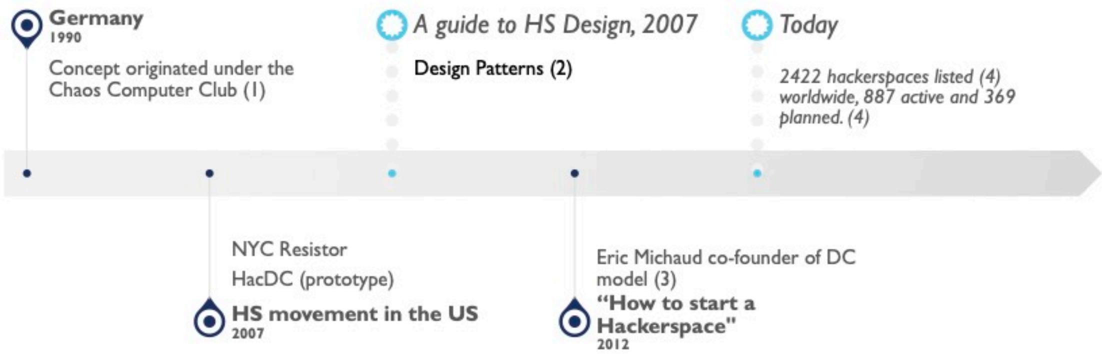

Figure 3, HS historical development

1.1.3. Makerspaces

The ***MAKE:*** magazine's (Make: Community LLC, 2005) first issue was published in February that generated the term 'makerspace' which became popular in 2011 with the registry of makerspace.com by Dale Doughtry -founder and CEO of Maker Media, Inc.- (Make: magazine, 2022) that catalyzed the MAKE movement. Many different definitions were used for MS, each entity chooses the terminology that best describes their activities. The definition -set by the registry state- is 'MS were described as publicly accessible spaces inside an education-related facility (school, library, university, etc.) that allows collaborative making, learning, exploring, and sharing in electronics, 3D printing and modelling, coding, robotics and woodworking' (makerspaces.com, 2022). According to the definition, the space is independent of the complexity of tools or materials used and is strictly process or output oriented. In terms of design, there are even some advice to create MSs at home, indicating a wide informality. However, the educational purposes seem to intertwine with STEM (Calito, 2019). The added values are **crafting**, **hands on learning**, helping with **critical thinking** and self-confidence.

The listed tools include but are not limited to; 3D printers, laser cutters, CNC machines, soldering irons and even sewing machines. In terms of design, A survey of 13 different MSs listed the most dominant tools, they were: 3D printers, laser cutters, mechatronics, CNC mills, vinyl cutters, sewing machines, lathe, welding, foundry, wood-working stations, 3D scanners and printer devices (Jensen et al., 2016). Many found examples were related to school and libraries with a focus on MSs for children in elementary schools and universities (Davis, 2018). There are no clear guidelines in terms of design for MSs but some recommendations to have high-voltage electricity and well-ventilated areas inherent of the tools used.

Figure 4, MS historical development

1.1.4. Fablabs

FLs originated as an educational outreach of the Centre for Bits and Atoms (CBA) at MIT (MIT's Center for Bits and Atoms, 2022), which is an interdisciplinary project that examines where computer science and physical science meet. CBA investigates methods to transform both data and objects. It oversees students, operates buildings, conducts research, collaborates with sponsors, launches start-ups, and engages with the public. FLs aim at serving and powering an under-served community through a platform of learning through project-based (fabfoundation, 2022b), hands-on STEM educational experiences and innovation. To date, there are over 2000 labs, in 120 countries associated with 860 academy alumni in the past 10 years.

These spaces have specific qualities that they need to comply to in order to qualify as a FL which are: public access, subscribing to the Fab Charter (fabfoundation, 2022c), participating in the network. acquisition of a common set of tools (fabfoundation, 2022a) found on a publicly available data base and process with the collective network of FLs and data sharing facilities to be able to recreate across the network. The Fab Foundation offers a complete set up of a new lab, in terms of purchasing and installing infrastructure and equipment, training managers in association with partners. In terms of design -from the outset- there are specific plans for the "ideal" lab layout. The Chicago Fab Lab at the Museum of Science and Industry (MSI) that is explained in the examples in section 4.2.1 is considered a flagship project. The layout of the different spaces for molding, laser cutting, and electronics are explained in detail; the placement and sizing of machines, working tables, monitors, electronic outlets, and internet drop points. These layouts make a very strong starting point for both new construction projects and development and incorporation.

1.2. The second dimension: The Pedagogical Approaches

Before the approaches are explained, a step back must be taken to explain EE. It started because of partnerships between several stakeholders, universities, industries, and governmental entities that are necessary to revitalize design and manufacturing through an integrated curriculum and physical facilities for product realization. These activities that are designed around EE result in superior, practice-oriented engineering graduates in a new paradigm for EE (Jorgensen et al., 1995). The concept is integrated on all higher education and travels back to the context of K-18 in a different form called STEM. EE should comprise a set of effective learning experiences that allows for a deep conceptual understanding and the capacity to apply important skills through practical practice, which necessitates the alignment of engineering curricula and teaching methods to achieve these aims (Litzinger et al., 2011). LFs' main goal was to enrich EE in higher education curricula, then it became a part of the movement to reemphasize practice and hands-on experience in EE in terms of design, manufacturing, and product realization. As an environment, it deepens the knowledge in minds of engineering students through both intellectual and physical activities, whereas the traditional methods such as lectures endorse a more passive activity (Lamancusa et al., 1997). From the description of the various spaces under study, it's safe to unite them under the same umbrella in terms of target, which is leveraging EE and increasing competences, however, with a different degree of maturity and scale.

1.2.1. Pedagogical Approaches typologies

Recently, approaches applied in education include **experiential learning** (Girvan et al., 2016) and **challenge-based** learning (Cachay et al., 2012), **action-oriented** learning (Tisch et al., 2013), **cooperative** and **participatory** (Lucas et al., 2012) learning that all aid in the development of critical 21st century skills in the fields of STEM. There is no one agreed term for these approaches, the terms blur and mix into each other, there is no one agreed approach in the case for active learning (Hartikainen et al., 2019). However, there is a consensus in the literature about the experience aspect of a learning process, the experience could be context-rich, multifaceted problems that acts as a bridge between textbook and realistic problems that serve the goals mentioned above, or Model-eliciting activities that are require justification in mathematical models and encourage deep engagement in the problem and a self-assessment progress schema (Lesh, R.A., & Doerr, H.M., 2003). Yadav et al. (2011) and Deborah E. Allen,Richard S. Donham (2009) investigated the impact of novel learning approaches in undergraduate engineering courses, they have proven quantitatively that student gains from **problem-based** learning (PBL) exceeds that from traditional lectures. Another noteworthy approach is **flipped** learning, which has been gaining popularity within EE in the last 10 years, although a concrete pedagogy is yet to be defined (Karabulut-Ilgu et al., 2018). Another form of a multi-sensory experiential learning approach includes simulation games, whose correct usage in EE allows for maximum transferability of academic knowledge (Deshpande & Huang, 2011)

The framework of **active learning** encompasses three distinctive dimensions: **behavioral** through resource employment, **cognitive** by making sense of experiences and fostering a knowledge construction model and **social**, which implies the active interaction with others (Drew & Mackie, 2011). **Active learning** classrooms are proven to increase student engagement and performance in comparison to traditional classrooms, which makes it an investment with high return in institutions of higher education (Hyun et al., 2017). . Deborah E. Allen,Richard S. Donham (2009) link PBL to active learning, in a way where it's an enhancer of it. Johnson et al. (1991) reviews the research validating the effectiveness of **cooperative** learning in higher education that promotes positive interdependence, face-to-face promotive interaction, individual accountability, and personal responsibility. Cachay & Abele (2012) regard **action-oriented** learning as a perquisite at universities to require comprehensive job-related competencies that depends on self-organizing activities, students reconfigure their own learning process in reference to a problem statement and a task completion goal. The paper shows that students have a greater application-performance and knowledge sustainability after attending **an action-oriented** learning event. Pors Knudsen et al. (2022) shed light on the importance of integrating the target of the learning experiences in LFs with the participants' diverse perception and experiences which in turn affect the activities and by extensions the design of the learning environment itself, this forecast the conditions listed for LS design in the next chapter. Goumopoulos et al. (2011) showcase an example of designing an integrative elective course named "principles of environmental sciences" that combines the dimensions, environmental education, principles of space design of a parametric model, introduction to information technologies in ecology and green ICT. The students redesign their school yard in a collaboration process with architects and agriculturalists with greenspaces, seating areas and shades. Brandenburger & Teichmann (2022) has an interesting take on designing **participatory learning** (a concept that originates from education science in Germany) and teaching process within FL to be implemented in LFs, on an individual level by involving both the teacher and learner and their interests, and on an organizational level considering the participants own interests. This approach allows for more involvement on the learners' side and more autonomy in the learning process. The other side of the coin centralizes teachers and practitioners, it takes into account the development of teachers, they are seen as students that experience the PA before implementation to analyze the overall experience and output to make reforms to the curricula (Roessingh & Chambers, 2011) (Girvan et al., 2016). An extension of the stakeholders circle materializes in a supportive online community in a PBL online class approach that uses real world assessment tasks (Barber et al., 2015). Virtanen et al. (2014) studies the three supporting factors of vocational students' learning which are: individual factors, social and structural features of the workplace and pedagogical practices. Päivi Tynjälä & Gijbels (2012) propose an integrative pedagogy model as an approach to develop a framework that combines academic learning with working life skills, it depends on four types of knowledge, theoretical, practical, self-regulative and socio-cultural all within the context of all the learning approaches previously mentioned in this chapter.

1.3. The third dimension: The Design

What is meant by Architecture is the tangibles of a physical spaces that includes the building material, furnishings, lighting, ventilation and acoustics (Jamieson et al., 2000). Another access that can be used to examine the current literature is frequency, Strobel et al. (2013) found that the majority of references is found in undergraduate education and far fewer in engineer education when studying design-based learning environments.

1.3.1. Importance of the dimension

The relationship between the physical place and a student's perception of learning and how a teacher carries the teaching procedure is not a primary concern even though the idea of a campus has changed largely (Jamieson et al., 2000). Temple (2008) notes that learning activities in higher education and the learning environment are independent from each other. Physical arrangements are not considered, practically "environment "and "space" refers to the pedagogical methodologies or methods. Moreover, the fields of architecture and design and educational foundations have largely remained mutually exclusive, and little has been written about how the strategic design of the physical classroom environment can be used to improve classroom spaces to align with the primary aims and mission of the field of education (Tannebaum & Tannebaum, 2019). If any, Marmot (2006) highlights the primacy of PA when designing teaching spaces, the room design needs to reflect the active and collaborative nature of these activities though pre-collected requirements from the prospective users of these spaces and these requirements to be translated in a single space design or separate rooms each with a different purpose. The space should also be reconfigurable to support a bigger range of purposes. Moreover, Blikstein (2018) states that the labs intended for educational student-use and labs designed for professional engineers are different, these two groups access labs in a different mode, therefore the number of machines and architecture should be distinct. Charteris et al. (2017) argues that special practice theories and principals of design are vital to pedagogical approaches within innovative learning environments that are laid out as an open plan.

Whiteside (2010) reached the conclusion that students exceeded the expected grades of them in hands-on activities within a finance course, thanks to the technology-enhanced learning spaces, in the Active Learning Classroom (ALC) which indicate the importance of the features of the space. Not only that, but students in these classrooms outperformed their peers who attended the same courses in a traditional classroom. (Walker, J.D., Brooks, D.C., & Baepler, P., 2011) investigates the same three dimensions under study in this paper: PA, student learning outcomes and the type of learning space in a case-based study using another model of an ALC, by keeping one of the three dimensions constant and changing the other.

1.3.2. Trends in the dimension

New visions for learning, teaching within innovative space design require a strong orientation and leadership. (Marmot, 2006) proposes a framework built on four axes: pedagogy, vision, people, and technology. Space-management, in cooperation with directors, students and support services as well as academic heads need to be involved in the design and development of the space.

Jamieson et al. (2000) state that there are two practices for the design of on-campus learning environments:

- The first is the **re-design of an existing space** by incorporating more advanced technological equipment, such as computers in labs, and projectors in lecture halls, while maintaining the main purpose of the space. This is done by facility management staff.
- The second practice is **designing new spaces** by architects based on pre-founded ideas of space usages.

In both cases, teachers and students are not considered as stakeholders whose input is valuable for the design or redesign process. As Lamancusa et al. (1997) states, the LF results from involving the stakeholders such as students, faculty and industry in the education process, which by extension, raises the question: should the same stakeholders should be involved in the design process also?

Ellis & Goodyear (2016) theorizes design and co-configuration of learning spaces, they outline the practice theory. Starting with the research methods "zooming in" and "zooming out" to make simplify the process of design for non-designers also to accommodate constraints and limitations. The paper highlights the dimensions: ergonomics, apprenticeship, pedagogy, and transfer. The same participatory learning approach mentioned by (Brandenburger & Teichmann, 2022).

Going back to the second practice of design mentioned before, Andrews et al. (2016) displays the case study of a **development of existing project** of Mann Library at Cornell University established in 2007 through redesign of collaborative space, their main methodology was composed of several phases:

- first phase in 2006: assessment of student's learning and study behaviors through gathered feedback and a pre- and post-occupancy study with the design department.
- second phase in 2012: space observations, surveys, interviews, usability tests, photo diaries, ideal-space design exercises, focus groups.
- Third phase in 2013: assessment of activities for the selection of appropriate furniture pieces and understanding of individual study needs.
- Fourth phase: scanning of several libraries.

Kreß & Metternich (2022) propose a method in designing of LFs in terms of technical systems that are selected based on intuition initially. The methods opt for selection of factory elements taking into consideration the primary goals of the LF budget and usable area by solving an optimization problem with possible combinations that are evaluated. (Enke et al., 2016) proposes a methodical approach of the requirements analysis of various stakeholders in 4 phases, where the identification of stakeholders is placed as a second step based on learning factory morphology, the stakeholders could be one of three groups: operating **organizations**: academic institutions, non-academic institutions and profit-oriented operators, **trainers**: professors, researchers, student assistants, specialists etc. , **target groups**: pupils, students, employees, entrepreneurs etc.

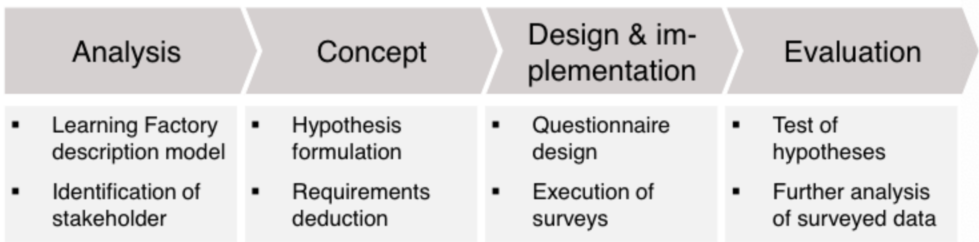

Figure 5, Methodical approach used for the requirement analysis

The (University of British Colombia & Facilities Planning, 2018) provides directions and recommendations in planning and design of learning spaces of their campuses. These directions apply to new construction as well as renew and renovation projects. Both a planning team and an Audio-Visual Team collaborate within a pre-defined process (Figure 8). The Building Project Plan (BPP) phases are listed below and explained further

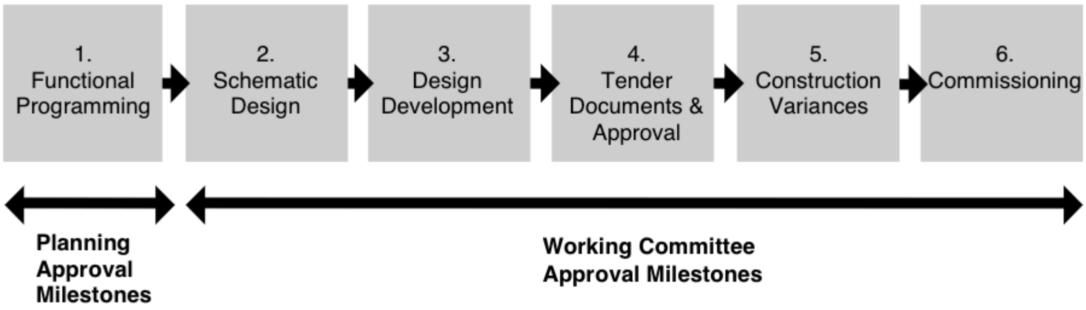

Figure 6, Project Plan as proposed by UBC

1. Functional Programming:
    - Collect the preliminary information about the project such as: project scope and goals, budget trade-offs and required learning technology options and the related implications on pedagogy and room design, to minimize potential conflicts between user PAs and the technical and operational requirements.
    - Conceptualize a “Functional Program” which is also more commonly known as “Space Program” (refer to chapter 4.1.1).
    - Planning: Selection of project team, setting project schedule, setting project budgeting
2. Schematic Design
    - Site analysis
    - Understanding of building codes that are specific to each country.
    - Size, location, interspace relations
    - Outlining basic design and operations
    - Plan approval
3. Design Development
    - Selection of building materials and finishings
    - Selection of fixtures (windows, doors and appliances) and furnishings
    - Laying out structure, plumbing, electrical, heating/ventilating system or any other systems.
    - Energy analysis
    - Interior and exterior design approval
4. Tender Documents & Approval
    - Finalizing all technical design of all systems
    - Structural design and detailing
    - Design drawings for approval from authorities

5. Construction Variances: depending on the level of approval of the output of the last phase.
6. Commissioning: this process takes into consideration multiple contractors to be hired.

1.3.3. Common practices

This section gathers examples from different institutions that attempt to model their spaces based on some design aspects or common practices that they decide. Any space can be divided into subspaces different in function, these spaces are outlined by partitions and walls. The examples range in application from a single element in a space or a subspace, to a single space up to entire zones, and they are explained in this order. These common practices along with the Design Aspects extracted from the results of the review (section 3.2.1) constitute some of the building blocks of the design guide line proposed eventually. For each space. A visual is accompanied by a paragraph explaining the feature that needs highlighting. Some key words are emphasized.

1.3.3.1. Elements and Subspaces

For **transparency**, Annie Purl Elementary School has replaced all walls with floor-to-ceiling glass walls, they've centralized a collaborative design lab withing between classrooms of the same year that can be viewed from any point in the learning environment. It's clear that bright colors schemes are used for circulation spaces while neutral colors are used for main spaces (Minero, 2018)

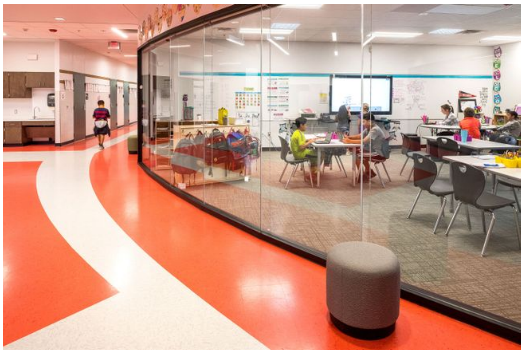

Figure 7, Annie Purl Elementary School, Texas, USA

Deerfield High School, Illinois removed opaque structures like walls and doorways for **fluidity** and to from an uninterrupted line of sight to facilitate supervision of interdependent and group works, like Google and Apple HQs (Minero, 2018). Vibrant colors are also used for each space to convey a sense of **diversity**, students are left to choose a different-colored space to diversify their experiences. This example is very similar to the renovations done on the first floor of BL12, Bovisa Campus at Politecnico di Milano.

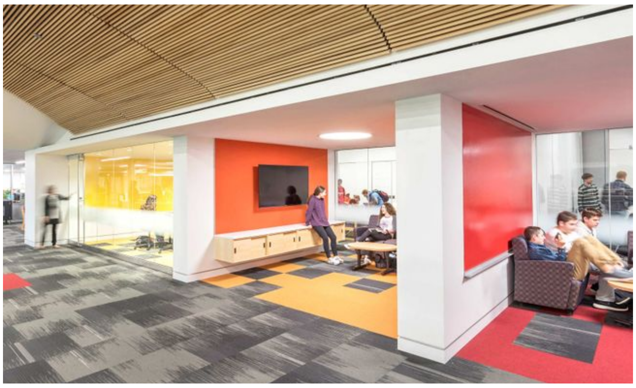

Figure 8, Deerfield High School, Illinois, USA

For FLs, the (fabfoundation, 2022b) has a detailed folder with layouts for specific activities, this is aided by the set tool list that dictates a minimum clearance and a specific methodology of utilization and an accompanied supply. The following examples shows these subspaces layout, the details related to placement, dimensions, furnishings, and fixtures are highlighted. This step aids in, first, understanding how the single space is addressed when the objective and tools are clear, second, how it can be synthesized for other spaces.

The first space is dedicated for molding, casting and silk screen printing activities, the design is a **simple modular** one that is used as a replicable building unit for the rest of the space with some addition and modification to kinder to the specific need of the space.

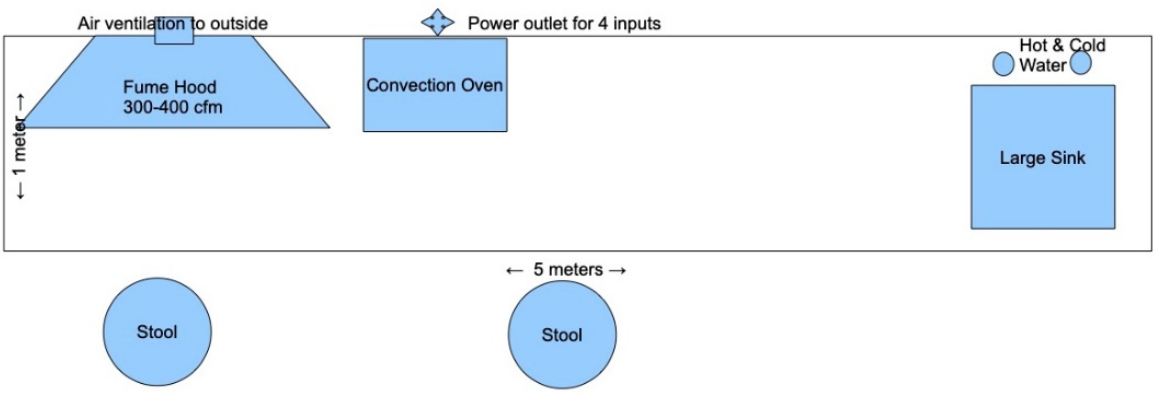

Figure 9, Molding space prototype by the fabfoundation

For 3D printing purposes, the space is 3.5x5m long and is divided into two main parts, work area and storage area, the work area is composed of a 3.5x1m table with a computer, a scanner and a printer placed on top aligned to a wall for easy internet access and power supply. The storage space can be composed of shelving (0.5x1x2m) or entire cabinets (0.35x3x2). The space can also accommodate another central table with tools for examination processes, refining work or brainstorming. Modern 3D printer are stand-alone machines whose sizes are bigger than the ones usually placed on a table. In this case, the machines are placed on the floor with the correct fixation and the table space can be utilized instead of an extra central table.

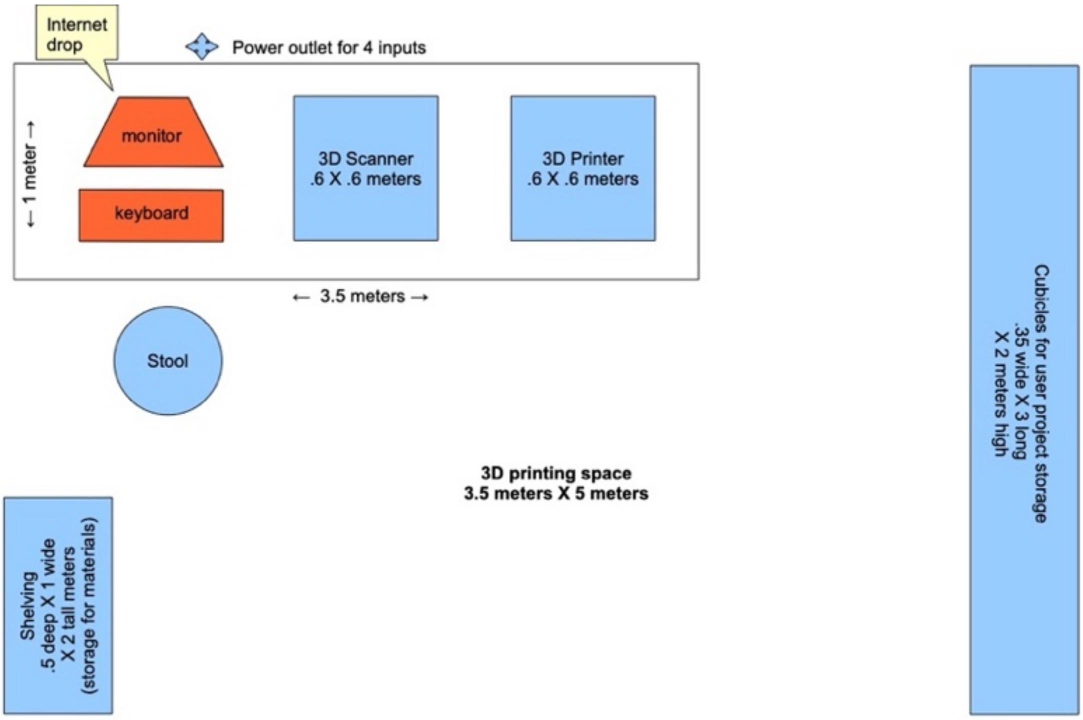

Figure 10, 3D printing space layout by the fabfoundation

The electronics area is designed in a back-to-back configuration, where two 1x5m counterspace are set with desktop height, computers and tools are lined in a staggered or mirrored pattern depending on best usage of these tools, rolling chairs are used to accommodate the length of the counters and for fast access. Overhead shelves for tool storage with clearance are installed. Internet drop points and power points are concurrent with the computer units used.

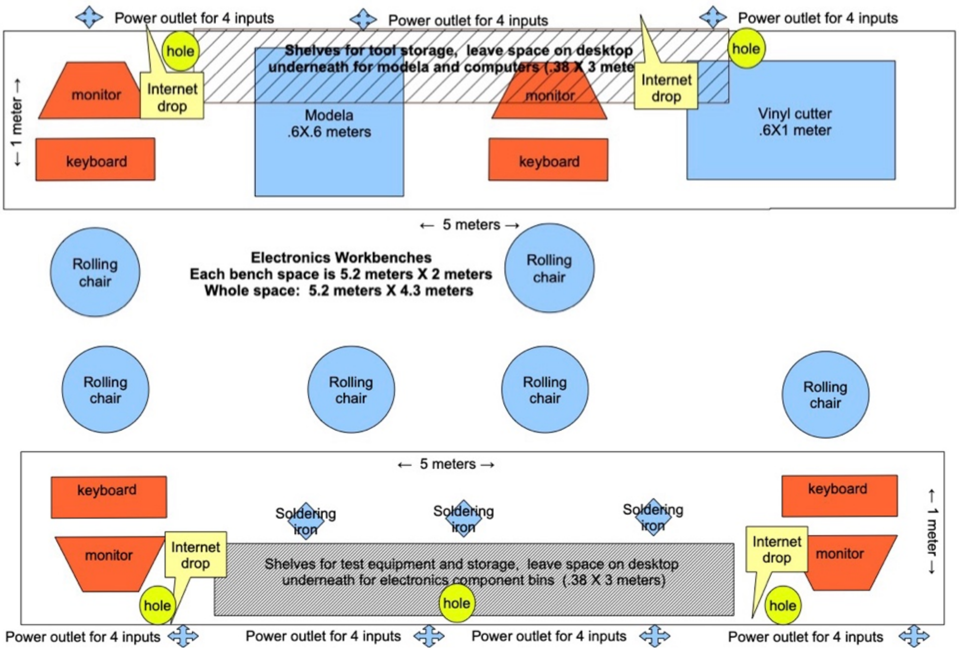

Figure 11, Electronics Area layout by the fabfoundation

The laser area is composed of a single unit mirrored on itself (laser machine, desk with computer 1x3.5m and a rolling worktable lined with high stools). This configuration utilizes a ceiling drop solution for power and internet for the centralized worktables. This configuration can be mirrored and/or multiplied many times depending on the number of machines used, it's recommended to keep the dimensions and adjacency of the elements fixed for maximum efficiency and utilization of the space.

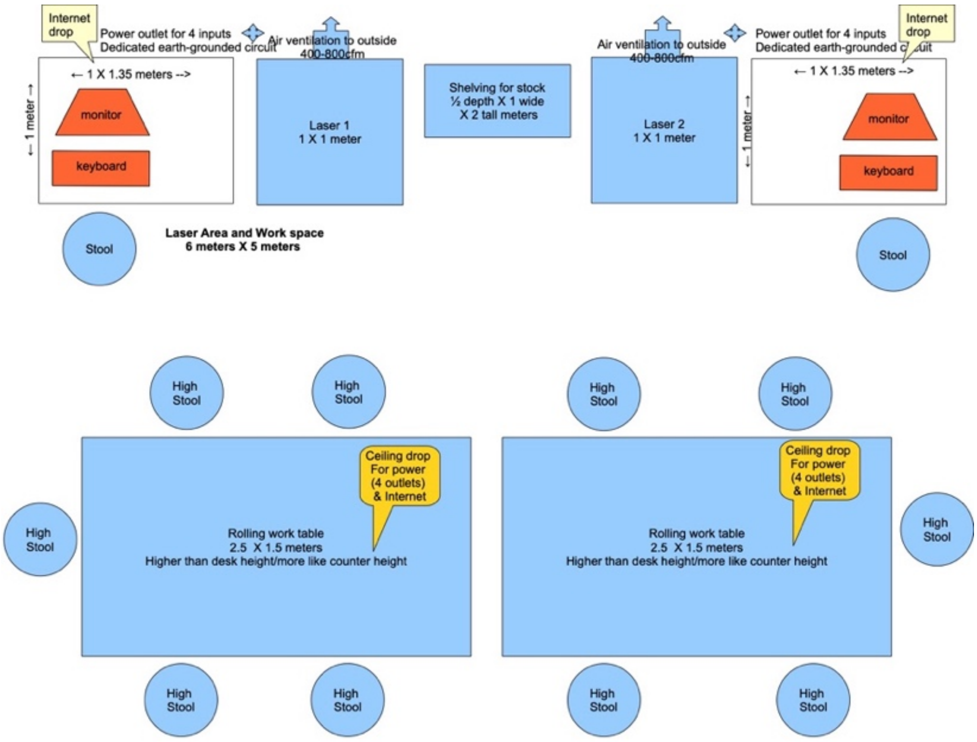

Figure 12, Laser area layout by the fabfoundation

Finally, a space dimensioned 6x6m dedicated for design, learning and conference purposes is laid out in a circular configuration facing a screen for projection coupled by a ceiling-suspended digital projector, power outlets are provided for each position and a rolling chair for easy movement and reconfiguration.

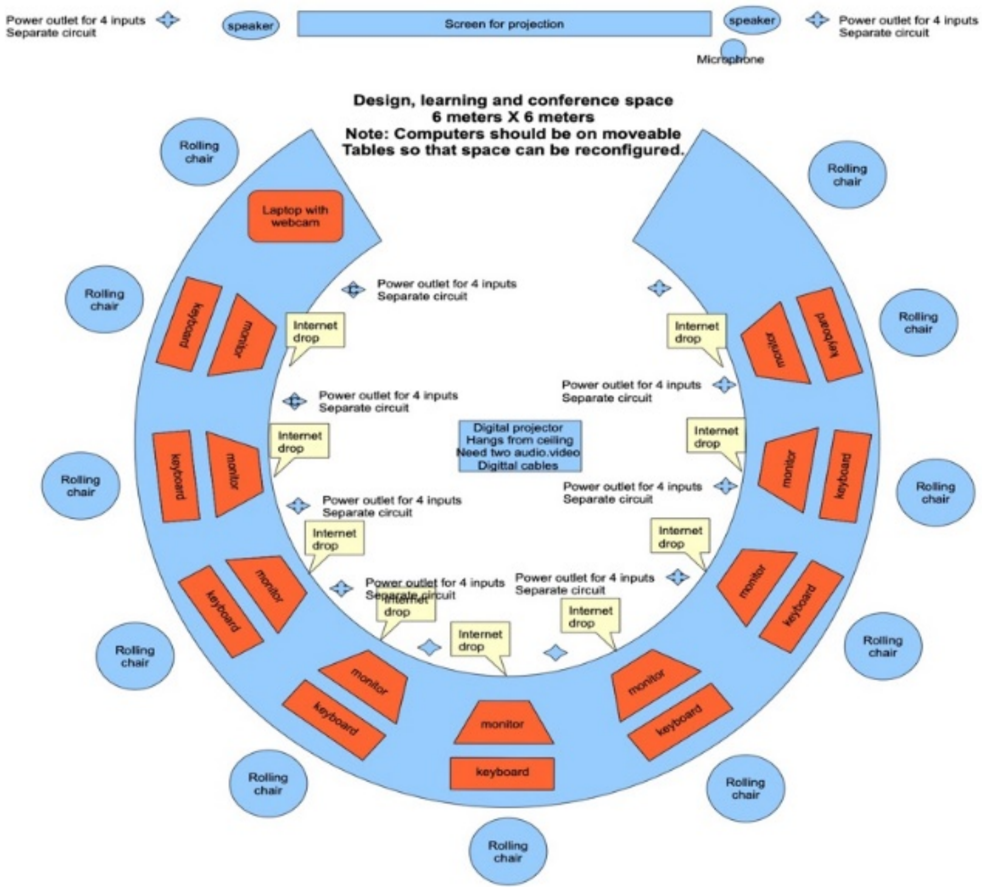

Figure 13, design, learning and conference space layout by fabfoundation

1.3.3.2. Single LS

The Learning research studio (LRS) at San Diego State university is an open plan room with two different types of reconfigurable tables (that accommodate small groups 15-40 students to 50 students) that emphasizes group learning and collaborative work without orientation of the room in one space, also a huddle-room system is used for presentations and discussions. It's equipped with multiple light-weight movable white boards. The spaces are design based on a student-centered instruction approach with a ceiling-mounted camera for documentation and live streaming and multiple projectors and display screen. For lighting: wall-mounted diffused glass light units with full-spectrum lighting fixtures are used (Frazee et al., 2014).

Figure 14, Learning research studio (LRS) , San Diego State University

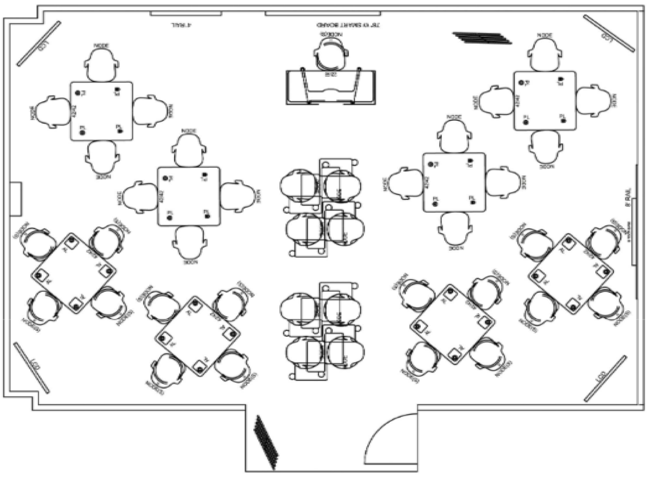

Figure 15. LRS Floorplan

(Posch Irene et al., 2010)present a case for adapting a FL into an interactive exhibition space at the Arts Electronica Centre (AEC) in Linz, Austria for informal learning, the design is accessible for all ages, open space with a focus on predefined elements, creative prototyping and shared creativity. The space also can accommodate doors for separate special workshops. The space is composed of three areas, design (1), fabrication (2) and a gallery (3). A supportive technical infrastructure is the basis of the interactive exhibition from design tools such as Air drawing and Cassius Box Interface to fabrication machines such as A3 printers, individually controlled 3D printers.

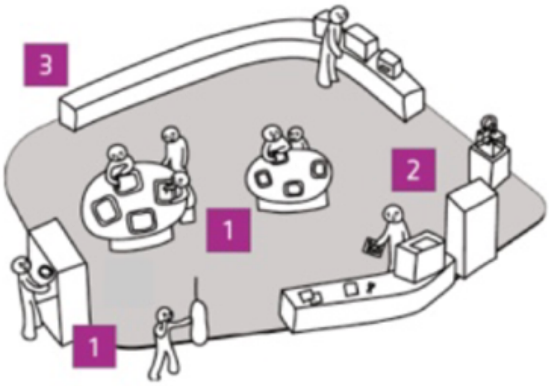

Figure 16, Pictogramm of FL, Aerts Electronica Center (AEC), Linz Austira

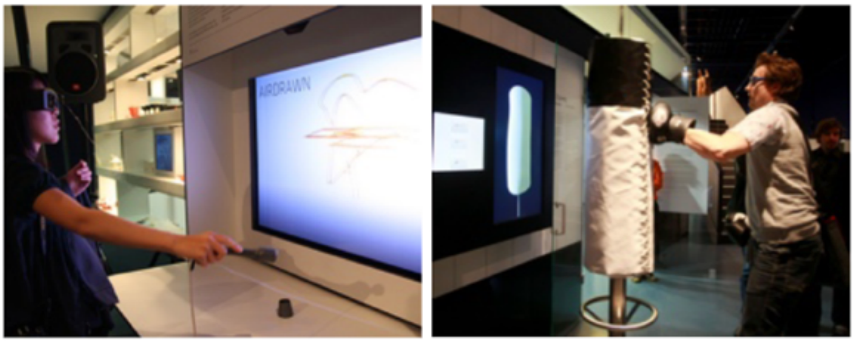

Figure 17, Interactive illustrations, Air drawing (left) and Cassius box (right)

(Minero Emelina, 2018) sheds light on the attention given to K-12 school design by interviewing top architecture firms in the US, where key insights into five common design principles were extracted: technology integration, safety and security, transparency, multipurpose space, and outdoor learning. St. John's robotics lab represents a good example of technology integration as part of its STEM commons.

Figure 18, St. John's robotics lab, Maryland, USA

(Marmot, 2006) proposes a design for a prototype for a LS. The space is composed of one open space with a folding/sliding acoustic wall (10) in the middle to create two separate spaces. The space has two entrances for circulation and to serve the separation. Both entrances are lined with lockable storage (1) and recharging stations and wireless hubs (3,4). For furnishings the same typology of foldaway movable tables (8) is used for all configurations; u-shaped, single and double, also stackable chairs (13) are used along with high chairs and rollers. Walls are utilized for lining tables populated with wired computers next power sockets (4). For presentations and video conferences, a ceiling-mounted projector (14) is used along with a movable screen (15) or a mobile interactive whiteboard (5). A lectern with control panel (6) for lighting and power/network points is used. Finally, a raised floor is installed with cabling and easy access to power points.

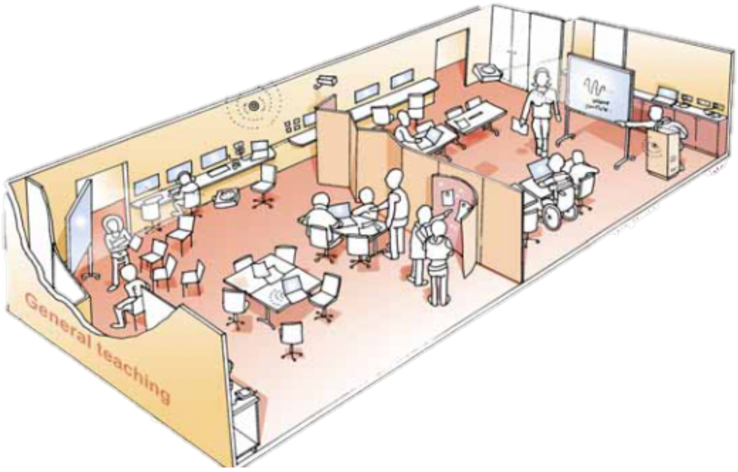

Figure 14, 3D model for LS prototype

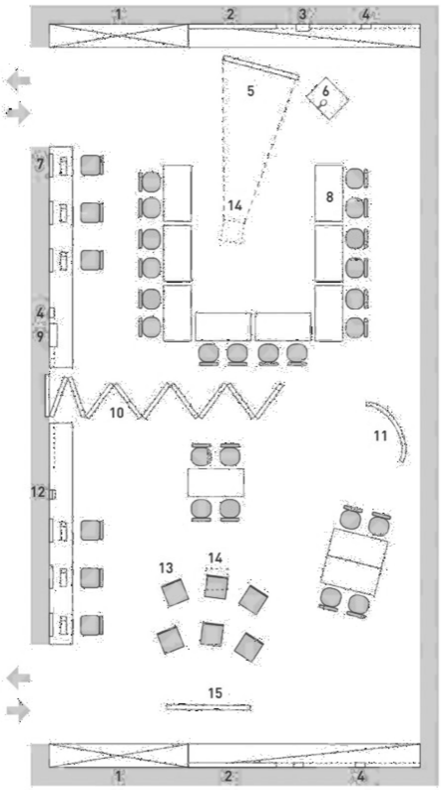

Figure 15, prototype for a LS floorplan

(Marmot, 2006) showcases a "Cluster design" at the Department of Design, Manufacture and Engineering Management at the University of Strathclyde, Glasgow. The project is a refurbishment one whose aim was to bring into one space the various stages of design and manufacturing processes. For design and drawing takes place in the M109 CAD suite in the middle of the space. Also, individual work can be done using one the single wall-facing workstations. A visualisation area for discussion is placed in the corner of the room for communication, discussion and presentation of concepts and design outputs using audio-visual aids. The printing & data capture area is separated with a glass partition for sound proofing, giving dominance to the main activity (CAD) while still being able to integrate the processes if needed. A breakout area is used within the space separated only visually using different furnishings.

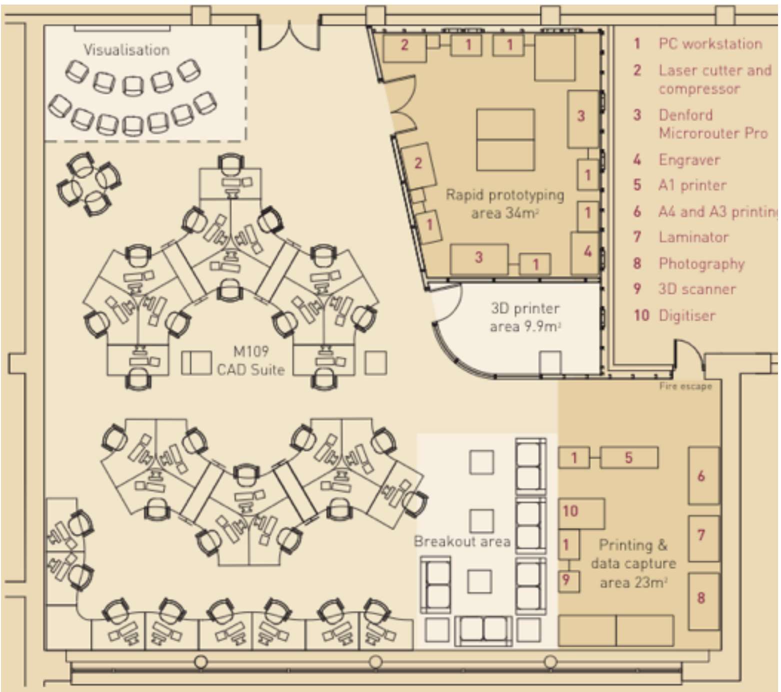

Figure 19, Department of Design, Manufacture and Engineering Management at the University of Strathclyde, Glasgow

1.3.3.3. Zones

The (fabfoundation, 2022b) posted a schematic layout of a lab space for those willing to construct a new FL along with a detailed description of the individual spaces. This schematic design can be easily used as guideline for entities that have expertise concerning the technical work that needs to be done but aren't necessarily aware of concerns and aspects related to space design. The proposed design is almost a square-shaped (18mx20x) with all the subspaces fitted nicely in taking into consideration clearances for circulation. The design is central around a 5x6m workspace with storage. The technical spaces (Laser area, modelling and casting, 3D printer, snapshot space) are spread around this central space and lined to 3 walls across the space, it's clear from section 1.3.2.1 that each subspace is designed around a machine that's placed adjacent to a wall on a table or countertop, this allows for ample space for above head storage and for clearance for the workers or students and easy access to electricity. These technical spaces can be considered the main spaces, and the rest can be considered the subspaces; the conference/learning space and the exhibition area also used as an office or as storage when, convenient.

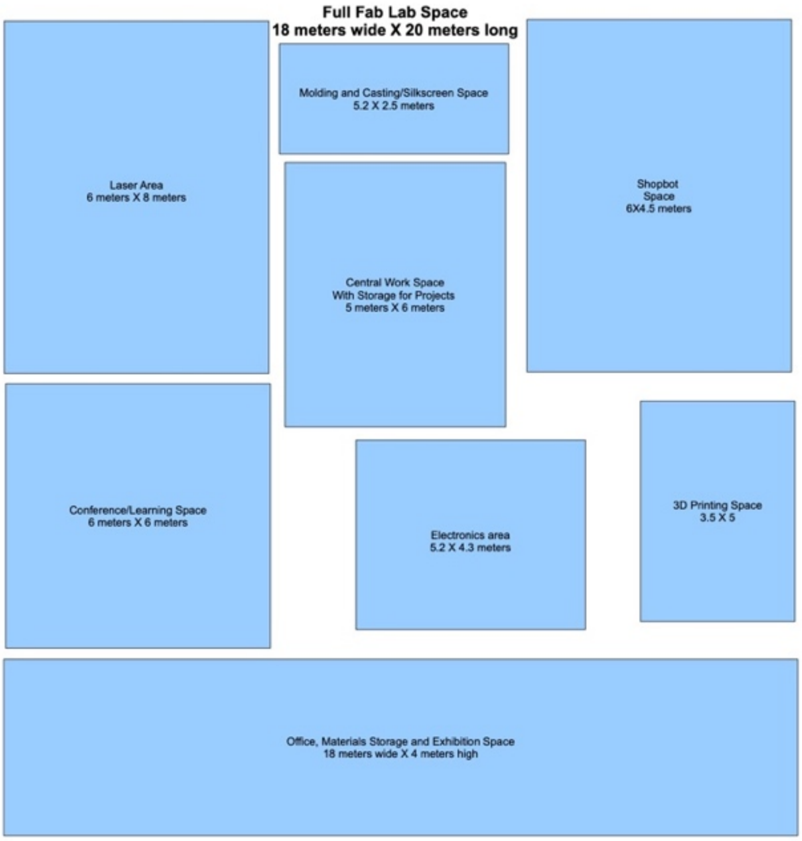

Figure 20, Fablab prototype layout

An initiative between the University of. Sussex and Brighton University lead to the development of "The Creativity Zone" based on the knowledge of both universities in engineering, cognitive science, pedagogy, and design. The space (300 m2) is based on the concept of removing boundaries between disciplines and creating an environment of mixed formal and informal learning though a reconfigurable structure. The unique element of this zone that allows this reconfigurability is the variable partitions, screens, and furniture items such as cubes (4) that can be used for both searing and mobile storage. The flexible infrastructure presented in the multiple projectors, wireless connectivity and location-aware technology allows for practitioners to act like designers within the space to simulate any practice using light, sound, and objects. These elements can be used as a prototype to be deployed in any other space. This is a strong example to how physical space design can impact learning outcomes. Individual activities are also taken into consideration and a small pod (1) is dedicated. Sliding screens (3,6,12,14) with various surfaces are used for display, projection, and partition. The same cube element is used in a larger scale to create a raised stage area (7). Both Doors (11) and windows (5) are used as surfaces for display.

The space is also equipped with a refreshment point (13) a control room (8) and a storage area (9) (Marmot, 2006).

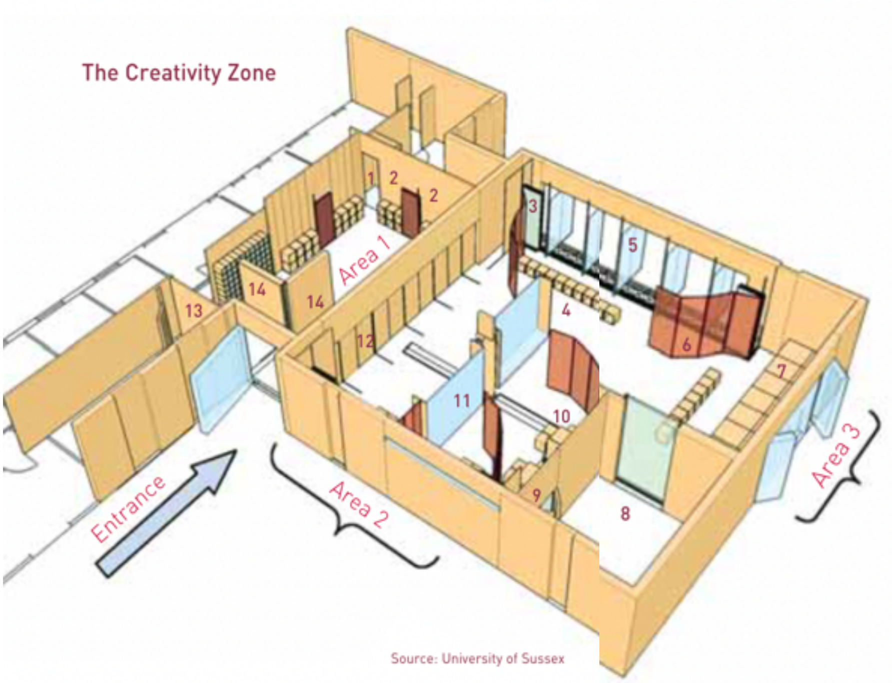

Figure 21, "The Creativity Zone" prototype layout

1.4. Introducing a fourth dimension: The Product

1.4.1. Learning Spaces as a Product and Cargotechture

The Lean Enterprise Institute (2022) recognizes the definition of a building as a product (Lean Enterprise Institute, 2015) or "built environment" that comes to fruition in a sociotechnical system that takes in consideration the interaction between technology and people in workplaces all within the industry of "Architecture, Engineering and Construction (AEC)" (Underwood & Isikdag, 2010). This definition is made easier when combined with another concept "Containers Architecture" or "Cargotechture" introduced by (Kotnik, 2005). He defined it as the type of architecture that is generally characterized by the re-use of steel shipping containers as a structural element and envelope to encompass a specific function or activity. These containers are used as a replicable building block from a small scale of an individual building to a larger scale. The containers have fixed dimensions and 3 categories based on their types. It's considered as a quick and temporary solution that is structurally safe with high capabilities (Radwan, 2015). Jim Poteet Architects which is a national award winning firm designed a guest house (Figure 6.) through cargotechture of 320 m2 in 2010 by adapting existing buildings material (ArchDaily, 2011). The space is comprised of an extended deck (1), the main space of the studio (2) and a storage space (9), the space is also equipped with an HVAC unit (8), a toilet (5) and a shower (3) which shows the extended capabilities that can be integrated within the space.

Figure 22, Container guest house by Poteet Archietcts

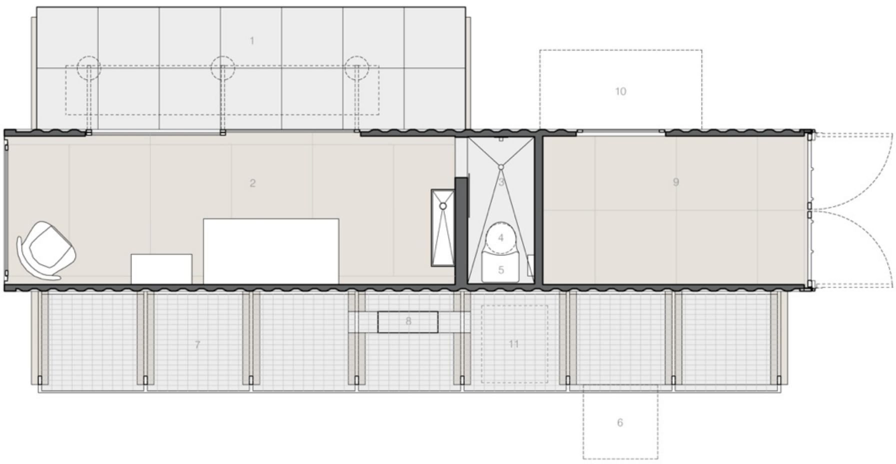

Figure 23, Container guest house, floor plan

The applications of Cargotechure expand beyond housing. It's used for commercial purposes, such as the Puma City (Figure. made of 24 containers with an area of about 1021m (Basulto, 2008). Also, it can be used for educational purposes, a good example could be the Vissershok container classroom by Tsai Design Studio (Rosenfield, 2012).This unit can be stacked on top of each other or staggered. This configuration process can be thought of as a game of Legos, that's guided by some rules and constricted by some limitations, like for example the requirement of a horizontal connecting element between two stacked units. This can be explained by the London container city designed by Nicholas and Partners Lacey in 2011 (WikiArquitectura, 2000)

Figure 24, Puma city shipping container store

Figure 25, Vissershok container classrom

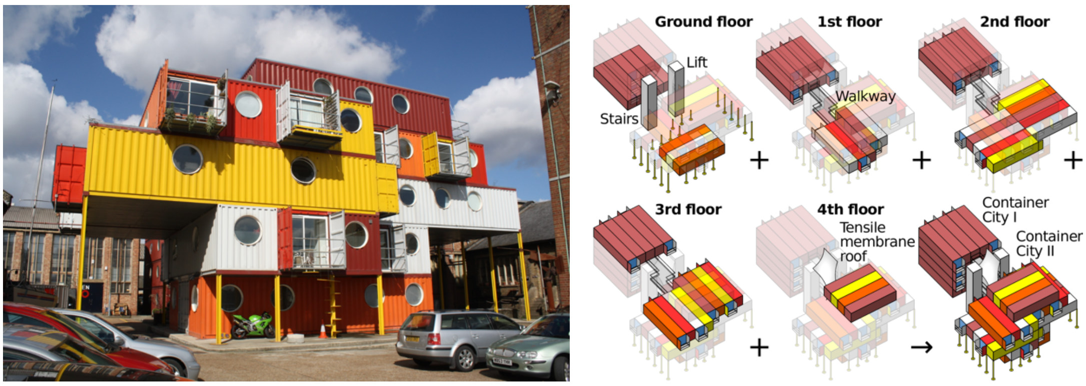

Figure 26, London Container city

1.4.2. Product Development Process

(Ulrich & Eppinger, 2012)proposes a Product Development Process (PDP) that can be applied to a set of variants of generic process. Each phase is explained below and expanded in a simplified checklist, as it will be compared and cross-referenced to a project plan designed for designing LSs. This analogy will help pave the way for the proposed LSDG in chapter 5.

0. Planning:

- Identification of opportunities within a pre-defined corporate strategy
- Assessment of available or required technological development and market objectives. Phase zero ends with the project approval.

1. Concept Development:
   - Identification of target marker needs
   - Identification, generation, and evaluation of alternative product concepts
   - Concept selection, where the concept describes the form, function, and features of a product
   - Listing a set of specifications
   - Analysis of competitive products
   - Economic justification of the project
2. System-level Design:
   - Definition of product architecture
   - Decomposition of the product intro subsystems and components
   - Identification of preliminary design of key components
   - Defining initial plans for production system and final assembly flow diagram
   - Geometric layout of the product, functional specification of each subsystem
3. Detail Design:
   - Specification of the geometry, materials, and tolerances of the parts
   - Identification of all standards parts of the product
   - Control documentation
4. Testing and refinement:
   - Construction and evaluation of multiple reproduction versions of the product (alpha and beta prototypes)
5. Production ramp-up:
   - Product realization using the intended production system.

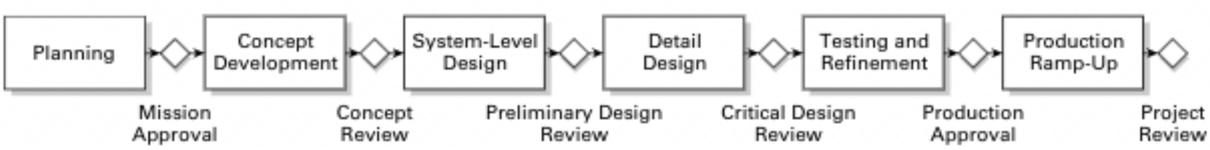

Figure 27, Product development stages

2 Research Design

2.1. Research question

The scope of this study has been defined to include LSs within the perimeter of **higher educational institutions** with a search frame between 1990 and 2022. The goal of this study is to assess the **intersections** between LSs for EE, PA and AD guidelines as described by the literature. This study's research question alternates between these three dimensions; **LSs** implemented in the context of engineering education, the **PA** that take place inside them and how these spaces are **designed**.

The paper attempts to answer the following questions:

- RQ1: *What are the design aspects and success factors of learning spaces for engineering education, if any?*
- RQ2: *How to design learning spaces for Engineering Education based on the different pedagogical approaches and success criteria?*

2.2. Methodology

The methodology used to produce this body of work is divided in two phases, the first is a thematic SLR, which is a replicable scientific process using criterion-based selection and analysis of published studies. It identifies homogeneity or heterogeneity within studies, trends, and knowledge growth as well as limitations within a specific area or field the second is a qualitative Space Analysis.

The first phase scours the available literature and focuses on the activities and design of PA, and the AD of the spaces and if there are any connections between the two. The aim is to find case studies or practical applications of design within the mentioned LSs and the justifications behind these applications.

The second phase uses the individual space as a unit of research, it goes beyond the boundaries of published literature to include spaces that are available online in terms of data. Selection criteria are mentioned in section 4.1.1

A detailed description of the phases is explained at the beginning of each dedicated section accompanied with schematics.

2.2.1. Phase 1: Systematic Literature Review

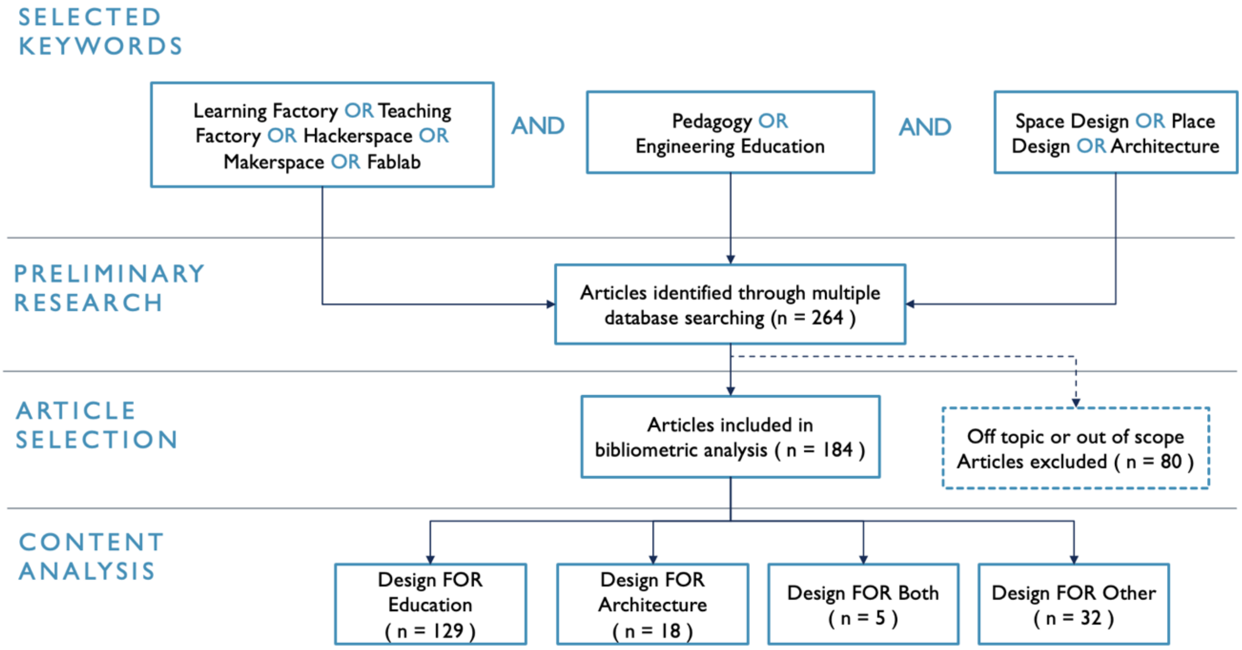

Figure 28, Structure of the SLR

The articles search is carried out using four indexed electronic scientific databases: Scopus, ScienceDirect, ResearchGate and IEEE Xplore. It's conducted in four steps: **keywords selection**, **preliminary research**, **article selection**, and **bibliometric analysis**. The steps are further explained in detail in section 3.1.

The three dimensions that organize the entire paper—the space, the PA, and the design—are reflected in the SLR's keywords. All articles within the framework of higher education are taken into account in order to retain the research's emphasis and bridge the gap between interdisciplinary researches. Even though initially the research boundaries were focused on universities and higher education, the papers that resulted in the K-18 environment couldn't be excluded due to their high added value, as concepts like FLs and MSs are integrated intro school curricula. With that, and the great attention educators in schools give to the appearance of the physical LS, a line of thinking could be to scale approaches from outside of higher education to achieve the required purposes

The implications of Learning Spaces design for engineering education are thus examined from both an architect's and an engineer's perspective. The research suggests new research issues in future works section and highlights the achievements of this interdisciplinary topic. The study seeks to synthesize the most significant subjects covered and looks for a logical framework for the dimensions.

2.2.2. Phase 2: Learning Spaces Analysis

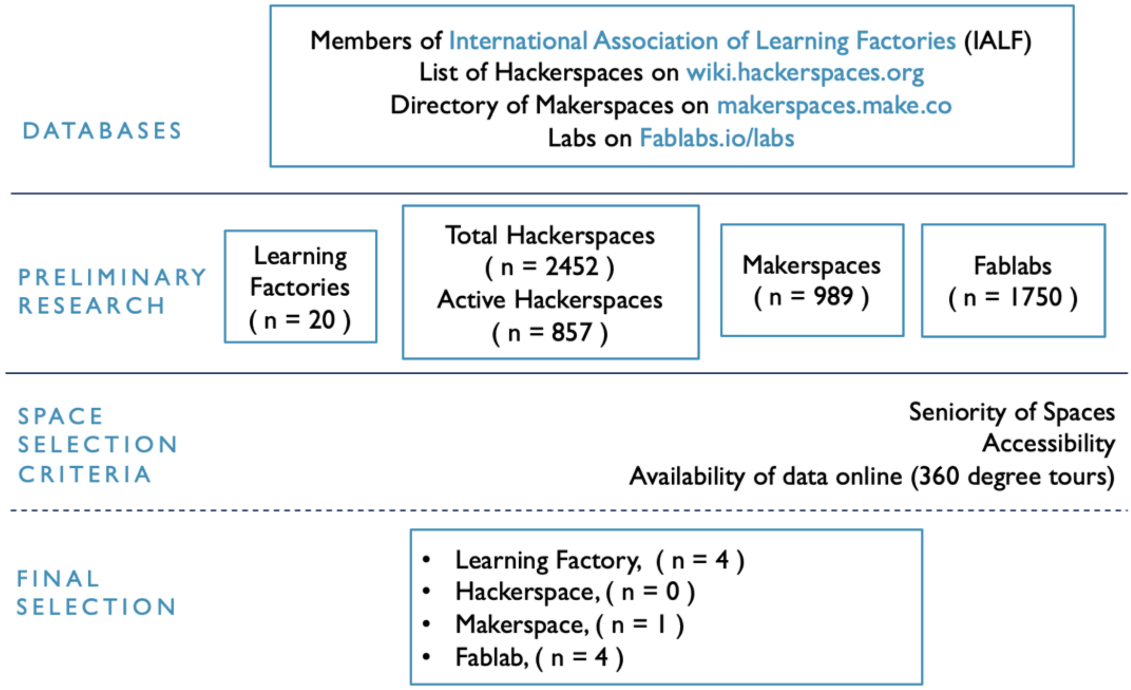

Figure 29, Structure of the Space Analysis

Not only does this chapter have a complimentary goal, but it is also utilized to identify visual similarities and variations between the LS and, if possible, to extract even more conceptualization criteria. This chapter makes extensive use of the author's five-year bachelor's degree in architectural design background. Since the degree develops visual analytical skills, many of the explanations are logically intuitive. It is possible to quickly assess a room's relative size, location of doors and windows, furniture arrangement, ceiling design in relation to the furniture, kind of mechanical systems in use, and dominant style based on aesthetic elements. LSA gathers information from videos, text and images other than the official ones listed on the directories, it uses articles and news clippings to simulate a virtual tour of the LS. The analysis tries to look at different angles of the space.

For example, in the case of LFs, The LSA goes beyond the outline of the core to explore the spaces as a whole entity, in other words, the analysis looks at the simulated assembly line, the complementary spaces, the storage spaces, the conference room etc., Also the paper covers scaled-down or full-size factory environment of physical LFs. Virtual spaces have a different set of requirements, and a focus on physical elements is required to achieve the target of this analysis.

3 Systematic Literature Review

The initial stage of the analysis process is the SLR. The first chapter paints a picture of the design elements of LSs and provides an overview of the framework in which the analysis is conducted (LS, HS, MS, and FL). In order to identify trends, areas that need further attention, and gaps, this chapter examines and synthesizes the academic literature on the subject.

3.1. Analysis Procedure

The procedure is divided into four phases explained further below: 1. Definition of keywords, 2. Preliminary research, 3. Articles Selection, and 4. Content analysis. The articles search is carried out using four indexed electronic scientific databases: Scopus, ScienceDirect, ResearchGate and IEEE Xplore

3.1.1. Definition of Keywords

The keywords used were retrieved from the context presented in the introduction. Three sets of keywords paved the way for the search:

1. The Context: this set included the words that define the boundaries of the context that's being investigated "Learning Factory" OR "Teaching Factory" (that are used interchangeably) OR "Hackerspace" OR "Makerspace" OR "Fablab" to outline the scope mentioned before.
2. Pedagogy and Teaching Activity: the second set related to the practices being taken inside these spaces included "Pedagogy" OR "Engineering Education"
3. Design: the third set relates to the physical aspects comprising the space OR "Space Design" OR "Place Design" (that are used interchangeably) OR "Architecture".

3.1.2. Preliminary Search

The preliminary search resulted in a reasonable sample of papers based on the defined keywords. On first examination of the keywords of the papers and cross-referencing them to search keywords, two groups emerge. The first groups deal clearly with design aspects the other deals with pedagogy and learning approaches. The preliminary search creates some doubts related to the presence of any overlap or combination of the second and third dimensions which are PA and AD which are being questioned in the first place, which in part confirms the gap and initial intent of the paper. In fact, the goal of the search is to look within the area that fall between two disciplinary areas: engineering and architecture. A general search was conducted from articles, magazines, and technical reports to confirm the selection of keywords, and a deeper dive should be taken past the used keyword filtration to determine the entire scope of the papers and if one dimension is extended to the other. The papers defined at the end of this stage were 264.

3.1.3. Articles Selection

A scan of the abstracts of those 264 resulted in the elimination of 80 papers, for various reasons including but not limited to:

- out of context: meaning papers about case studies conducted outside the scope of higher education or university campuses, design for production or design for development.
- out of scope: meaning papers touching the streams of ethics, specific cases such as tools design, design for feminists and safety aspects, repeated papers across the search and between papers and references.
- out of reach or access: papers that weren't accessible to the public on any search engine or database.

The step resulted in identification of 184 worthwhile papers for full reading, extraction and referencing. The papers were then divided into four categories further explained in the next section, ideally the ones with case studies showcasing live pictures and/or architectural plans were prioritized to investigate the first dimension, the ones with pedagogical frameworks were picked as well for further investigation. The preliminary search revealed a dominance of articles related to LFs and a scatter of MSs, HSs and FLs as a context or an environment for study. Also, most papers are related to design aspects of curriculum without a clear reference to the PA or vice versa.

3.2. Results

On examining the literature, a separation is clear between the three dimensions being investigated; the LS as an entity, the PA, and the AD over time It's interesting to see that FL (n = 13) are the most advanced in space design and the most covered space found in the literature, the space analysis also confirms this superiority. This could be due to the presence of the published fabfoundation guidelines could be an attributable reason, or the nature of FLs would be implemented in the design and setup phase. On the other side of the spectrum, LFs papers (n = 22) are more focused on the educational aspects in terms of design of PA, showcasing case studies.

Ideally, a bibliometric analysis would have been used to conclude this part of the research, however for the uniqueness and the specifics of the topic being researched, a thematic analysis is used to find intersections and common traits. This body of work is investigating a very specific overlap of two dimensions within a predefined context, The objective is to try and understand what type of design is being done in LS in the EE field. The design can be that of curricula or a specific PA or it could be of the actual physical aspect of the space. The figure below shows the results in the form of intersections:

- Intersection A indicates Design FOR Education. This intersection contains 129 papers. The papers that fall into this category have a general theme, PAs and didactic techniques are shaped to achieve a specific target taking one of the LSs or a project being executed as a test field. These predefined targets could be competence development, providing future skills. The approaches used include but are not limited to the ones mentioned in section 1.2.1 such as action-oriented learning, networked learning, simulation games, connected learning. There is a predominance of papers within LFs.
- Intersection B: This puddle of papers includes 18 papers. This category includes active attempts to model or design the spaces either within new spaces or a redesign in an existing space.
- Intersection C contains 32 papers that fall outside the context, these spaces aren't categorized as any of the spaces under study. They constitute the main part of the literature review. The design aspects have been extracted of this category to form a more generalized view of the practice. The approach in these spaces doesn't only pass or mention the importance of including the PA within space design but it guides the design process in the. implementation of the design.
- Intersection D contains 5 papers where the authors attempt to design spaces based on both the typology of learning activities being practiced and some design criteria.

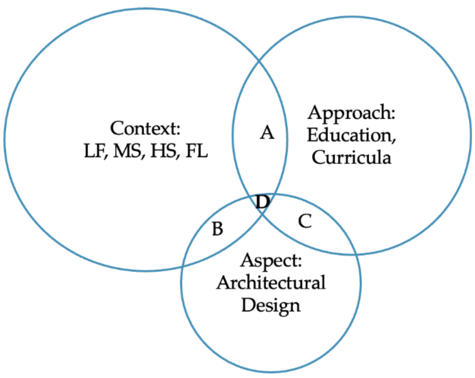

Figure 30, a visual of SLR output

It's noticed that papers either discuss one or the other in conjunction with the space. For example, a paper might discuss teaching methodologies and modality within a space along with the required objectives without giving much attention to the required tools or layout. For example, Enke et al. (2016) state the absence of systematic approaches for LF design resulting in uncertainty with an unclear target orientation. This highlights the incomplete conceptualization of LFs in the early stages and by extension the other learning spaces for engineering education that will be later mentioned. (Enke et al., 2016) links the design of LFs with action-oriented learning approaches in a systematic approach for competency building, integrating three levels:

1. Macro level: the context expressed in the learning factory itself including the socio-technical infrastructure, product environments etc.
2. Meso level: the teaching module, including sub-competences and general learning sequences
3. Micro level: the specific learning situation and their design interplaying both the informal (acting, problem solving) and formal learning (relativizing and abstracting). However, with no connection to the first level

On the other hand, a LS can be examined in terms of design with a brief passing over the activities carried out. For example, (Abele et al., 2019) define three pillars for the structuring of a LF starting from a manufacturing workshop for training purposes, based on three pillars: didactic, integrative, and engineering. A focus on the didactic pillar confirms the importance of taking the learning strategy and educational goal into consideration along with the target group, also, the physical learning factories can be supported by means of digital factory systems and tools (ERP, MES, etc.); most physical learning factories have digital systems implemented. The physical value streams can be expanded virtually. LFs can be categorized by scale or degree of the presence of a physical environment.

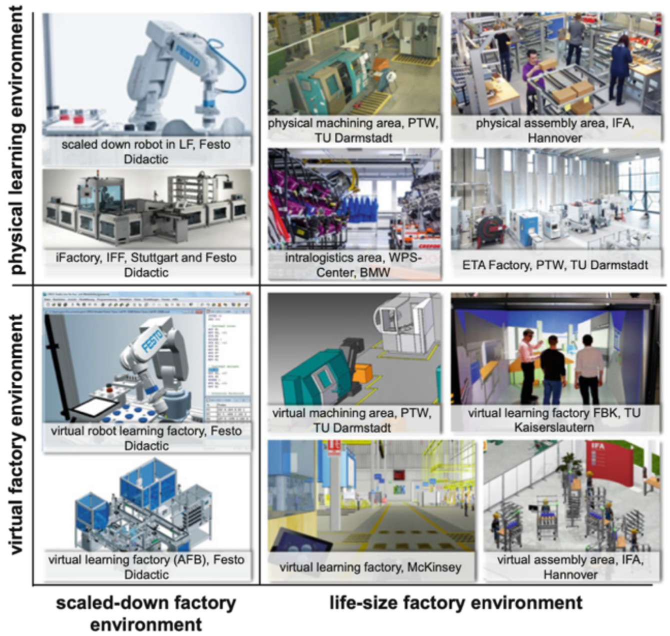

Figure 31, Size-Typology Matrix of LFs

(Simons et al., 2017) present an example of a holistic fully automated I4.0 LF called AutFab and the education within this facility, the employ problem-based lab work in the framework of project-based courses, its size is 50 m2, it uses RFID and a batch size of 1. It consists of a high bay storage, two assembly and two inspection stations, and three axis motion-controlled robot. The layout resembles that of an assembly line with workstations outlining the parameter.

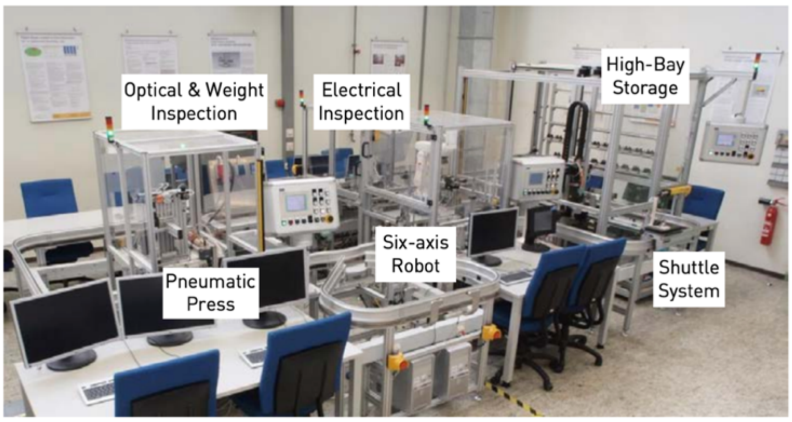

Fig. 2. The fully automated Industrie 4.0 learning factory AutFab of the University of Applied Sciences Darmstadt

Figure 32, The fully automated Industry 4.0 LF Autfab of the University of Applied Sciences Darmstadt

Another example is mentioned by (ElMaraghy & ElMaraghy, 2015) of the LF at IMS, University of Canada, where the layout changes according to system-oriented variants and reconfigurable processes.

Figure 33, The modular and reconfigurable LF at the IMS Centre, University of Windsor, Canada

According to a survey conducted with 56 colleges and research libraries in England to gather basic data about the size and structure of current MSs, 60% of students stated that the reason for operating an MS is to create an open environment that is available to the public rather than limited access to a specific discipline, which ultimately promoted social justice and encouraged engagement at university compasses. The survey concluded that none of the examples within the sample fit a mould or pattern in terms of their size, educational model, or classification. (Davis, 2018). Generally, designing the didactic of LSs can be extended and applied to the design of the LS itself to consider the learner as an active designer through new communication technologies and design tools, in a way the design can be more powerful if the learner himself is made aware of their role within the space.

A reported case study of one of the LS for EE in terms of design and education requires an author with both an architecture and engineering pedagogy background. These case studies have to be triggered by a development entity and a scholar has to document them, like the case of the novel topic produced by the CLF for this year's submissions, which is how to design LFs within existing work environments, this requires the contribution of both an engineer that understands the requirements of the tools, equipment's and machines as well as an architect that understands special requirements of the space users the specific guidelines to implement and how to integrate the existing infrastructure with the new one. This collaboration could be like that of engineering disciplines to design and construct a building. An approach is proposed in chapter 5.

3.2.1. Design Aspects and Success Factors

It was important to start from the underlying theories to extract LS design aspects and success factors. Theories regarding informal learning spaces, which can be defined as non-discipline specific spaces that are visited and used by both students and staff, to perform self-directed learning activities. can also be studied, they can be easily applied to the modality of spaces that is being discussed. Some theories regarding design are laid out, for example an LS can be observed as a theatrical stage design and not as a single function facility. (Jamieson et al., 2000) proposes the concept of a "shell" that allows flexibility and mobility of features in a space to maximize usage in a limited space constraint and budget governed by the pedagogical practices and the explored student behaviors. Planning a floor layout by the modular approach and standardizing the sizes and shapes of the individual laboratories will create a flexible floor plan that is space efficient and less costly to construct than one with fixed assorted-sized laboratories (Minero Emelina, 2018). A modular approach to laboratory floor layout is generally recommended by design professionals and often used. The single laboratory module is the starting point for the floor layout. Larger laboratories, which can support group research activities, sharing of support facilities, and the larger area required for teaching laboratories, can comprise multiple laboratory modules. From an architectural standpoint, due care must be given to these spaces to make them well organized, inviting, full of color and engaging (Blikstein, 2018). (Frazee et al., 2014) explores the idea of a LS that includes technology in all the campus' LSs for innovative course design and promotion of the learning process. The design foundation of these studios is to promote **collaborative student-centered** activities are technology, furnishings and lighting. (Harrop & Turpin, 2013) contributes to the discourse of LS design with a set of 9 attributes that define a successful learning space drawing from learning theory, placemaking and architecture, to evaluate existing spaces and guide towards redevelopment in higher educational institutions.

A summary of the aspects and the specific takeaway of each methodology is laid in the table below. Further, a conceptualized list of aspects is represented in chapter 5. This list formulated a consensus of common aspects.

References	Description & Methodology	Aspects and success criteria	Takeaways
(Marmot, 2006)	Case based studies of different existing universities' LS and Learning Centres	**Flexible** to current and evolving PA, **Future-proofed** for reallocation and re configuration, bold, creative, enterprising to support various purposes	Planning and redesign of LS for senior managers planning, to consider spaces as agents of change
(Harrop & Turpin, 2013)	A longitudinal, quantitative, and qualitative study at Sheffield Hallam University, explore learners' behaviours, attitudes, and preferences	Destination, Identity: that represents the main usage of space, **Conversation for collaboration** and	Typology used to evaluate existing spaces and guide towards redevelopment in higher educational institutions.

	toward informal learning spaces in higher education, within and outside of the context of the academic library	interpersonal communication, Community, Retreat, Timely, human factors, Resources, Refreshment	
(Frazee et al., 2014)	Case study at San Diego State University that includes technology in all campus learning spaces for innovative course design and promotion of the learning process	The design foundation of these studios to promote collaborative student-centered activities are technology, furnishings, and lighting.	Develop the model of Learning Research Studio (LRS) to promote collaborative student-centered activities
(Lau et al., 2014)	The study expands the scale to open space learning environments within the urban settings of university campuses	healing gardens, **flexible** spaces, and green buildings, creating a guideline in three design approaches; landscape design, spatial design, and green design.	Flexible spaces can be applied to the context under study, exploring the concept of architectural simulation.
(Cha & Kim, 2015)	A survey in the academic library of Eindhoven University of Technology, in the Netherlands which can be taken as an example for the educational spaces for individual tasks at	amount of space, noise level, crowdedness, comfort of furnishing and cleanliness	The factors that influence the choice of space. The paper concluded that inefficient spaces design lowers student's learning abilities.

Table 2, Comparison of aspects and success factors retrieved from the literature

3.3. Discussion

This chapter's objectives were to draw a picture of the context this paper is investigating, to describe the LS in their current state and to take snapshots of instances in the past where design guidelines might have emerged, trying to understand how they came to creation from concept to application and practice helps to develop a more profound and concrete understanding, this understanding constitutes the basis of the design guidelines and original contribution of this paper. Putting the three LSs into comparison

-HSs and MSs are grouped for simplicity, some HSs changed into MSs by time-, some deductions can be formulated:

1. Design within the context of LFs indicated design of product or assembly or manufacturing line (Simons et al., 2017) (ElMaraghy & ElMaraghy, 2015), the technological I4.0 component of the LF is considered as the core and all the other components are designed around this core. This coincides perfectly with the main objective of these spaces, but they serve very little contribution to the target of this paper. However, this design method of allocating a core that forms the main purpose of a building and then designing the subspaces around it is used in many architectural design processes, a park design around a lake or a monument or an apartment building designed around an inner court. This methodology can be used and incorporates when outlining the guidelines, it can also draw to lines of thoughts each with a different methodology.
2. HSs and MSs emphasize the communal aspect, which once again originates from their objective, through a strong design-for-needs approach. This emphasis on the human component made these spaces human-centered instead of product-centered or process-centered. HSs and MSs try to accommodate their visitors or guests. These spaces are well prepped with secondary spaces (mentioned in Figure 26), such as shower-equipped bathrooms, lounge areas and usable kitchens etc. Not only is this aspect important, but it’s also overlooked in the previous category LFs, even though the human component is the main user. It could be said that the product-centricity of LFs overlooks but even overshadows the human-component. Again, this plays in favor of the guideline from the secondary spaces design aspect.
3. FLs -compared to the other spaces– give particular care to the design aspect. The reason for this can’t be exactly pinpointed in the literature however, it could be attributed to the strong support of the fabfoundation. Interested entities in starting a FL can contact the fabfoundation and follow a specific road map, they can use the listed hardware list mentioned before and follow the sample layouts with a prototype as an example. There is also training programs with experts and posted tutorials. The prototype and it’s implemented example provided -the MSI lab- act as a strong starting point for any project and is considered as valuable material for the guideline. The underlying concept is simple; a general layout with predefined allowances constitutes the whole and the building blocks that fit within these allowances can be used as they are or reconfigured. Modernization of these layouts is feasible through modern technology but in concept dimensions, layouts and furniture remain the same.

LS Design aspects and success factors were found in publication outside the engineering field, such as technical reports and articles. The importance of integration the design dimension and the pedagogy dimension are highlighted in all the publications related to this field. The field of search was even expanded outside higher engineering facilities to include high schools that apply STEM, this expansion came fruitful, many development projects have been implemented in schools giving attention to details related to partition materials, colors, and furnishings. This step-back raises some questions: why LS design in K-18 are important as curricula design and PA but not in higher education.

3.4. Research Gaps

The comprehensive evaluation of the literature evaluates 182 papers. These papers were found through a keyword search across various databases. The review produced the following outputs:

1. The existence of several intriguing intersections that demand additional research
2. A better comprehension of some learning environments' guiding principles during their conception, planning, design, and implementation.
3. a compilation of design elements and success variables used in diverse learning environments; these elements are the product of numerous techniques.
4. The tendency for some space to focus on the design dimension while others focus on the educational dimension

Based on the results of the SLR, the following research gaps were identified, and further steps were outlined:

1. LSs frequently ignore the design aspect; instead, they tend to concentrate on the didactic aspect, particularly in articles published in databases or conferences devoted to engineering. Understanding the architecture of a space is crucial since it serves a vital role.
2. Even in settings that perform surveys or questionnaires to assess the success of a space design or design elements, the visual dimension is frequently overlooked. In publications that analyze design studies, both the qualitative (visuals) and quantitative (survey findings) components should be present.
3. In most pedagogy-related publications, the human element is absent; papers address approaches while students or the subject is hidden from view on the receiving end.

Due to these limitations, a second phase of qualitative visual analysis is required. This phase analyzes the visual and physical components of learning settings in addition to the goals of papers and publications. Because this search uses articles, online pages, news reports, and YouTube videos, a structured process is employed to lay out the necessary information before getting started.

4 Learning Spaces Analysis

The following section shows the output of the second phase of the analysis, in the form of a qualitative analysis which was carried out by means of visual analysis. The LSA methodology is explained below. The SLR couldn't be used to cover both dimensions of the research, as demonstrated in the output of the previous phase, purely theoretical results are demonstrated in the papers unless the paper showcases a case study, that's why a different approach had to be taken to support the success criteria found and displayed in chapter 1.3.2

4.1. Methodology

From the author's bachelor education, any space can be analyzed architecturally using a reversed engineering process to understand how the space came into creation (figure 26). First, A **Scope Definition** phase identifies the main objectives of the building. In theory, a. hospital is different than a school in the components than comprise them. Second, the space is divided in subspaces different in function, these spaces are outlined by partitions and walls for **Subspaces Definition**. Following the example of the school, A generic school can be divided into the following subspaces: classrooms, libraries, teachers' lounges, courts, administrative offices, cafeterias, gyms, locker rooms, bathrooms, kitchen, Mechanical, electrical, and plumbing rooms (MEP), storage etc. These spaces are listed in the **Space Program**, the space program contains the number of spaces from each category and their minimum surface area, each space is annotated a number. Next, these spaces are categorized in **Subspaces Categorization** based on function. Preliminary spaces comprise the main activities of the building, these main activities can't be removed from the space program otherwise the building can't carry its main objective. Secondary spaces are those that aid the preliminary ones, they constitute the infrastructure of the building, without which the building doesn't function. In the school example, the preliminary spaces are classrooms, libraries, and the office spaces. If you imagine a school without any of these spaces, it would be a dysfunctional space. On the other hand, all the other spaces listed above are complementary functional spaces, they are still vital to the integrity of the school. Next, **Circulation** is identified to connect these spaces and identify the type of relation between these spaces, pathways could be vertical or horizontal, private, or public depending on the spaces being connected. Finally, **Furnishings, Finishings and Equipment** are listed for each space typology. **Lighting and Ventilation** are considered as part of the infrastructure of the building related to MEPs. This process is quite intuitive, the depth of the analysis and level of detail increases depending on the objective of the analysis and the background of the person conducting the analysis. Lighting is analyzed in passing depending on the positioning of the fixtures in the space and the overall space to void ration. Unfortunately, due to the absence of floor plans of the spaces understudy, blind spots are eliminated from the study. Also, ventilation isn't an element that can be deducted from images and therefore it's skipped in this analysis.

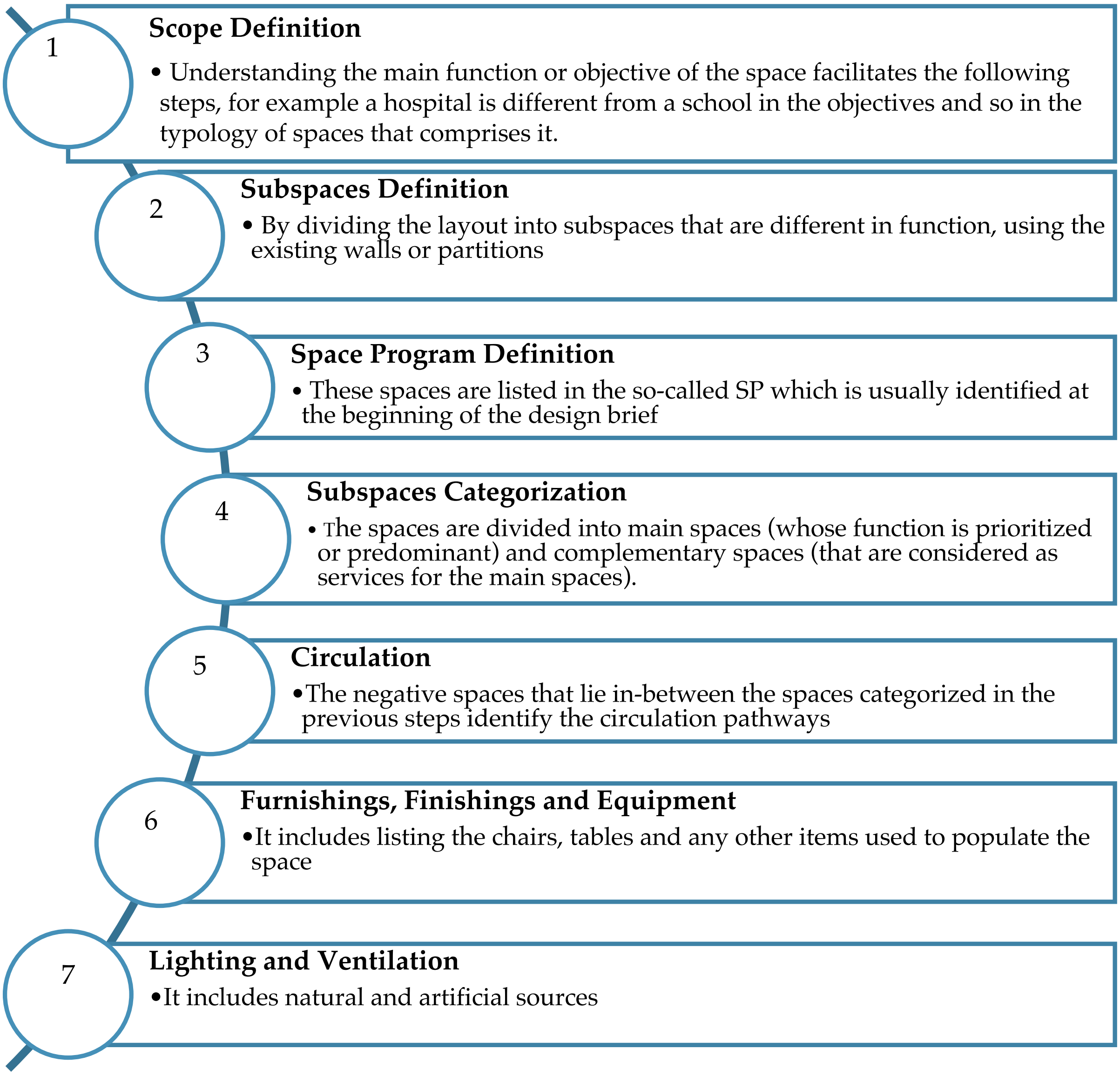

Figure 34, 7-step methodology for Space Analysis

4.1.1. Selection Criteria

This phase of the analysis is mainly qualitative, it takes individual examples of learning spaces as a unit of visual analysis based on:

- **Seniority**: as older spaces tend to be more mature as they undergo several phases of development.

- **Accessibility**: visiting near locations at Bovisa Campus in Politecnico di Milano.
- **Availability of online data** such as walking tours and 360° videos are used.

In this phase, sources such as articles, YouTube videos and videos published on other channels were used. This research results in the comparison of the spaces in terms of design features including space utilization, material used and color to determine their defined factors and the reasons behind their successful implementation. The output of this analysis is a description of the single space aided by pictures and snapshots.

4.1.2. Analysis Framework

The set of attributes covers both dimensions that the paper is pursing; **PA** and **PD**, trying to understand where they overlap and interplay to affect each other. The author puts forward a framework which is outlined built on three axes representing the three dimensions mentioned in the introduction chapter.

1. Identification: This dimension reflects the first chapter of the introduction. The responses are retrieved from the official websites of these spaces. It's important to categorize the space as it identifies itself. The year of establishment is based on the seniority criteria mentioned before. This axis answers the question:
    - What is the space?
    - When was it established and which entity is it affiliated with?
2. Pedagogical approached: The second axis asks the questions:
    - How is the space executing its objectives?
    - What are the approaches that they utilize in their projects?
3. Architectural Features: The third axis asks the questions:
    - What are the architectural features of the space?
    - How is it designed?
    - Is there a specific layout?
    - What are the subspaces that comprise the space?
    - Which of these spaces are main and which are considered secondary?
    - What is the equipment used and listed by the space?
    - How are they placed within the space?
    - How does the space layout and furniture promote collaborative design and student-cantered work?
    - Is there sufficient lighting to execute the tasks?
    - What type of educational assisting tools are used?

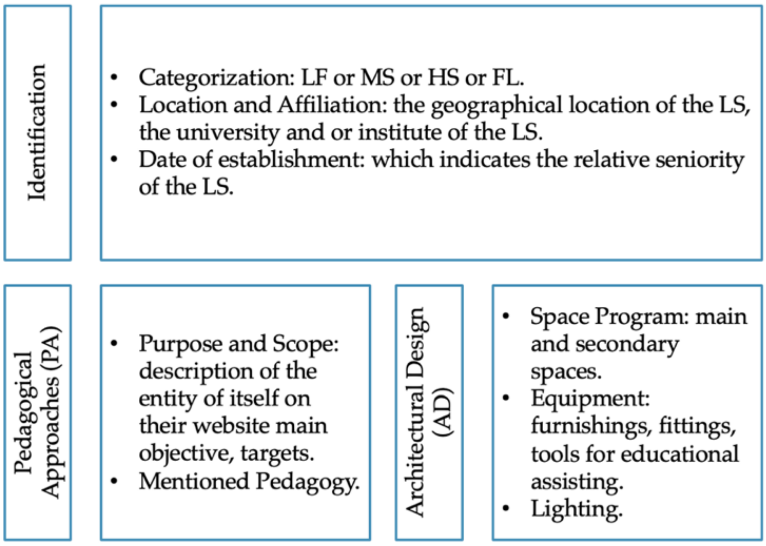

Figure 35, LS Analysis Framework

4.2. Results

4.2.1. Werk150 - Reutlingen University, Germany

- The Factory of the ESB Business School on the campus of Reutlingen University, Germany, Network of Innovative Learning Factories (NIL). It was founded in 2011 (Werk150, 2022), where it started as a set up in 2013 in a building basement "ESB Logistics Learning Factory", later it was renamed "Pilot Factory Industry 4.0"
- They identify their scope as production and statistics, represents a technical plant and a place for creativity production. The learning factory Werk150 houses the assembly line of a multi-variant scooter in a hands-on learning experience.
- With a Surface area of 800 m2., The space is composed of a technical plant that is centralized in the space with a clear separation from the secondary spaces, The place includes workspaces for students and a room for seminars in the mezzanine floor separated with a glass partition that always for visibility. In the far corner – in parts with low circulation and are considered dead – lies an archive whose structure entails the walls of the room. Mobile chairs and cars are scattered around. Also, a large display screen is stated at the far end of the room for presentations. For lighting, large side doors like those of loading decks are used in addition to artificial lights handing from the ceilings.

Figure 36, Main floor and Conference room in mezzanine floor at Werk150

4.2.2. Process Learning Factory CiP , Technical University of Darmstadt, Germany

- The factory was established in 2007 (TU Darmstadt, 2020) that serves as a learning centre for research and training.
- It's a small-scale real-life training manufacturing site that offers easy access to hands-on training experience whose aim is the development of engineering competences.
- The space is around 500 m2 and contains 2 machining lines with machine tools, 2 assembly lines, Cleaning and QS shop floor management, learning cells situated in multiple rooms along with work areas and computer stations in a separate mezzanine level, storage areas, conference rooms. There are movable tables/chairs, boards. It's also noticed that yellow tape is used on the floors to highlight locations of movable objects to create clear pathways for circulation and safety. For lighting, Floor to ceiling glass facades, artificial lights are used even though the space to void ratio could be improved (Institute of Innovation and Industrial Management, 2021; PTW TU Darmstadt, 2020)

Figure 37, Snapchot of CIP's tour

4.2.3. Model Factory@SIMTech, Singapore

- To increase the competitiveness of Singapore's manufacturing sector, the Singapore Institute of Manufacturing Technology (SIMTech) creates high-value manufacturing technology and people capital. In the fields of precision engineering, medtech, aerospace, automotive, marine, oil & gas, electronics, semiconductor, logistics, and other areas, it works with several local and international businesses.
- The Model Factory@SIMTech (SIMTech, 2020) is a cutting-edge facility that gives businesses the opportunity to experience and experiment with advanced manufacturing technologies before integrating them into their own production processes. It was introduced in October 2017.
- The 604 square meter facility at Fusionopolis 2 in one-north contains state-of-the-art, fully automated, industry-ready technologies that enable live demonstration in a manufacturing setting that supports lights-out. The factory is a creation of research in numerous fields, including microfluidic science, automation, systems, and industrial processes. The LF offers a 3D model of its space, the blue-colored areas represent shop floor areas, green represents resource management, the nerve center is in yellow and enterprise in orange, purple represents supply chain logistics. A virtual tour is also offered on their website. The space is divided differently, instead of centralizing the shop floor it is divided in two and all spaces are accessed through a central pathway. An entire room for simulation is dedicated equipped with a real time dashboard that provides total operations visibility over the shop floor.

Figure 38, Model factory 3D model

4.2.4. AIA Laboratory, University of Los Andes, Colombia

- The “Integrated Learning Space” or AIA Laboratory was established in 2018 (Universidad de los Andes, 2020).

- The space is designed with a student-centric approach in mind, Projects are design with a problem-based learning objective through various didactic activities by professors and researchers. The scope of the lab includes metrology, process simulation and industrial automation as well as additive manufacturing.
- On their website, there is a clear description and a model of the separate spaces, and their utilization accompanied with a 3D model visualization. The separate the lab into two spaces AIA 1 for complementary activities, workshops and games with 60 workstations and movable furniture for a capacity of 54 students. The front part AIA 2 is where the industry 4.0 simulation Centre takes place, with a modular conveyor belt and automatic feeders. From the images, both spaces look well-lit with a semi opaque partition separating the two areas which doubles in function as a board.

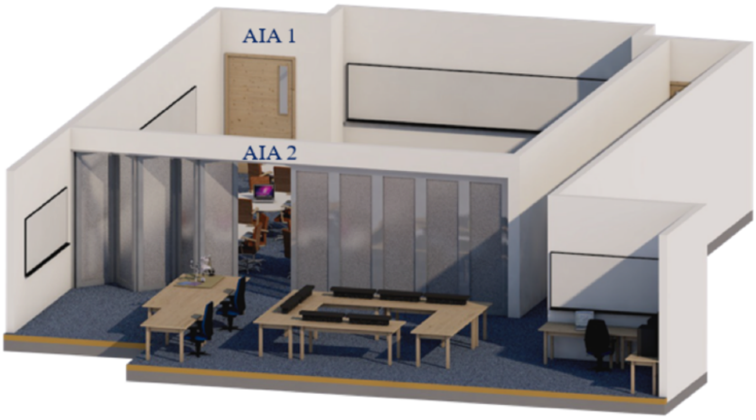

Figure 39, AIA 3D model

Figure 40, AIA interior

4.2.5. Machbar Fablab, Postdam Germany

- The lab was created in 2011 (fablabs.io, 2022)
- It is an open workshop for every to meet and learn, they offer free, low threshold and self-creative use of workshop rooms, with and without specialist instructions

and guidance in an environment that encourages collaborative transfer of knowledge and skills. The directory lists the lab capabilities as 3D printing, CNC-Milling, Circuit production, Laser cutting, precision milling and vinyl cutting. They list (machBar-Potsdam, 2022)their equipment in three categories: wood workshop, rapid prototyping, and an electronics laboratory. They have a repair café where people fix faulty household items in cooperation with the city and stare library in a campaign to promote personal initiatives and a more circular economy.

- There is a 3D model visualization on their website and some videos (Parade, 2014)as well. From videos, the space looks like a one-story warehouse-like structure that's partitioned inside for the different activities, tools are lined on the walls and miscellaneous cupboards are used to store materials, large windows are used for lighting along with artificial units.

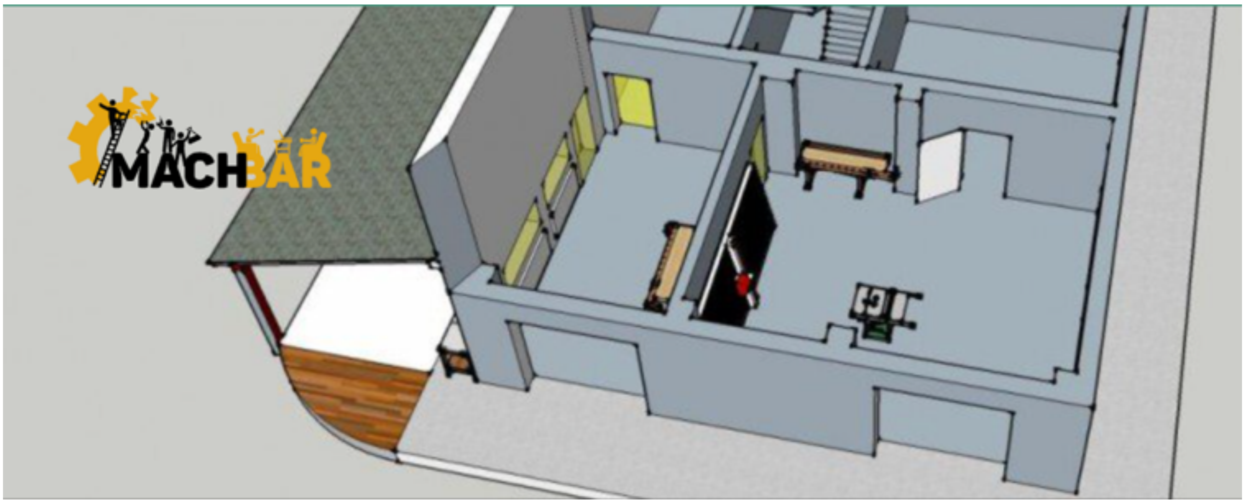

Figure 41, Machbar 3D model

4.2.6. Museum of science and industry Wagner Family Fablab, Chicago, United States

- The lab was opened in 2007
- The space is dedicated to computer-based innovations lab offers services for personal, corporate, and independent projects, one of the noteworthy workshops is the Dream it, Design it, Fab it! for guests and interested teenagers to develop their fabrication skills. It also offers a one weeklong summer camp for.an immersion in innovation and design (Wanger Family, 2022)
- From the offset the FL offers a blueprint of their space, with a detailed listing of the furnishings and finishes used in the space. This blueprint can be used as a guide for future FLs along with the list of tools mentioned before. The space is approximately 177 m2, the space can be easily separated into two main spaces,

color coded in red and blue in this tour (MSI, 2007) the FL area with an entire wall lined with a modular workbench furniture system that comprises of a workstation, and overhead shelves with tools and components divided in labeled boxes

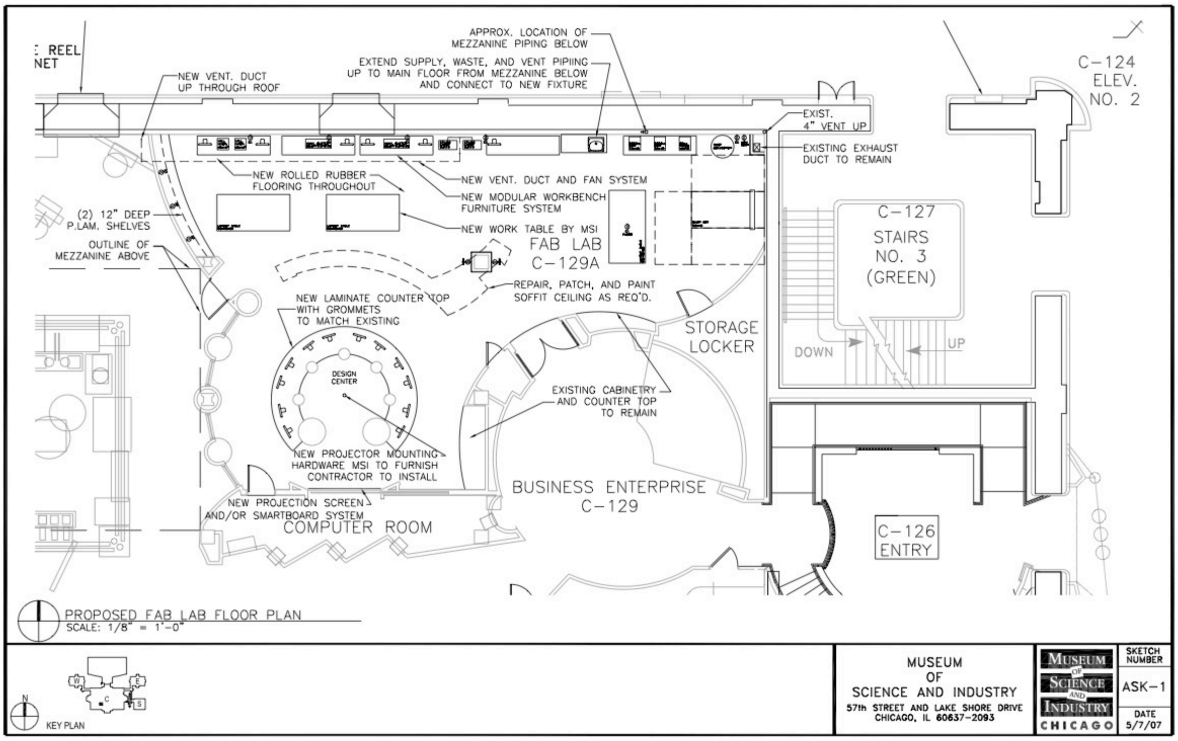

Figure 42, Proposed FL floor plan, MSI, 2007

Figure 43, FL C-129A zone indicated on floor plan

4.2.7. Polifactory, Politecnico di Milano, Milano

- The Fablab was established in 2016 (Polifactory, 2020a)

- It is a multidisciplinary collaborative initiative between designers and engineers at the Bovisa campus in the north of Milano. The lab advertises itself as a makerspace in function, it's registered on the Fablab database, it's dedicated to new design and production models for products and services. The experience offered is experimental training and research to explore new scenarios and tackle various challenged. The activities (Polifactory, 2020) offered are hackathons and workshops and scenario building.
- The inauguration (Polifactory Politecnico di Milano, 2016b) of the space gives a view of the spaces and a detailed zoning layout is posted on their website and a guided tour (Polifactory Politecnico di Milano, 2016a) of the tools explains the equipment used and are also listed here (Polifactory, 2020b). The place is equipped with a CNC milling machine a 3D Printer a vinyl cutter in the additive manufacturing area.

Figure 44, Polifactory Poltecnico di Milano

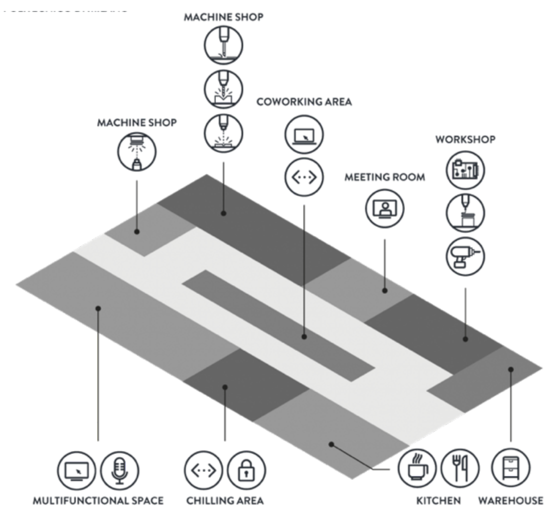

Figure 45, Polifactory detailed zoning layout

4.2.8. Full Sail Fab Lab, Full Sail University, Florida, US

- The Fablab was built in 2017 (fablabfoundation, 2022).

- It is a platform that allows Simulation students to rapidly prototype, test, and invent new things. The manufacture of parts for simulation projects will be a key component of several courses in the Simulation and Visualization curriculum. The curriculums are hands on and project-based that require custom parts.
- A detailed tour (Full Sail University, 2020) of the lab lists the equipment used inside The space contains advanced machines such as Fusion deposition modelling machines with switching cartilages, Resin printer with 200 materials, CNC mills, universal laser cutter, injection modelling machine. Electronics centre -in the figure below- contains tools and instruments for prototyping and testing of chips, with an adjacent, a laser scanner. The space is laid out similarly to the prototype, tables aligning the walls with overhead shelves and a middle space with workstations and tables, ceiling suspended cables are used to power these island stations. Lighting units line the ceiling in a staggered manner.

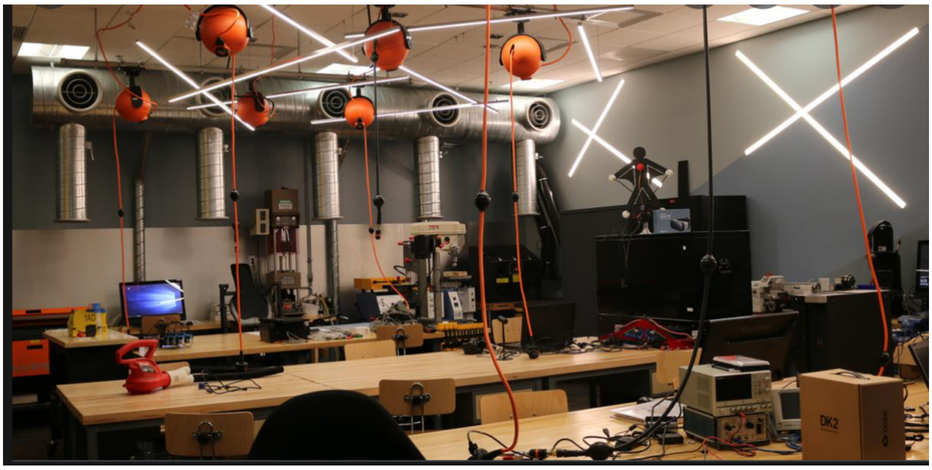

Figure 46, Fablab Full sail

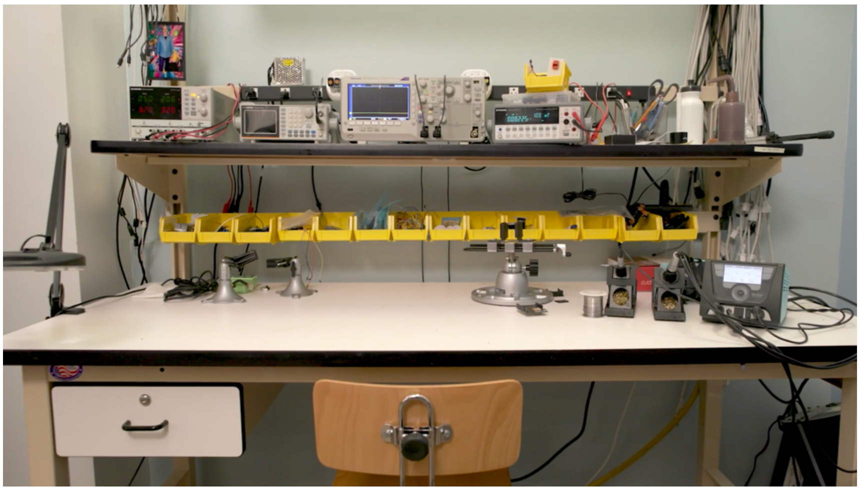

Figure 47, Electronics Centre

4.2.9. i3Detroit makerspace, Detroit, US

- This makerspace publicizes itself as the biggest run DIY workshop (i3Detroit, 2021).
- Through Fab Lab components, the location offers materials, classes, and workshops in a variety of fields including woodworking, metalworking, welding, electronics, crafting, and digital fabrication.
- The space is built in a warehouse with an open plan design, the space is divided in 20 zones by physical grouping of equipment on function base.

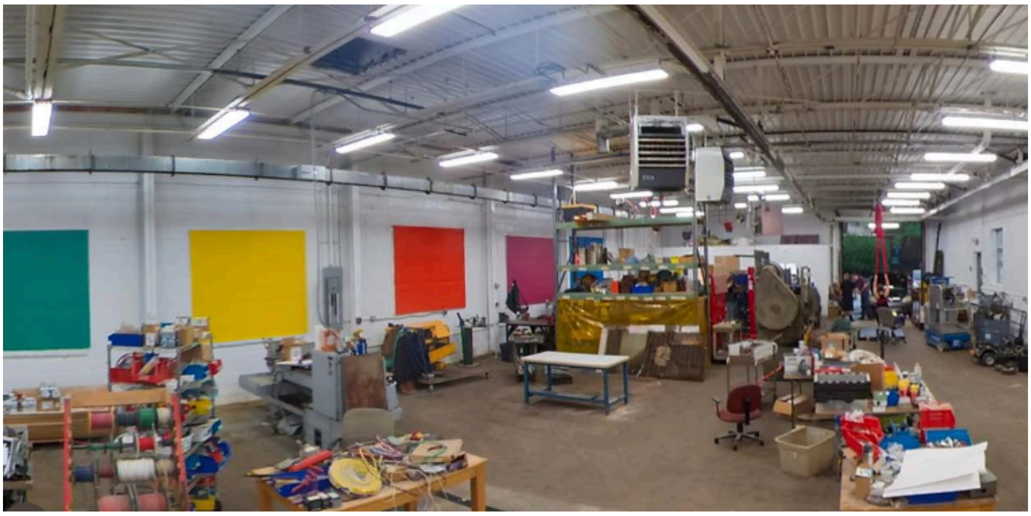

Figure 48, i3Detroit makerspace

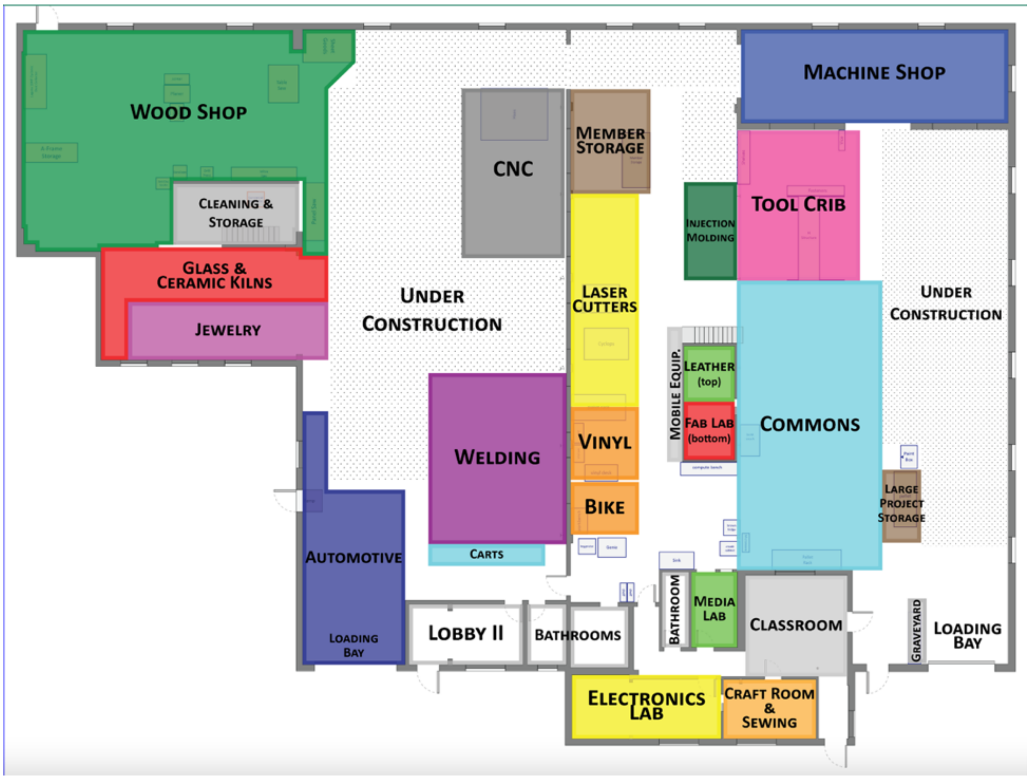

Figure 49, i3Detroit layout

4.3. Discussion

In respect to the second dimension which is PA, it was found that the spaces don't conform to a specific approach, when outlining their curriculum or setting their goals and outcomes, the entities set up these spaces don't state a link between the intended projects or activities and the overall design of the space. An LS sets out with general goals such as: create an environment or platform for DIY, which echoes the design-for-need approach taken by HSs which is mentioned in section 1.1.2, Furthermore, from the reviewed "About Us" pages of several FLs, It seems that curriculums come second in these spaces after imagination, design, and reflection in an iterative process to find solutions for challenges.

From the third dimension related to AD, some similarities and differences were observed between the spaces which lead to dividing them into two clusters:

1. LFs can be identified visually despite the different scales and levels of maturity or digitalization (figures below) The dominant aspect within these spaces are the equipment and corresponding attachments and tools. There seems to be a shared design layout, where the assembly or manufacturing line is centralized in the space and the other subspaces are placed around this central position. This could be due to the fact of the prevailing importance of the tools and equipment.

Figure 50, Lead Factory Institute of Innovation and Industrial Management (IMM), Graz University. Of Technology, Austria

Figure 51, Lean Learning Factory, University of Split, Croatia

Figure 52, Pilot-Factory Industrie 4.0, Vienna University of Technology, Austria

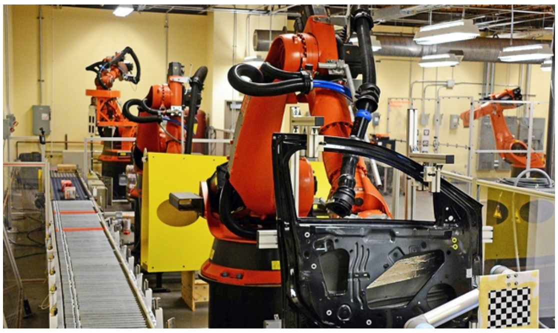

Figure 53, Intelligent Learning Factory (ILF), Purdue University, United States of America

Figure 54, LPS Learning Factory, Ruhr-Universität Bochum, Germany

Figure 55, Die Lernfabrik | The Learning Factory, Technische Universität Braunschweig, Germany

Figure 56, Lernfabrik für Schlanke Produktion (LSP), Technical University Munich, Germany

Figure 57, FSRE Learning Factory, University of Mostar, Bosnia and Herzegovina

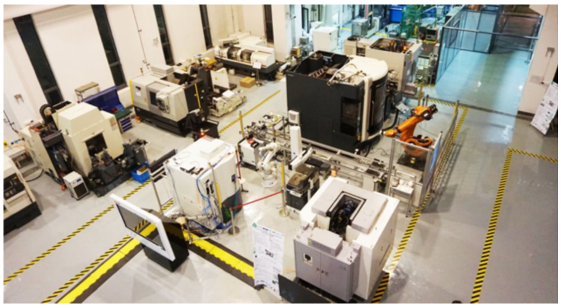

Figure 58, Learning factory for 5G and AI in production, Tongji University, China

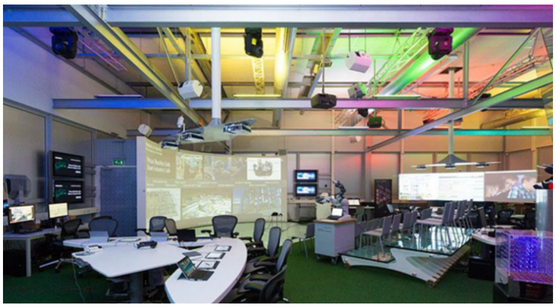

Figure 59, University of Twente, Faculty of Engineering Technology, Department of Design, Production and Management

2. MSs, HSs and FLs could be grouped together in a single cluster due to some visual similarities. First, according to identification, the spaces don't conform strictly to a specific identification, for example a FL can easily have the term "makerspace" in their description and vice versa, due to their objectives and common tools and equipment used. Second, the layout of the spaces is as follows: an open space with multiple zones, each zones contains a grouping of tools and equipment that serve the same function. This layout is characterized by flexibility and fluidity. Ample storage space is lined on the walls and multiple shelving units are installed.

Figure 60, Insper Fablab, Insper University, Brazil

Figure 61, Fablab Cali Universidad Autónoma de Occidente, Colombia

Figure 62, Makerasyulum, Mumbai, India

Figure 63, Wagner Family, Fablab

Figure 64, ProtoSpace Fablab, Utrecht, Germany

Figure 65, Noisebridge HS, San Francisco, US

5 Design Guidelines

A complete Learning Space Design Guideline (LSDG) is considered as a standard document for the planning and design of LS. The LSDG offers a general direction and recommendations, as well as specifications with a higher level of detail to include technical considerations. The main objectives of the LSDG include but are not limited to:

1. Creating standardized Learning Spaces with pre-defined design aspects.
2. Documenting Learning Spaces design aspects and success factors to support users including students, teachers, and space operators.
3. Minimizing problems related to design and construction that have an adverse impact on learning settings.
4. Reducing change orders and assisting in project cost savings.
5. Creating an environment that is future-proof and resilient to developing pedagogical approaches and technological advancements.
6. Constructing a communication mean between architects, engineers, and technicians that form the project team.

The LSDG could be used by a project team consisting of a facility planner, Audio-Visual team, project manager, architect, consulting and building users. The LSDG is intended for new construction projects that allows the design and construction of a new space through the compliance with the guidelines. Leveraging the databases International Association of Learning Factories (IALF), wiki.hackerspaces.org, makerspaces.make.co and Fablabs.io/labs can be used to circulate the guideline and update in periodically by inputs from different spaces. The different spaces share their experiences and practices in a unified platform. The platform releases a LSDG to act as a snapchot of the current state of the spaces. An entity such as a university can consult the Process and the Guidelines to construct a new space. The proposed approach can be used for any of the LSs tackled in chapter 1.1. The result of the expanded analysis of the selected pool of LS indicates the possibility of regarding LFs, MSs, HSs and Fablabs as a single entity, to start the design process.

5.1. Proposed Approach

In this context, a LS can be considered as a **complex system** according to the listed variants of generic products, that can be decomposed into several subsystems that are developed by many teams working in parallel. In a sense, a functional space is shares commonalities with an airplane or an automobile. They both have mechanical systems (ventilation, hydraulic and electrical), both can vary in scale to occupy more than one user.

On examining both processes, the project plan (Figure 8) and the PDP (Figure 9) some overlaps can be found. Generally, both flows start with a planning stage, then a conceptualization of the product, then implementation of the design concept on one or more than one levels; system-level and detail design, then finally, a realization of the product. To confirm this overlap, all the listed outputs of the BPP are rearranged to fit the PDP without elimination or alteration (Table 3) These outputs are emphasized in bold.

The integrated Planning phase within the Schematic Design can be extracted and separated to create a phase zero. The difference in the starting point or phase zero is that usually Building Projects originate with a pre-defined need which explains the absence of a concept selection step in the BPP. This case applies to small scale projects or specific client base. This is different, however, in the case of larger scale urban projects where the objective is to develop an entire area. For example, a communal development project might require the construction of a medical center, a library and shopping center. For a university, that's a single client, the objective of building a cooperative learning space can end up in only one of the alternatives mentioned in chapter 1.1 or a different variation of these same spaces.

The additional outputs in the PDP are underlined. These outputs shed light on a broader field of study that can be further investigated in future works. For example, market objectives indicate a competitive environment where companies aim to compete a competitive advantage. In the field of educational institutions, the goals are competency development as initially stated in the introduction. However, ranking among top universities can be considered as a competitive advantage, where the design of high-end state of the art learning spaces contributes.

The analogy between Product Architecture that comprises the geometric layout of the product and its subsystems fits very well with the Space Program and the Zoning in phase 3 Detail Design. It also echoes the proposed premise that a building can be considered as a complex system. Phases 4 and 5 regard product realization and not Design, they are considered outside the scope of this study.

Table 3, Cross-reference Project Plan and PDP

Phase	Building Project Plan	Product Development Process
0 Planning	❑ Selected project team ❑ Project schedule ❑ **Project budgeting** ❑ **Project scope and goals**	❑ opportunities within a pre-defined corporate strategy ❑ **Assessment of available or required technological development and market objectives.**
1 Concept Development	❑ budget trade-offs ❑ **required learning technology options** ❑ **technical and operational requirements** ❑ Site analysis ❑ Understanding of building codes that are specific to each country.	❑ <u>Identification of target market needs</u> ❑ **Identification, generation, and evaluation of alternative product concepts** ❑ Concept selection ❑ **Listing a set of specifications** ❑ <u>Analysis of competitive products</u> ❑ **Economic justification of the project**
2 System Level Design (2 Schematic Design)	❑ **"Functional Program" or "Space Program" (That lists the spaces and subspaces)** ❑ **Size, location, interspace relations (Zoning)** ❑ **Outlining basic design and operations** ❑ Plan approval	❑ **Product architecture** ❑ **Decomposition of the product intro subsystems and components** ❑ **Identification of preliminary design of key components** ❑ **Defining initial plans for production system and final assembly flow diagram** ❑ **Geometric layout of the product, functional specification of each subsystem**
3 Detail Design	❑ **Selection of building materials and finishings** ❑ Selection of fixtures (windows, doors, and appliances) and furnishings ❑ Laying out structure, plumbing, electrical, heating/ventilating system or any other systems. ❑ Energy analysis ❑ Interior and exterior design approval	❑ Specification of the geometry, materials, and tolerances of the parts ❑ Identification of all standards parts of the product ❑ Control documentation
4 Testing and Refinement		❑ Construction and evaluation of multiple reproduction versions of the product (alpha and beta prototypes)

Guidelines

5.2. Selected Design Aspects

Based on the gathered design aspects from the SLR (Table 2) a finalized design aspect framework is conceptualized, these aspects are to be considered as principles when applying the guidelines to the specific LS or subspace.

Aspect	**Explanation**
Interaction	• The space should enable meaningful, collaborative interactions, it should create a conversation for collaboration. • It considers all human factors that would utilize the space • All elements of the space (chairs, tables, equipment etc.) should support student work.
Flexible and Future-proof	• Furniture should be easily movable and supports quick changes from one layout to the other (for example from a classroom to a conference room and vice versa) • The infrastructure should be adaptable to technological advancements and space objectives developments.
Environment	• Design must be sustainable and healthy to allow for effective carrying out of the learning activities. • MEP systems need to be well adjusted to the needs of the place. • Thermal comfort must be achieved throughout the space. • Acoustic and lighting control system should be available • Colours, materials, lights, and acoustics have control on the user's learning experience and well-being.

Table 4, Design Aspects

5.3. Guidelines

As previously mentioned, each space is made of its unique subspaces. The guidelines don't consider an entire LS but the individual subspaces that comprise them. The guidelines choose and focus on three basic types of subspaces found in almost all the LSs that were analysed, the author considers these subspaces as a necessity for the achievement of the objects of the space, and for a round learning experience.

This section includes quick references that summarize information on the key aspects of the 3 subspaces described in the LSDG:

1. Collaborative workspace
2. Conference Room
3. Informal Space

The subspaces are described as discrete types but in practice there is a continuum of rooms and spaces. It's advised for instructors to use all spaces in a creative way.

5.3.1. Collaborative workspace

This subspace is the most common subspace in all the investigates LSs, a single collaborative working space is most effective for 20 to 40 people with a single unit (table) multiplied across the space. The collaborative workspace is usually placed in the middle of the layout of the LS do its importance. With correct manipulation collaborative workspaces can transform into conference room and vice versa.

- Structure: flat for to accommodate users.
- Movable layout and furniture with high tables
- Sufficient table space is required to support different activities, a single table can hold between 4-6 people with equipment and tools
- Tools and Equipment: multiple boards and marker, interactive projectors and screen, overhead cameras can be used to record the work being done.
- Power supply: 100% of spaces, solution like the one in the full sail Fablab (figure 73) which is an overhead supply can be used
- Lighting: multiple lighting zones.

Figure 66, Museum of Science FL

Figure 67, OpenDor fablab, Milano

Figure 68, Fablab Facens, Brazil

Figure 69, Fablab SAPeri& Co, Roma

Figure 70, Fablab du Quart, Saint-Céré

Figure 71, Fablab IED, Madrid

Figure 72, Fablab Webschool

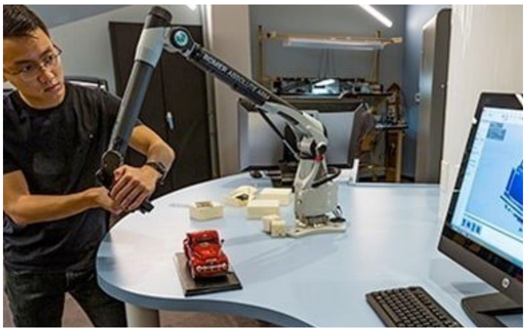

Figure 73, Full Sail Fablab

5.3.2. Conference room

This subspace can be used for lectures, presentations, demonstration, and media viewings. The design should be flexible to accommodate active learning opportunities, such as break-out and small groups, discussion, and debates as well as small group project work. The subspace in this context is not intended for numbers higher than 75 to 100. From the analysis, the LSs range in area between 200 and 1000m2 for the largest scale LF found.

- Structure: Tiered or flat, note that for tiered structures loads need to be calculated and a steel structure need to be installed. Other more flexible options can be used (Figure 72)
- Multi orientation: variations have no front of room instructor area similar to LRS in section 1.3.3.2
- Sufficient table space is required to support different activities
- Tools and Equipment: multiple boards and marker, interactive projectors.
- Power supply: 100% of spaces
- Lighting: multiple lighting zones.

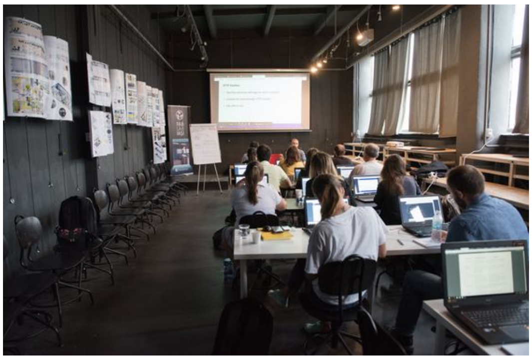

Figure 74, Example, moveavle small groub tables and chair: fablab at the politechnic University of Laso, Romania

Figure 75, Example modular movable tables and chairs

Figure 76, Staffordshire Univeristy Classroom

Figure 77, Bentley University Conference Center, MA

Figure 78, Event and Conference area, Emory University

Figure 79, Flexible training and conference facility, Moller institute

Figure 80, conference room with built-in floor rake

Figure 81, Werk150 Conference room

5.3.3. Informal Space

This is the most effective type for unscheduled meetings between students and or instructors. It was noted that this type of subspace is overlooked in the LSs. Each LS needs an area for groups of smaller numbers to do simpler activities such as brainstorming away from the collaborative workspace crowded by tools. The space is not to be considered recreational, it's different from a break room.

- Design should be purposeful and attractive. It should be considered in the design phase.
- Furniture: it's considered to be the star element of the subspace; clever furniture allows for minimal maintenance and operational staff management.
- Sufficient table space is required to support different activities
- Tools and Equipment: integrated screens, socket boards, and even display screens (Figure 83)
- Location: these furniture items can be cleverly located in circulation pathways (Figure 87) or in unutilized corners and spaces
- Inviting colours should be used
- Allow for privacy in some areas
- Power supply: 100% of spaces
- Lighting: multiple lighting zones.
- Acoustic controls

Figure 82, The Idea Garden, Indiana University, Indianapolis

Figure 83, Immersive pod, St. Edwards University

Figure 84, learning space, by steelcase

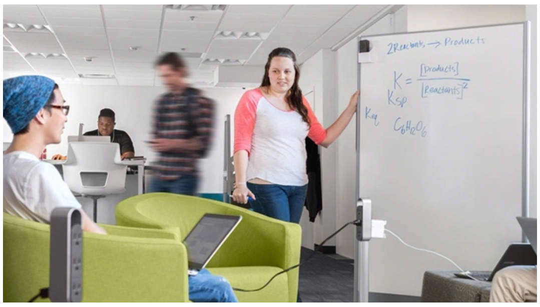

Figure 85, standing power outlit is used

Figure 86, motivational learning space by rosan bosch

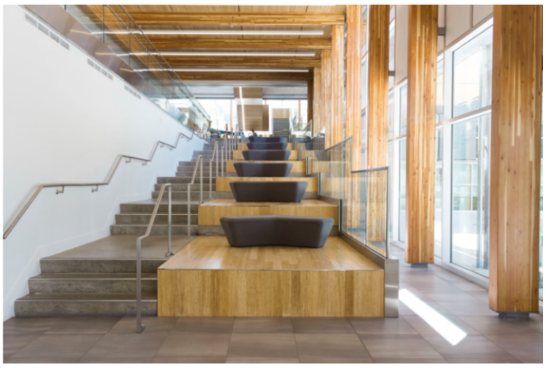

Figure 87, smart utilization of space, University of British Colombia

6 Conclusion

6.1. Research objectives

The paper succeeds in achieving the objectives it set out to, in conclusion the following goals are attained by the paper:

1. Carefully **reviewing the literature** to investigate how LSs in higher education interact with the PAs working in these settings and with characteristics of their physical design. A **conceptual framework** encompassing LS typologies, instructional methods, and architectural design has been created through the analysis of 182 works. Also, design practices are summarized.
2. A **picture of the current educational spaces' physical layout** and design was obtained, structural similarities across the various categories were identified, and additional research questions were posed to fill in the gaps.
3. By comparing the processes of a building and a product, it is possible to view a building as a product and **standardize the process** to comply with the given design guidelines. Additionally, a **novel construction approach is suggested** to meet the design sector.
4. A **comprehensive framework** made up of a **design theory**, design elements and success factors taken from the literature, as well as a **design guideline** to document the work, is proposed.

6.2. Future work

1. The IALF data is still limited to the 16 members of the association. For each member the following data are provided: operational status, latest developments, topics for research and training, partners, media, and a direct link to the website. The media section contains some videos of specific processes, a handful of spaces provide a virtual tour of their space. Some virtual tours only emerged due to the emergency state in the beginning of 2020. Some LFs publish

a few pictures on their website that are not enough to understand the entirety of the space. The other databases don't support images all together, so the addition of a section dedicated to the physical aspect of the space design to the database.

2. A qualitative analysis in the form of a survey should be done with each entity to understand the process of creation of these spaces, the factors taken into consideration, satisfaction of users of the space, suggestions of improvement. The results should be compiled to understand common factors, best practices, and development plans.
3. A cooperation between architects and engineers is needed starting from the collaborative interdisciplinary nature of these spaces and the works they do in the design of LS. LS should be considered as a design project with objectives and stakeholders. Design aspects and success criteria should be incorporated in the design based on best practices and literature. The first and last chapters take a step in the path of this process. An archive of space layouts based on the different type of tools and equipment used should be available in an online database.
4. A collective PA framework should be outlined that connects the process, output and required goals to achieve. This framework can be built through inputs from different learning spaces that are willing to contribute and collaborate. This framework can unify the processes and reflect on the design scheme mentioned in the previous point. This allows for bottom-up diffusion of knowledge and expertise from the individual entities to reach a unified approach.
5. The LSDG can be adapted to renewal and renovation projects. These projects have pre-defined structural grids, pre-set dimensions, and other fixed elements. The LSA can be used as an initial step alongside a satisfaction survey as a starting point.

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