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TECHNICAL PAPER

A new mechatronics laboratory for technology integration

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Abstract While teams and projects tend to be multi-domain, the infrastructure required to integrate and build prototypes lags behind to allow an efficient interaction and to offer multi-disciplinary facilities. Hence this paper presents an infrastructure approach developed in a Latin American academic context, where the concept of an Engineering Building is explained in order to support the demands of a 3rd Generation University. A deeper emphasis of this article is placed upon the development of a Technology Integration Laboratory in terms of functionality, capacity, adjacencies, furnishing and, physiologic and psicologic support. The layout design is based on the concepts of Mechatronics and Technical Systems while enhancing a teaching–learning-building process. After 5 years of operation the results obtained in terms of prototyping, filed patents and projects with the triad government-industry-academy are discussed. Our experience shows that such hands-on engineering facilities are worth having, especially within a virtual education growing trend, and that openness has influenced an increment of the Intellectual Property results.

Keywords Collaborative space · Technology integration · Academic architecture · Open laboratory · Mechatronics · Technical systems

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1 Introduction

A Third Generation University (3GU) is an institution that equals its efforts around education and research with the exploitation and/or commercialization of the knowledge that it creates. It requires to collaborate with technology driven enterprises and search for the best students, in order to become the nucleus of an international know-how hub, a site where academic institutions mix with institutions of industrial and other research, a place that no-one in the field of interest can miss [15]. Recent successful experiences such as the Learning Factory show indeed the convenience of these facilities, based on the fact that students want to do engineering and that the industry wants change [7].

Besides, students should resemble, during their proffessional career, everything experienced during their studies. Therefore by having extraordinary facilities could lead into making the difference with the future employees, leaders and entrepreneurs.

On this effort, Universidad EAFIT opened the current Engineering building in August 26 - 2010 during the University's 50th and the Engineering Faculty's 30th anniversaries (Fig. 1a). It represents a milestone for the university itself and the city of Medellin-Colombia due to (i) its architecture as it was awarded the 2nd place at the CEMEX Institutional Building award in the year 2011, (ii) its sustainability due to its lighting and ventilation systems as well as its green living facades and (iii) its conceptual interaction underneath each floor. One clue for its success was the involvement of the eventual inhabitants during the design and development; as quoted by Mejia [9] the University's president: "It is not a building that stores a faculty, but a faculty that designed its own building".

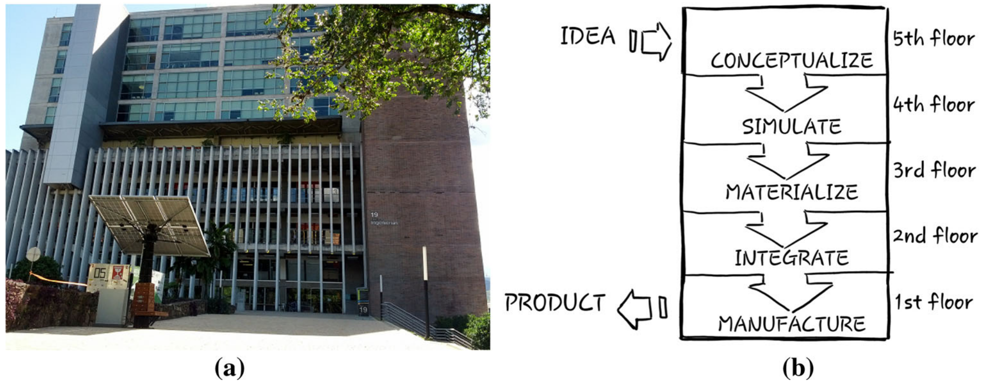


Fig. 1 **a** Front facade of the Engineering building (May 2015). **b** Engineering building concept conceived in 2008

1.1 The engineering building's concept

Four general indications were given from its inception: (i) to vertically distribute from top to the ground floor an analogy of the steps usually performed during an engineering project, from its idea conception until its manufacturing (Fig. 1b), (ii) to share high quality laboratories among academic departments instead of medium quality ones owned independently, (iii) to facilitate the creativity process of its inhabitants and (iv) to incorporate in every floor a gross area of 1000 m^2 (25 m wide × 40 m long), nearly eight times bigger than the former laboratories that were moving into it. In order to tackle these indications, each floor had designated a team composed by professors from different academic engineering departments, technical staff from different laboratories and the architects to whom the construction was commissioned. Additionally, specific guidelines for each floor were given as follows:

Fifth floor—conceptualize. The 5th floor's team was in charge of conceiving a place to bring ideas and concepts along with other institutions, whether academic, industrial or governmental. A place where the once separated worlds of academic and industrial research could increasingly intertwine [15].

Fourth floor—simulate. The 4th floor's had the goal to design a place for simulation and modelling in order to represent and comprehend objects, ideas and technical systems in a virtual environment, allowing also to anticipate eventual faults in the real world [4]. Thus software and hardware for CAD–CAM–CAE were gathered, including "Apolo", a high performance computer donated by Purdue University, which is the 11th fastest computer in Latin America and which centralizes the computation of the time most demanding projects within the University.

Third floor—materialize. The 3rd floor's team had to facilitate the transition from a mental domain (software) into a real world (hardware), where students, industry and staff members could interact and select materials with tools such as a Material ConneXion® library, and perform destructive and non-destructive tests to either characterize and/or select materials.

Second floor—integrate. The 2nd floor's team was given the task to ease the integration of different domains and its functional prototyping, a place to highlight creativity in group and incubate interrelationships within engineers [4]. This is the main topic of this paper.

First floor—manufacture. Finally the 1st floor's team had to realize a machine shop similar to the manufacturing plants found in the industry. It ended up having manufacturing processes distributed in a polar array according to the type of the materials (angle) and the specialty of the process (radius).

These guidelines would give a personality to each floor and organize faculty members according to the expertise they had, and it came to be very strategic as the heaviest machines and hardware were located on the ground, while the lightest equipment were located on the top floor.

1.2 The challenge

After reviewing how education, research and commercialization coexist in a 3GU, and summarizing the concept of the Engineering's building, the remaining question is how to put together the three basic types of engineering laboratories: development, research, and educational [2] in the same place. And the answer gains relevance specially in a Latin American context, where having individual facilities for each of the three objectives is not economically feasible. Additionally, up to date there aren't any references to describe a laboratory design process based on the output itself, in this case Mechatronic Technical Systems.

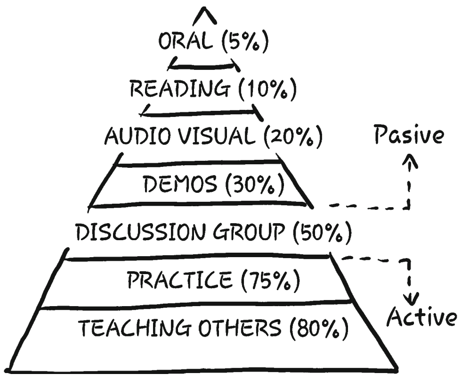


Fig. 2 Average student retention rates according to Dale's Pyramid. Adapted from [1]

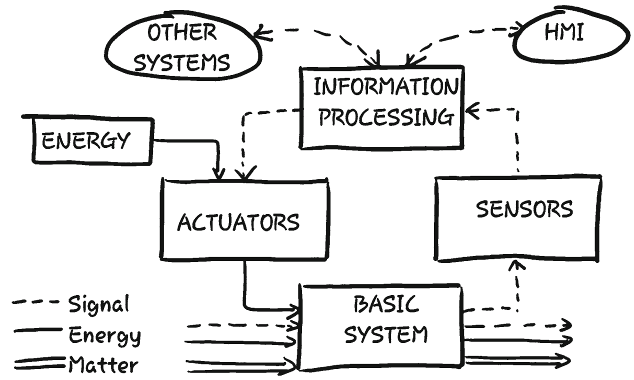


Fig. 3 Mechatronic system structure. Adapted from [5]

2 Method

If the Technology Integration Laboratory (TIL) was to ease the creativity, what better start than creativity itself to design it? Our approach consists on answering the 5W's and H questions described by Tassoul [12], leading us to understand (i) what is happening at the laboratory, (ii) who makes it happen, (iii) why is it happening, (iv) where does it happen, (v) when does it happen and (vi) how it happens. Several meetings were performed in order to tackle these questions, and the following guidelines were defined.

2.1 Why: Dale's Pyramid

As mentioned in Sect. 1, the objectives of a 3GU are to educate, create knowledge and apply it. According to the pyramid shown in Fig. 2, the highest retention rate in students is achieved by practicing and teaching others. Furthermore there is a great potential for students to organize and construct knowledge at their own pace in unique ways [11]. Thus a special attention was given to emphasize the hands-on engineering.

2.2 What: Technical systems

While there seems to be a general agreement that laboratories are necessary, little has been said about what they are expected to accomplish [2]. This absence of consensus has also been the reason for the limited research results accomplished on instructional laboratories. Therefore a clear definition of the TIL's output was highly relevant.
Technical systems (Fig. 3) is an appropriate definition of the products to be developed within the TIL, since they deal with the three fundamental flows that designers and engineers have available for the creation of technology: signals, energy and material [2].

2.3 When: Design for change

As stated by Long and Ehrmann [8] a critical element in the design of new learning spaces is the need to design for change, because students are not always using the new facilities in the ways the faculty originally imagined. Furthermore people change and so does the way they learn, therefore the more flexible the space to overcome these changes, the better, so it can be reconfigured in time.

2.4 Who: Cross pollinated inhabitants

Instead of following a traditional academic model with separated classrooms and one teacher for each (Fig. 4a), twenty-

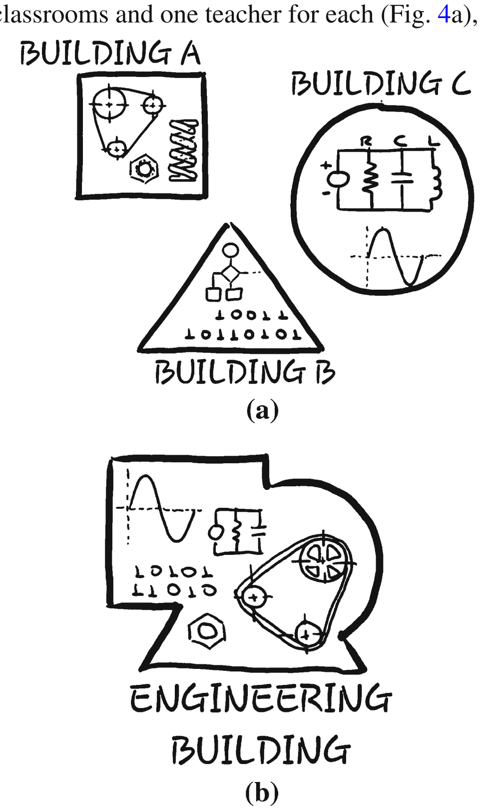
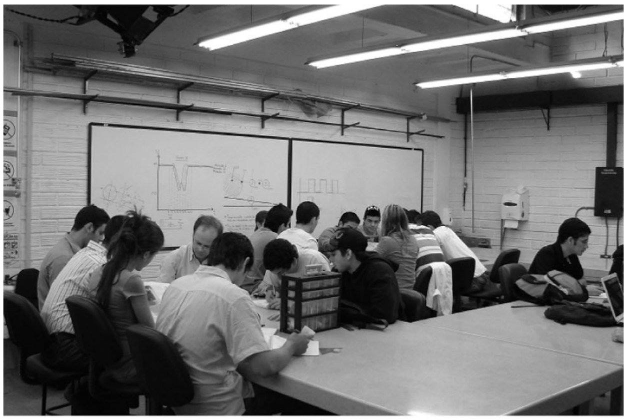


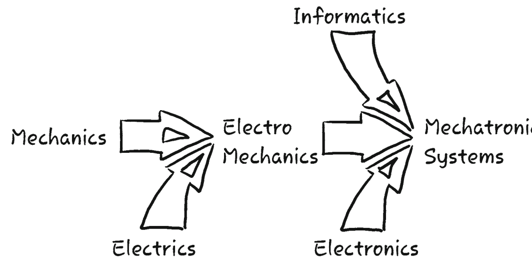
Fig. 4 **a** Traditional academic architecture. **b** Twenty-first century academic architecture



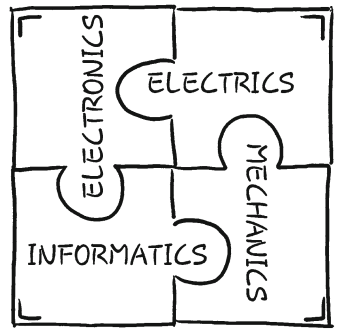
(a)

(b)

Fig. 5 Former Mechatronics Laboratory. **a** With wall (May 2008). **b** Without wall (October 2009)



(a)



(b)

Fig. 6 **a** Evolution of mechatronics. Adapted from [13]. **b** Mechatronic domains

first century models share spaces and lecturers (Fig. 4b) in an open space with permeable boundaries [3]. This should allow students from different disciplines to interact between them, like cross pollinating, an inspiring concept taken from nature [6]. Nevertheless this guideline initially encountered many skeptics because it would also change how the majority of the staff members were used to teach. Therefore it was verified in the former Mechatronics Laboratory by removing a dividing wall in order to break traditional educational schemes as shown in Fig. 5a, b.

2.5 Where: Semantical definition of areas

The vast majority of scientists nowadays work in interdisciplinary teams that focus on specific research areas. For interdisciplinary teams, faculties are often an obstacle and new organizational forms have to be sought [15]. In this seek, Mechatronics became an idoneous start for the design of the TIL layout, which was born only after the evolution of the electronics and informatics as shown in Fig. 6a. It meets its biggest advantage, and also challenge, in the synergetic integration of the Mechanic, Electric, Electronic and Informatic domains (Fig. 6b). Each of these domains is given a subarea within the TIL:

Mechanics. Within a technical system the mechanics is what defines the system or product. It is responsible of the attributes such as: robustness, tangibility, ergonomics and functionality. Therefore as a subarea within the TIL this is the place to materialize with CNC and conventional tools the hardware of prototypes such as (i) frame, (ii) bearings and (iii) transmission.

Electrics. Despite most of the literature do not differentiate electronics from electrics within a Mechatronic frame, in our case it was helpful to clearly distinguish both. Within a technical system the electrics is the main responsible for bringing power and energy attributes into the products. Therefore as a subarea within the TIL this is the place to use electricity for power electronics, protections and energy (generation, distribution and storage).

Electronics. It is responsible for giving the following attributes to the products: interface the physical world with a digital world. As a subarea within the TIL this is the place to use electricity for signal conversion, data transferring, Human Machine Interface (HMI), machine-environment interfaces and machine-machine interfaces.

Informatics. It is the main responsible for adding attributes to the products such as performance, flexibility and ubiquity. Furthermore an intelligence attribute could be added when adaptive and learning behaviours are included [5]. As a subarea within the TIL this is the place to deal with algorithms, data processing, calculations, control and communication protocols.

These declarations were relevant to differentiate furnitures, equipment and flows required for each subarea as will be shown in Sect. 3.

2.6 How: Design project-based learning

Finally a reasonable way to accomplish the three objectives is through a Project Based strategy. According to [16] six aspects must be kept in mind for it: (i) structural aspects (ii) group size, (iii) physiology and psychology, (iv) adjacencies, (v) furnishing and (vi) functional aspects, with the same importance as depicted in Fig. 7.

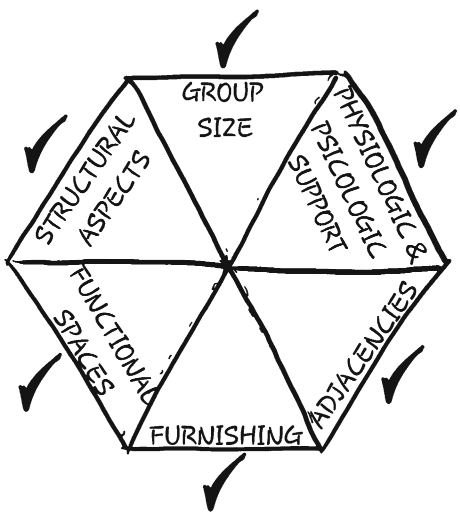


Fig. 7 Design features of the physical learning environment for collaborative, project-based learning. Adapted from [16]

3 Construction and equipment

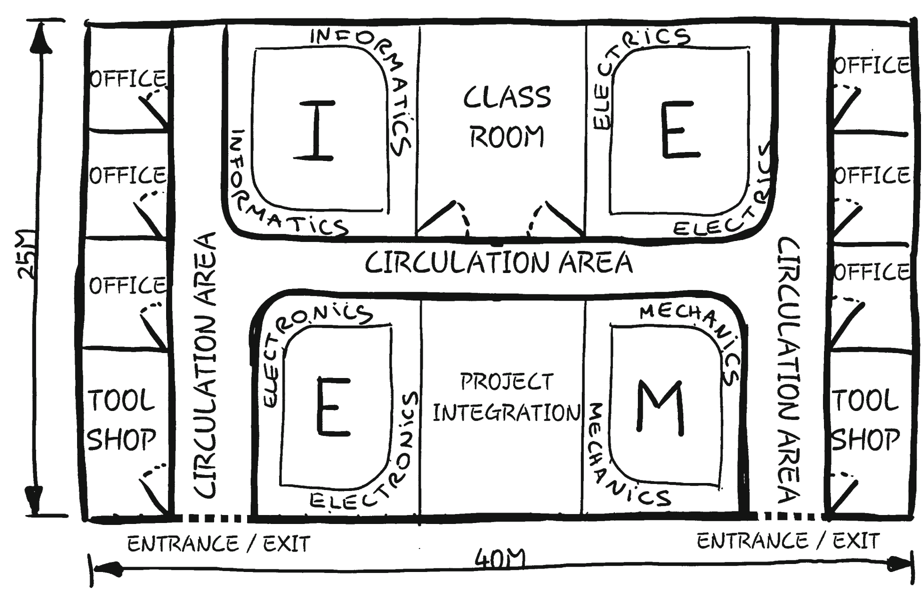
3.1 Final layout

After considering different layout designs, the one shown in Fig. 8 is chosen, with 1000 m^2 (25 m × 40 m) for a maximum capacity of 200 people (5 m^2/person). Although not illustrated, two balconies are located on the western and southern sides, allowing employees and students to take a break anytime they want. Only one enclosed classroom is left, and yet it is translucent as seen on the back of Fig. 10a, b. Each subarea has furnitures according to the tasks to be performed (i.e. Electronics has working surfaces coloured "optical green"). Along the circulating path (Fig. 9) inhabitants and visitors may read encouraging quotes written on the floor, while watching posters with previous projects developed at the TIL. Additionally Men's and Women's WC are located next to the entrance.

3.2 Hardware and software

The assets upon which every subarea is equipped are described in Table 1, besides the desks, cabinets and chairs. The tool shops located on the lower corners of Fig. 8 store consumable components of each subarea (e.g. screws, gears, bearings, cables, connectors, capacitors, breadboards and microcontrollers).

Fig. 8 Illustration of the TIL's final layout



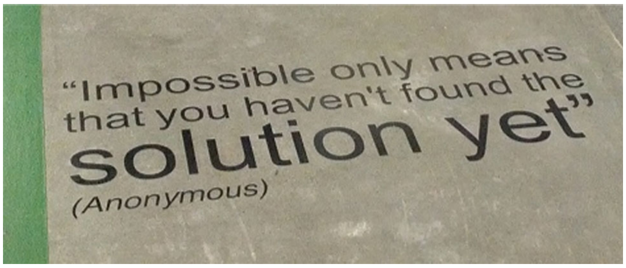


Fig. 9 Quotes written on the floor along the circulation path

3.3 Real view

After the construction of the TIL and the installation of the equipment described in Table 1, and the required furniture, the subareas appearance are displayed in Fig. 10a–d.

4 Results

After almost 5 years since its opening, the TIL's results can be measured in terms of course enrollment, multidisciplinarity, occupancy, projects executed, spin-offs created and Intellectual Property (IP).

4.1 Course enrollment

One way to measure the effectiveness of the described process is the demand of the academic program Technical Systems Integrated Design (TSID) which was funded in June 2009 [14]. At the beginning only a few students were enrolled and therefore the program's economic feasibility was compromised. After the Engineering building's opening the TSID program gained a place for its own. Despite a steady population of engineering students, the TSID program has been increasing, reaching a current average of fourteen (14) students per course as shown in Fig. 11.

4.2 Multidisciplinarity

Another way to measure the TIL's effectiveness is its multi domain occupancy, which through the TSID program has currently reached an average of 3.5 different academic domains per course as seen in Fig. 12. While initially only Product Design Engineering students took part in this program, nowadays the participants come from different undergraduate programs such as Mechanical Engineering, Production Engineering, Physics Engineering, Electronics Engineering and Mechatronics Engineering. The latter two from other Universities.

4.3 Occupancy

As an occupation indicator, the amount of students has been measured at different peak occupancy times. Although initially planned to house 200 people among employees and students (about 5 m^2 per person), during the last semester a peak occupancy of 150 people was reached, approaching its 80 %.

Table 1 Hardware, software and flows available at each domain of the TIL

Domain	Software	Hardware	Flow
Mechanics	SolidWorks, Autodesk inventor	Tachymeter, Micrometer, Torquimeter, Grinding machine, Modal exciter, Bench drill, CNC machine, CNC lathe, Laser cutting machine, Laser engraving machine	Compressed air, 110 VAC 60 Hz, 220 VAC 3phase, Gas exhaust
Electrics	AutoCAD electrical, Automation studio	Multimeter, Inverter, Soldering station, Function generator, Electric motor test bench, Electric motors and controls, Power supply, Li batteries, Oscilloscopes, Network tester	110 VAC 60 Hz, 220 VAC 1phase, 220 VAC 2phase, 220 VAC 3phase, 440 VAC
Electronics	Proteus, Eagle, Crocodile 3D	Amperemeter, Multimeter, Function generator, Power supplies, Oscilloscopes, Servos, Soldering station, Multirotor test bench, Pneumatic test bench	110 VAC 60 Hz, 220 VAC 1phase, 220 VAC 2phase
Informatics	LEGO NXT, Proteus with PIC, LabView 2014, Matlab, Tiaportal, Arduino	Oscilloscopes, PLC, DSP Starter kit, Crane simulator, LEGO mindstorms, Laptops × 40, PC × 40, Zigbee, Arduino MEGA	110 VAC 60 Hz, 220 VAC 1phase, LAN, WLAN

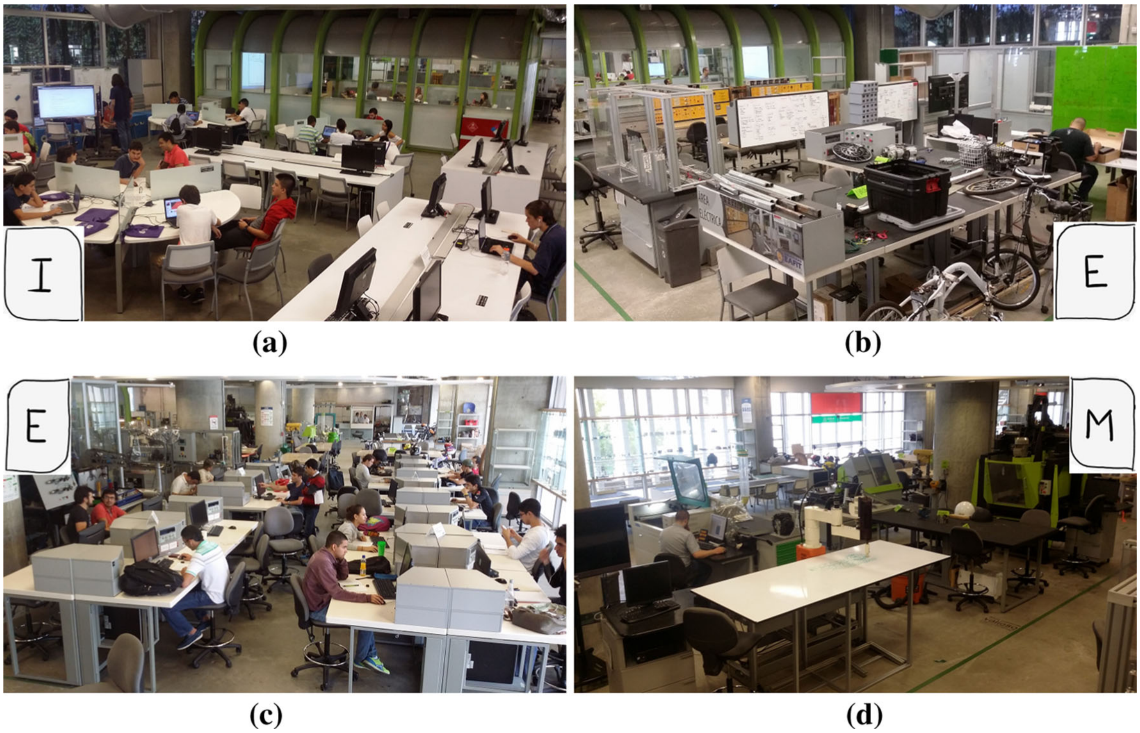
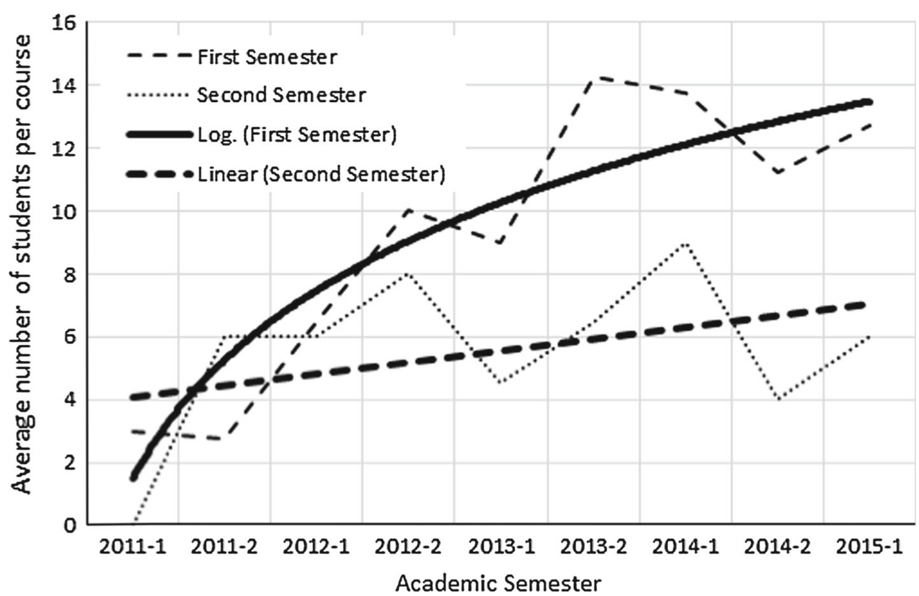


Fig. 10 Pictures of each subarea at TIL (June 2015). **a** Informatics. **b** Electrics. **c** Electronics. **d** Mechanics

Fig. 11 History of enrollments in TSID's courses. *Source*: Universidad EAFIT's Academic Management



4.4 Projects

Since the TIL's opening, several projects have been developed along with their respective prototypes each semester. Table 2 summarizes research and academic projects developed so far, and how the triad university–industry–government interacted. Among these projects, ubiquitous products and services have been also developed along with other universities from abroad [10].

The variety of the projects proofs the flexibility of the TIL, some of which are describes as follows:

Health care. A mechatronic bed for hospitals (Fig. 13) was developed with financial support from the government. Mechanics were used to design and manufacture the mechanisms that pitch, roll and lift the patient. Electrics consisted on electric linear actuators and their respective switching devices; while electronics consisted on sensing the atti-

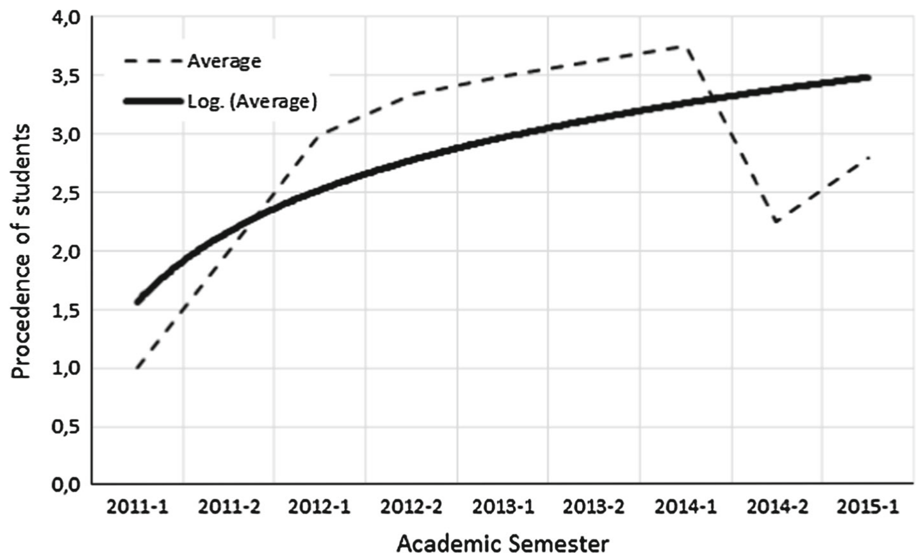


Fig. 12 Different precedence of students in TSID's courses. *Source*: Universidad EAFIT's Academic Management

Table 2 Types, partnerships and amount of the projects developed from February 2011 until June 2015

Projects	Type	Average per semester	2011–2015
Interactive devices	Academic -Product Design Eng	12	120
Electric vehicles	Academic -Product Design Eng	6	60
Robotics	Academic - TSID	4	12
Ubiquitous products	Academic -with other Universities	4	12
Renewable energies	Research -with Government	3	3
Health care	Research - with Government	2	2
Cement industry	Research - with Industry	1	1
Textile industry	Research - with Industry	1	1
		Total	**211**

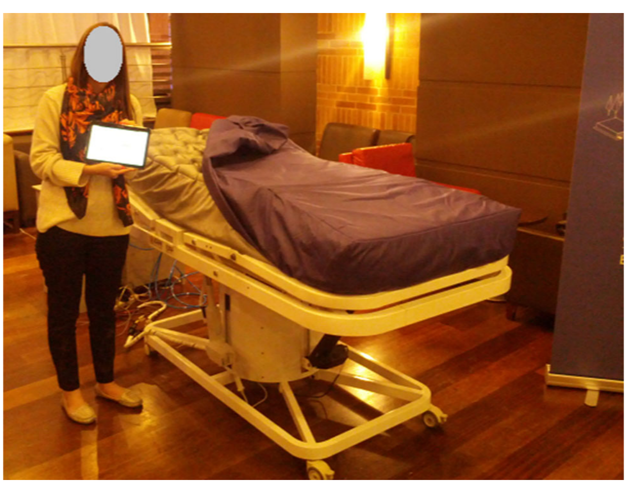


Fig. 13 Mechatronic bed for health care with a human interface

tude of the bed. Finally informatics were used to control the movements through a Programmable Logic Controller (PLC)with a network interface to allow different users to interact remotely.

Renewable energies. A 1500 W photovoltaic station (Fig. 14) was developed with financial support from the government. The mechanic subsystems consisted on a standing structure, a sun tracking mechanism, an upper frame to hold the solar panels and a wooden bench. Among the electric subsystems were an electric cabinet housing the switching devices, a 200 AH battery, an inverter, a charge controller, cabling and grounding. And informatics consisted on a PLCto control the movement of the sun tracking mechanism.

4.5 Spin-Offs

TIL has seen the dawn of one spin-off that designs, develops and commercializes electric bicycles, which has been already around 3 years on the field.

4.6 Intellectual property

The IP results obtained between 2010 and 2015 are summarized in Table 3.

Fig. 14 1500 W photovoltaic station intended for public lighting and charging of electronic devices

5 Discussion

Course enrollment. The initial behaviour of the tendency lines (Fig. 11) is characteristic of a new program before it reaches a certain maturity and recognition. However the upper limit of the TSID's enrollment depends on the demand and supply, the capacity of the classroom and the internal politics.

Multidisciplinarity. The diversity of the inhabitants has been reached by factors such as that (i) all the courses are given in the same floor, yielding other students to see what is happening and get pollinated, (ii) the internal policies of the engineering faculty which permits students from different undergraduate programs to enroll into programs such as TSID and (iii) the transversality of the courses offered by TSID.

Occupancy. Despite the subareas were originally conceived to house inhabitants for certain tasks, the TIL receives not only Engineering but public in general. Therefore the occupancy, specially during "cold seasons" is more related to those willing to find a place available to study, no matter the discipline.

Projects. It is important to keep working within similar topics, and follow the governmental directions in terms of the relevant development areas for a certain geographic region. Cooperative projects with other universities were possible to accomplish by collaborating online and having a 1 week final workshop by the end of the semester.

Spin Off's. Although it is a low number, the only firm conceived so far at TIL has been commercializing its own products since 3 years ago. The incubation at the institution has facilitated its research and development for new products, one of its differentiating factors.

Intellectual property. Despite the openness of the TIL, the IP's results have considerably incremented. Before the year 2010, Universidad EAFIT had only seven issued patents. Nowadays this amount has nearly doubled to 13. Besides, five patent applications and two industrial designs have been originated at the TIL. One influencing factor is that people feel more jealous about their intellectual property when their projects and creations are more exposed.

Table 3 Intellectual property conceived at the TIL

IP result	Office	Number	Date	Original title
P.I.A.	PCT-IB	050 588	24 Jan 2013	Proceso de compactacion por compresion de material particulado
I.D.	CO-SIC	13 014 944	28 Jan 2013	Forma externa presentacion de producto
I.D.	CO-SIC	13 108 580	29 Apr 2013	Vehiculo electrico de tres ruedas
P.I.A.	CO-SIC	14 181 165	19 Aug 2014	Cama adaptable para obtencion de distintas posiciones
P.I.A.	PCT-IB	065 886	07 Nov 2014	Adaptable bed for obtaining different positions
P.I.A.	CO-SIC	14 248 214	10 Nov 2014	Elemento estructural tipo ladrillo que permite la fijacion de elementos electricos, opticos, electronicos y electromecanicos
P.I.A.	CO-SIC	14 248 222	10 Nov 2014	Dispositivo de presion alternante con regulacion de temperatura y humedad

P.I.A. patent of invention application, *I.D.* industrial design, *PCT-IB* Patent Cooperation Treaty—International Bureau, *CO-SIC* Colombia - Superintendencia de Industria y Comercio

6 Conclusions and future work

After 5 years of operation, the original interaction between architects and faculty's staff during the planning stage of this academic facility resulted in an effective laboratory where different technologies and students from different disciplines interact. A significant institutional result is that shared facilities have reduced the lack of communication among professors regarding the available equipments, and prevents different departments from buying similar devices for either academic, research or development purposes. Before the TIL, four different laboratories were involved with Mechatronics but without any synergy at all, and after these facilities were gathered and joined at the TIL the management has been finally centralized.

From an academic perspective, the visibility obtained in such open space has increased the enrollment into the courses. While visitors get a glance of the practices and challenges that the inhabitants such as students and teachers get to deal with every day, they also get pollinated and some of them may even apply for the TSID program. From an industrial point of view, only a few companies in Latin America have the possibility to afford having research and development facilities. By converging the three types of engineering laboratories (academic, research and development) the TIL has become flexible enough to deal with projects from different funding sources and partnerships (government, industry and academy). Furthermore by getting involved with projects, more researchers have found a job at the TIL, which is a positive indicator in terms of employment.

In terms of privacy, while open spaces may affect it, they also encourage people to take care about their IP and to assume a proactive role, instead of a reactive one.

Although originally planned for informatic purposes, the Informatics subarea has not yet acquired the personality as the other three do (Mechanics, Electrics and Electronics). The reasons are that (i) the equipment has been missunderstood as computers available for everyone and (ii) that informatic tasks can be performed on any computer at the other subareas. Therefore further efforts will focus on this subarea.

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