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FROM THE ISLANDS OF KNOWLEDGE TO A SHARED UNDERSTANDING: INTERDISCIPLINARITY AND TECHNOLOGY LITERACY FOR INNOVATION IN SMART ELECTRONIC PRODUCT DESIGN

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In the context of the evolving Internet, a balance between technological advances and meaning change is crucial to develop innovative and breakthrough “connected electronics” that enable the Internet of Things. Designers and technologists are key enablers of this process respectively, ensuring adequate users´ needs and technology development, inside the evolving context of social environment and human relations. Smart electronic product design must be a truly interdisciplinary process, in which technologists are aware of how much their decisions impact the user-product relationship and designers understand the full potential and associated limitations of technology involved. Shared knowledge and communication are essential in this scenario, but, due to their technological limitations, designers are often excluded from high-level decision processes. In this paper, we address the design of constructivist tools and associated strategy to enhance the technological literacy of designers, as a strong foundation for knowledge-based dialogue between these realms. We demonstrate its effectiveness in a long-term multidisciplinary Project-Based Learning application with Design and Electronics students. We present the cases from two years that demonstrate improvement in the quality of teamwork; in learning results; improved performance of the students reflected in the quality of the projects developed; and positive teachers’ and students’ evaluations. We conclude that the use of the proposed tool not only provides the designer an active voice in the process of designing smart electronics, but also promotes an effective common language between these two worlds.

KEYWORDS: technology literacy; design; smart electronics; teamwork; shared understanding; collaborative learning.

1. INTRODUCTION

Information and communication technologies (ICT) have already transformed modern life: as a key enabler for the natural sciences; underpinning capability, competitiveness and innovation in every industrial sector (automotive, aerospace, health, security); enabling energy savings and emissions reduction (smart industrial automation, smart buildings); and creating a huge market for ICT-based consumer electronics and services that improve users' quality of life.

The rapid incremental improvements in electronics that have occurred in the last decades have been based on the continuous miniaturisation of components. These improvements have been decelerating, provoking ICT to move beyond the silicon-age of the 20^{th} century to the Knowledge Society, in which massive amounts of data are being processed and given meaning, and enabling action at a distance. The Internet of Things (IoT), in which smart devices connect to the "information ether", constitutes a new era of electronic devices (Perera et al., 2014). The development of smart infrastructures is moving from monolithic, centralised and hierarchical systems to highly distributed networked systems with local and global autonomy, modularity, scalability, low cost, robustness, self-organisation and adaptability.

In parallel, we are witnessing how electronic technologies and programming models are becoming increasingly attractive and accessible to wide audiences (Mohomed and Dutta, 2015). This is creating a society-centric technological innovation culture that is multidisciplinary (information and communication technology and science; human and social sciences; arts and industrial, graphic and interaction design), pluralistic (a variety of paradigms are promoted in a competitive and co-operative fashion), and multi-cultural (its research is grounded on a variety of cultural traditions and seeks to open them to others' experiences). As a result, DIY (Do It Yourself) and maker movements are catalysts of the demystification of technology that facilitates technology literacy.

In this changing and expanding context, as Norman and Verganti (2014) observe, the drivers of any technological innovation are not only the advances in technology itself, but also the deliberate changes in the meaning of the product. As it happened with the design of mobile devices (Faiola and Matei, 2010), designing smart products becomes a complex activity that implies the coordinated development of a system of elements that belong to different fields. It entails not only the definition of technologies, services, components and communication processes –among other technological aspects-, but also the consideration of new relationships of understanding, using and interacting between humans and technology.

The challenge is to combine deep multidisciplinary knowledge from several points of view. The holistic training of the designer fits perfectly with this profile (Wells, 2013), as the designer is used to teamworking and to research in diverse areas not related to his/her discipline, revealing as the appropriate professional *analysing user needs* (including environment and market perspectives) and standing out in the *generation of new concepts*. The designer is a good *connector between user and technology*, translating ideas to user language and emotions (Norman, 2005). Through techniques borrowed from fields as diverse as ethnography, marketing and social sciences, designers become in each project authentic experts in the user's universe. Design thinking has developed a system of techniques useful to analyse almost any kind of problem, and to apply and focus creativity in the generation of insights, solutions and new meanings. These solutions must help to solve users' needs, while also being technologically feasible and economically viable (Cross, 2011; Stickdorn et al., 2012). In fact, design is increasingly becoming a major element in technology innovation, and it is clear that technology and design must work closely together (Goto et al., 2014).

Nonetheless, initiatives in this realm do not usually truly integrate both of the disciplines of technology and design. Development processes tend to be too often initiated only from a partial point of view, following a linear scheme that is not consistent with the basis mentioned previously: neither with the multidisciplinary, pluralistic and multi-cultural philosophy, nor with the fulcrum between technology and meaning. Some projects are initially developed by designers who lack the technical knowledge to properly consider the advantages and disadvantages of the new technology, and who propose concepts that will have to change subsequently when brought to function by technologists, or that remain mere conceptual exercises. Other projects are led and developed exclusively by technologists who lack soft skills (Fernandes et al., 2012), creating solutions that are not user-friendly. Surely this is a cause of the high percentage of resources by organisations is spent on failed products, and the small percentage of the designed products that arrive to the market. It is clear that there exist two worlds with different skills, languages, references, and profiles: in brief, different object worlds (Bucciarelli, 1994), which sometimes meet to “play phone tag” among themselves (see Table 1).

DESIGNER WORLD	DEVELOPER WORLD
Design methodology	Development methodology
User knowledge	Technological knowledge
Divergence	Convergence
Conceptualisation /Meaning change	Implementation
Desired functionalities	Technological constraints
Pragmatic/syntatic/semantic object levels	Technological performance

Table 1.Designers’ and developers’ visions

Due to these factors and also as a result of tradition, in real IT projects, *the designer and developer relationship is not usually conducted on an equal footing*. In the majority of cases, technologists are those who lead and develop smart electronics, and tend to trust only themselves. In a way, this is understandable, because the designers’ lack of technological literacy causes them to suggest technologically unfeasible proposals. Consequently, they must lean on technologists’ knowledge in order to properly generate the concept, many times losing some of their potential of innovation in the process (Faiola & Matei, 2010). As a result, designers’ labour is usually not esteemed enough to consider it in the concept and initial phases or in key decisions, which means that they are usually relegated to the final phases of style design (user interaction, graphic design, or formal interface design) and causing their conceptual contribution to be diluted. In this context, it seems obvious that the designer has to become sufficiently familiar with technology literacy to earn an active voice in key decisions of the smart product design process.

According to the International Technology and Engineering Educators Association (ITEEA), technological literacy is defined as the ability to “use, manage, assess, and understand technology” (International Technology Education Association, 2000/2002/2007, p.7). According to Moore (2011), *technology literacy has three levels* (i) to identify technologies relevant to a task, (ii) to understand how to use the technology and navigate its interface, and (iii) to understand the inner-working structure of technology. For his part, Fruchter (2001) lists *four dimensions in the process of cross-disciplinary learning:* (i) *Islands of knowledge*, where understanding is restricted to their own discipline; (ii) *Awareness* of other disciplines; (iii) *Appreciation*, because there is an interest to understand and support other disciplines' goals and concepts; and (iv) *Understanding*, where the abilities to negotiate, to be proactive in discussion with other disciplines, to provide input before the input is requested, and to use the language of another discipline are present. We found that *smart electronics design requires Moore's third level of technology literacy to achieve the understanding of the other discipline in Fruchter's sense.* Thus, not just knowing, but understanding the basic principles and functionalities of technology behind smart electronic devices would boost a designer's capacity to create new concepts and allow a change in the relationship between designer and developer.

It is also evident that to achieve breakthrough innovation in smart electronics, it is necessary that these two visions overlap, bringing together divergent (typically designers) and convergent (typically developers) minds, leading to novelty and usefulness (Onarheim and Friis-Olivarius, 2013). In this sense, Table 2 shows the relationship between meaning and technology to produce four types of innovation (according to Norman and Verganti 2014, p. 89), related to the designer's technology literacy (according to Moore, 2011) and the role of technologists and designers (according to Table 1). The example of a watch illustrates the outcomes of each dimension.

TECHNOLOGY	MEANING: *Incremental change*	MEANING: *Radical change*
Radical change	*Technology-Push innovation* Leads: Developer Participates: Developer (+ designer) *Tech. Literacy*: Level 3 Digital watch with alarm and tachometer	*Technology Epiphanies* Leads: Inter o transdisciplinariedad Participates: Designer + developer *Tech. Literacy*: Level 3 Smart watches with movement detection, connection to smart phone, etc.
Incremental change	*Market-Pull Innovation / HCD* Leads: Designer Participates: Designer + developer *Tech. Literacy*: Level 2 Watch for blind people	*Meaning-Driven Innovation* Leads: Designer Participates: Designer (+ developer) *Tech. literacy:* Level 1 Switch from watch as tool to watch as fashion accessory

Table 2. Dimensions and types of innovation, level of technology literacy and roles

The effective implementation of these interdisciplinary and innovation capacities is not an easy problem to solve. It requires coordination and consciousness at various levels of the project, considering all barriers and enablers that it implies (Kleinsmann, & Valkenburg, 2008; Kleinsmann, Buijs, and Valkenburg, 2010), and implementing different approaches to ensure that understanding is truly shared. Shared understanding barriers between disciplines should be solved, or at least softened, by instruction. Table 3 summarises the key factors of our approach*: a common project methodology, an interdisciplinary grasp from the project initiation, a codesign process based on iterative stages and shared product assessment, and an adequate level of understanding of the basics of the other discipline.*

DESIGNER WORLD	DEVELOPER WORLD	DESIGNER + DEVELOPER (SHARED UNDERSTANDING)
Design methodology	Development methodology	Project methodology
User knowledge	Technological knowledge	User empathy awareness (developer) Technology literacy (designer)
Divergence	Convergence	Design and implementation iterations
Conceptualisation /Meaning change	Implementation	Co-design methodologies Design and implementation iterations
Desired functionalities	Technological constraints	Co-design methodologies Design and implementation iterations
Functional and user acceptation assessment	Technological performance	Different stages of evaluation (partial evaluations to decision making and final evaluation to validate)

Table 3. From islands of knowledge to a knowledge-based dialogue

In this paper, we address the design of constructivist tools and associated strategy to enhance the technological literacy of designers. We contextualise our proposal in the overall approach of the teaching intervention based on collaborative learning between disciplines and on project-based learning. The remainder of the paper provides an overview of technology product design education frameworks in different institutions. We subsequently discuss the rationale behind our designers' technology literacy approach and the methodology to effectively implement this approach in students. Finally, we show the results over a two-year period and discuss how the rationale and methodological proposal effectively impacts designers' technology literacy.

2. EDUCATION FOR TECHNOLOGY PRODUCT DESIGN FRAMEWORK

Design as a discipline is taught in different types of institutions, within and beyond the university structure, from engineering schools to arts and crafts schools. The different approaches for design teaching have origins as early as the Industrial Revolution (Pevsner, 2005), and have been a controversial matter (Dormer, 1993; Dym, 2005). Table 4 shows how in year 2014, different programmes of some relevant institutions for teaching design in Europe offered a variety of approaches with respect to ICT. The institutions in this table proceed from different countries in Europe (Spain, Italy, Sweden, France, UK and Germany) and from different approaches (engineering field, arts field); and were selected because of their reputation as some of the best design schools in Europe. Some authors, like Dyrenfurth & Barnes (2015), describe a similar situation in other worldwide technology innovation realms.

As we can see, the lack of contents linked to technology knowledge is common in most of the listed cases, and therefore it should be expected that designers do not know or understand the technology sufficiently to include all possible considerations in the electronic product development process. Furthermore, some designers might encounter problems understanding the information or identifying the requirements/opportunities proposed from the perspective of technologists. To fill this gap and to foster a truly shared understanding and a substantial interdisciplinarity, one option could be to obtain a deeper knowledge of technology even from the schools of design. But obviously, designers cannot pretend to be technology developers, as this is not their field of concentration. Besides, a deep knowledge and understanding of the technology on a basis that is updated daily requires a full dedication that needs to be constantly renewed, and that is not realistically sustainable.

For these reasons, our effort is centred in two strategies. On one hand, the students' acquisition of the basics of technological literacy is required for electronic devices' design (Section 3). On the other hand, with the main aim of strengthening the link between theory and practice (Tempelman and Pilot, 2011), we contextualise this literacy in a Project Based Learning (PBL) environment shared with electronic students, as we explain in section 4.

PROGRAM	SUBJECTS PROVIDING ICT INSIGHT (CREDITS USED)	COMMENTS
Design Engineering and Product Development University Degree, University of Zaragoza, Spain	Informatics (6 ECTS). Electric Technology (6 ECTS)	University School of Engineering and Architecture; Compulsory subjects
Product Design Degree ESDA, Zaragoza, Spain	None	Arts School of Design
Master in Design and Communications, Politecnico di Torino University, Torino, Italy	Ambient Intelligence: Technology and Design (6 ECTS). Digital and Connected World (6 ECTS). Digital revolution (6 ECTS). Technology, communications and society (6 ECTS).	University School of Engineering; Elective subjects.
Master program in Innovation and Design, Malardalens University, Sweden	Innovation Technology: Innovation Techniques in Innovation and Design, (7.5 credits).	University School of Engineering; Compulsory subjects
Master program product development and materials engineering. Master program Industrial Design. Jonkoping University, Sweden.	None	University School of Engineering
Design Degree, École nationale supérieure des Arts Décoratifs, France	None	Arts and Design School
Master Design and contemporary technology. ENSID Les Ateliers, France	None	Industrial Design School
Product Design BSc, Product Design BA, De Monfort University School of design, Leicester, United Kingdom	None	University School of Design
Product Design MDes, BSc, Leeds University, United Kingdom	Basic Electronics for Product Design (5 ECTS) Advanced Electronics for Product Design (10 ECTS) Design of Complex Human-Technical Systems (7.5 ECTS)	University School of Design; Compulsory subjects
Master program in Products of Design. Royal College of Arts, London, United Kingdom	Basic Electronics and Engineering for Designers (ECTS not specified)	Master of Arts
BA Industrial Design and Technology, Loughborough University,	None	Design School
Bachelor Interactive Media Design. Darmstadt University of Applied Sciences, Germany	Media Informatics & Technology (5 ECTS)	University School of Design

Table 4. Design programs in Europe

3. SMART ELECTRONICS' LITERACY RATIONALE

As discussed in Section 2, being up-to-date with the latest technology is a vast duty that is not to be expected of designers. Teaching about this topic would just create an ephemeral knowledge that would quickly become obsolete; it would be like "giving a man a fish", while we prefer to "teach him to fish". Thus, we apply constructivist theory, in line with Tempelman and Pilot (2011), to create a third level of technology literacy in designers: understand the inner-working structure of technology (Moore, 2011).

HIGH-LEVEL QUESTIONS	EXISTING KNOWLEDGE	TECHNOLOGY LITERACY ACQUIRED
How do electronic devices behave and interact with people and surroundings?	Ackoff's knowledge pyramid	Functionality and behaviour of smart devices
How are electronic devices built?	Human senses and actions	Smart electronic devices' architecture
Where does energy come from and how do electronic devices spend it?	Vehicle and fuel	Smart electronic devices' energetic restrictions
How do electronic devices send and receive information?	Human communication	Electronic communications

Table 5. Constructivist foundations

To this end, we created analogies with well-known and understood systems and realities, and linked them with the fundamentals of technology. Key aspects that we considered to teach are: (i) to understand the *functionality and behaviour* of smart electronic devices; (ii) to know the building blocks of devices, and their *architecture*; (iii) to understand the factors that affect electronic devices' *energy lifetimes*; and (iv) to understand the factors that affect electronic devices *communications*. Table 5 lists the high-level questions that a designer needs to understand in order to properly design electronics and the existing knowledge we use to create such technology literacy.

The next subsections illustrate the way we theorise and illustrate this concept to ultimately transfer it to the students. We also propose a guide to the basics of electronics to be considered by professional designers involved in smart electronics design processes.

3.1. FROM KNOWLEDGE PYRAMID TO SMART DEVICE FUNCTIONALITY

Smart electronic devices are the basic components of a higher class of concepts such as *smart environments, ambient intelligence or the latest Internet of Things*. These concepts originated in 1991, when Mark Weiser first wrote an article introducing the concept of ubiquitous computing (Weiser, 1991). Technologically, this refers to a digital environment that proactively, but sensibly, supports people in their daily lives (Augusto and McCullagh, 2007).

Figure 2 provides an integrating snapshot that merges the vision of a smart device, the real world (context categorisation), and Ackoff's (1998) hierarchical relationship among *data*, *information* and *knowledge*, applied to our topic.

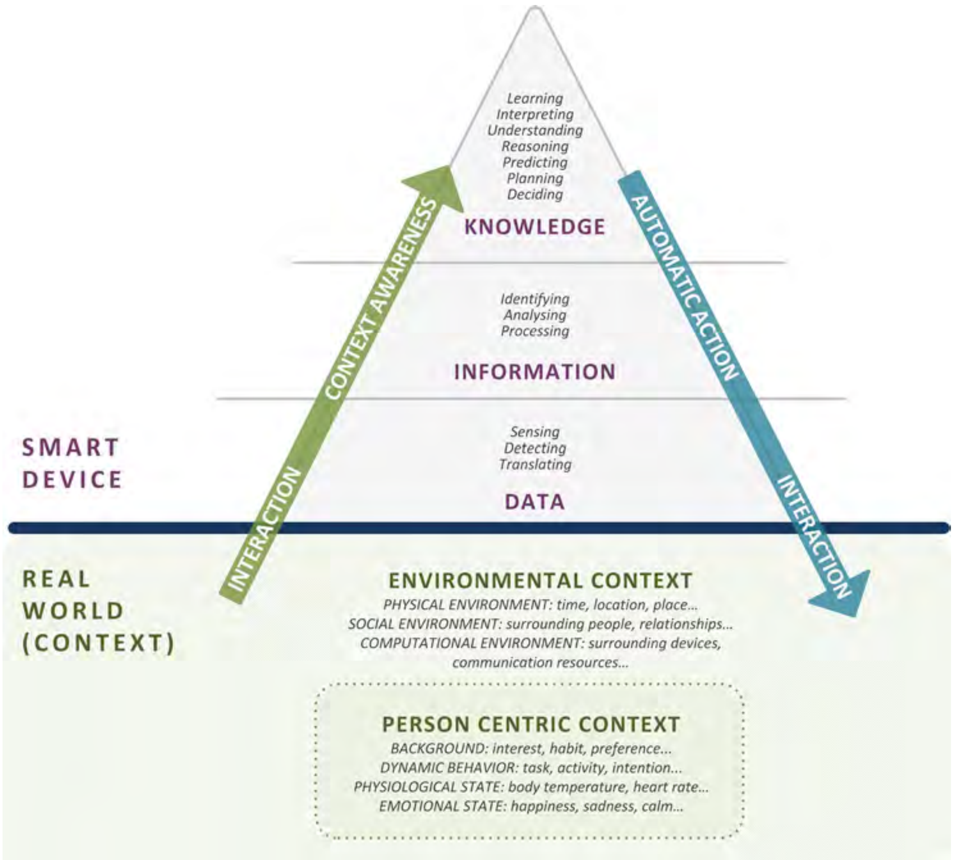


Fig. 1 *System intelligence pyramid*

The three levels of the pyramid (data, information and knowledge) can be performed by the electronic system. We could add a top level, wisdom –also considered by Ackoff- as an ability reserved for humans. However, we focus on the link between the smart device and the real world. Below the pyramid is the real world, categorised in two different contexts (Feng et al., 2004):

- ENVIRONMENTAL CONTEXT: There are physical environments (e.g. time, location, temperature, noise, etc.), social environments (e.g. traffic jam, surrounding people, etc.), and computational environments (e.g. surrounding devices, communication resources, etc.).
- PERSON-CENTRIC CONTEXT: The personal context includes background (e.g. interest, habit, preference, etc.), dynamic behaviour (e.g. task, activity, intention, etc.), physiological state (e.g. body temperature, heart rate, etc.), and emotional state (e.g. happiness, sadness, calm, etc.).

Electronic devices interact with the real world by means of three paradigms framed in Figure 1's arrows: context awareness, user interaction and automatic action:

- CONTEXT AWARENESS provides information about the people, places, devices and objects present in the environment. We can adapt the definition of Dey et al. as: "any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and a device, including the entity and device themselves." (Dey et al., 2001).
- AUTOMATIC ACTION can be viewed as the opposite of context awareness; i.e. technology changes the environment.

- Finally, while context awareness and automatic action define interaction among the system and the world, USER INTERACTION defines interaction among people/user and the system.

Understanding how system intelligence integrates all paradigms is essential to acquire technology literacy: smart electronic devices are distributed across the real world to ubiquitously interact with it (including people). Context awareness generates knowledge from the real world by sensing, processing and analysing data to create information that is subsequently understood and learned. Then, this knowledge is used for reasoning, predicting, planning and deciding automatic actions within the environment, and establishing a natural interaction with the person.

To implement this theory, Table 6 can be completed as part of the design process of the electronic product. In order to facilitate understanding, we completed this table and the following tables using the smart thermostat (Nest Labs, 2015) as an example. We find this smart device very convenient to use as an example because it is simple and easy to understand, but relatively complex and innovative in its design and in the technology involved.

AMBIT	REAL WORLD – PERSONAL CONTEXT	REAL WORLD – ENVIRONMENTAL CONTEXT
Data captured, detected or sensed from the real world	*Presence detection* *Temperature level defined by user*	*Temperature measurement* *Humidity measurement* *Day and time (get from Internet)*
Information identified (from data processing and analysis)	*User presence; habits at home* *User preferences*	*Thermal comfort level at home (different depending on the time and day)*
Knowledge extracted (from learning and interpretation of information)	*Matching comfort level with user preferences and habits*	
Knowledge applied to real world (reasoning, predicting, planning from extracted knowledge)	*Control of climatisation according to user preferences and habits* *Procurement of information to the user*	

Table 6. Electronic product functionality design guide (example: Nest)

3.2. FROM HUMAN SENSES TO SMART ELECTRONIC DEVICES' BUILDING BLOCKS

Smart electronic devices usually perform some sort of function in contact with the user and context, facilitate communication, and have a virtual representation on the Internet (Asensio et al., 2014). Depending on their functionality, they are usually designed using the following building blocks:

- *Interfaces such as sensors* (to sense the user/context), *actuators* (to modify the environment) and/or *human interfaces* (to interact with people).
- *Computing resources (memory and processing capabilities)* that allow them to implement functionality from the simplest logic to complicated services.
- At least one (usually wireless) *communication medium*, commonly following a standard and adapted to communication requirements (range, power consumption, and data throughput). This is required to interoperate with other devices and to integrate it with the Internet.
- When mobility is required or there is no electricity available, they must be battery powered or harvest energy from the environment; in either case, energy *power consumption* is an important issue.

Figure 2 shows the general block diagram of smart electronic devices.

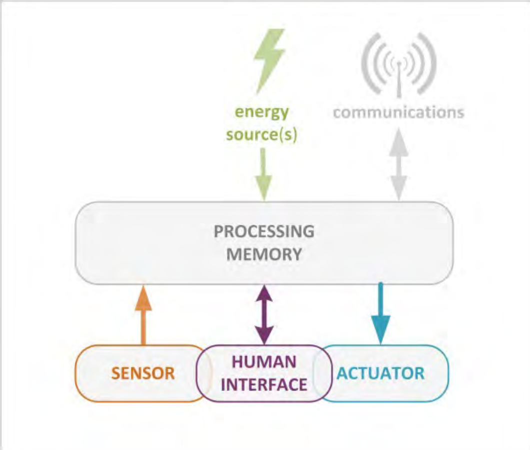


Fig. 2 Smart electronics devices architecture

From a design perspective, we found a double classification to be the most appropriate to ease understanding: device's capacities and device's restrictions.

The device´s capacities are related to the three paradigms in the System Intelligence Pyramid (context awareness, automatic action and user interaction) and with the three linked intrinsic functionalities it might perform (sense, modify, interact). Thus, smart electronics can have:

- SENSORS: Similar to human senses, the device can measure physical properties of its surroundings. These properties can be environment-related (temperature, humidity, gas concentration, etc.), movement-related (acceleration, orientation, location, etc.), physiologically-related (heart rate, skin conductivity, etc.), etc.
- ACTUATORS: Similar to human limbs, the device is able to modify its environment; it can switch on/off a light, open/close a door, turn on/off heating, set motor speed, release odour, etc.
- HUMAN-MACHINE INTERFACES: The device is able to interact with humans. This necessitates providing information to the user via visual (LED, graphics, text, etc.), aural (buzzer, voice synthesis, etc.), or haptic (vibrating motor, braille, etc.) media, and receiving commands from the user via voice, video or touch.

This segmentation does not mean that we have to choose between these three options when we design a device; indeed, smart devices usually perform several of these functions. We can also design a system with several complementary devices that serve different functions but function as a whole.

Any smart device must have a "brain", a processor and memory, to be called "smart"; it also requires an energy source to operate; and usually a communication media to make this intelligence effective. From these basics, we can find different architectures, more or less complex. We can also classify devices based on their device restrictions; *restrictions* refer to a device's features such as lifetime, communication method and computational resources. Under this classification, a device can be:

- MOTE: Portable or fixed device with reduced computational capacity, which performs defined simple functions, low-power communications, and is battery powered or is an energy harvester, providing a long lifetime. Motes are typically sensors, such as wireless environmental sensors or small wearable sensors (e.g. Nike+).

- **Mobile**: Portable devices with medium-high computational capacity and communications; lifetime is usually a period of days. Mobile devices are typically user interfaces that embed some sensors such as smartphones or tablets.
- **Static**: Usually fixed devices that are electrically powered with extensive computational capacity and communications. Statics are usually infrastructure devices or actuators with fixed user interfaces such as information panels or motor controllers.

Energy, computation and communication are the most critical issues that impact in device design; we propose the use of Table 8 as a design guide to develop a device's architecture and to specify each electronic block. The example in Table 8 remains the Nest thermostat.

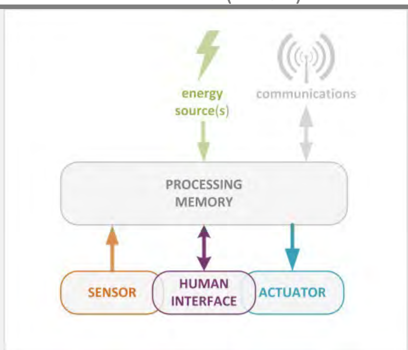
	INSTRUCTIONS	EXAMPLE (NEST)
Architecture	*Draw building blocks*	
Dimensions and weight	*Define approximately*	*10 cm x 10 cm x 3 cm; 150 g*
Energy sources and expected lifetime	*Define approximately*	*Rechargeable battery providing 1 week life expectancy*
Communications	*Define the basic features that are needed (range, data throughput, topology, etc.)*	*Wireless communications are needed to set time and to serve remote user interface and console.* *Range: Local (few meters)* *Bandwidth: Few bytes per second* *Topology: Point-to-point or star* *Desired energy consumption: Very low* *Open standard options: Bluetooth, WiFi*
Type of sensors	*If included, what kind, where they will go, how they should perform*	*Temperature, humidity, presence*
Human Computer Interface	*Quote basic features*	*LCD screen, button, knob*
Actuator	*If included, what kind, where they will go, how they should perform*	*Relay output to control climatisation*
Processing and memory	*If needed; specify for what they are needed*	*Memory needed to save logs* *Processing to take decisions about climate control*

Table 7. Product electronic blocks guide (example: Nest)

3.3. FROM VEHICLE/FUEL TO ELECTRONIC DEVICE'S ENERGY - POWER

The lifetime of an electronic device is one of the features that most significantly determines its success or failure in the marketplace. *In order to develop an effective design, it is essential to understand the implications of each design decision for energetic performance, and vice versa: to understand the energetic constraints that must be addressed in the design process.*

The lifetime of a device is determined by the amount of energy available and how it is used by the device. (Obviously, as static devices are mains powered, this principle is mainly applicable to motes and mobiles). We can establish a direct analogy with a car, where fuel is energy; a car's weight and speed are related to the power required for performance in computation and/or communications; and kilometres of use represent lifetime (see Fig. 3). Also, analogous to cars, technological advances produce more efficient batteries (increasing energy/cc), more efficient performance in terms of computation (increasing computational capacity per joule consumed), and communications (increasing data throughput and range per joule consumed).

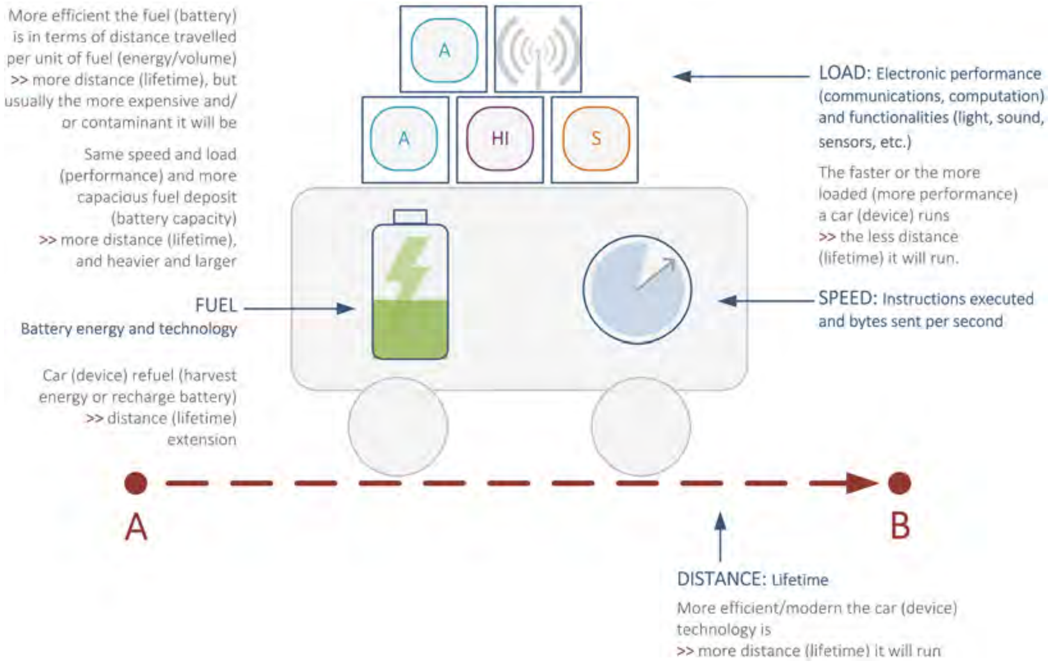


Fig. 3 Lifetime metaphor for electronic devices.

Thus, in order to plan an effective design, it is necessary to know how much energy is available from various energy sources (Table 9 lists the main types) and how much energy is consumed by each thing's functional component (Table 10 shows power and energy required by typical electronic blocks in a device).

	ENERGY SOURCES						
	Lead car battery	Laptop battery	Li ION mobile battery	2 x AAA alkaline batteries	CrO_2 button battery	Solar harvester (per cm^2)	Vibration harvester
Energy available in Joules*	*4300 kJ*	*273.6 kJ*	*24.6 kJ*	*11.5 kJ*	*3.2 kJ*	*50 J/hr*	*1.8 J/hr*
**battery capacity is provided by suppliers usually in A·h indicating how many amperes (unit of current) can provide in one hour. Energy (in joules) is calculated multiplying capacity times the battery voltage and 3600 (number of seconds in one hour)*							

Table 8. Energy available in most common energy sources

The energy expended is calculated as the sum of the products of the power required by each electronic block inside the device times the time this piece is running (in seconds).

$$energy\_required = \sum_{electronic\_blocks} (running\_power \times time\_running)$$

The mathematical calculations required to provide an estimation of the lifetime of a device are simple and similar to those needed to predict how many kilometres a car will run, knowing the fuel available and the fuel consumption per kilometre (which depends on the speed and load). Life-time is calculated simply by dividing the energy available by the energy required.

$$lifetime = \frac{energy\_available}{energy\_required}$$

Once the electronic blocks have been identified as in Section 3.2, the next step involves completing a table indicating the power, time in use and energy required of each block. Then, simple mathematical calculations are performed in order to estimate the battery lifetime.

	ELECTRONIC BLOCKS							
	LED on	LCD screen (per cm^2)	Full power data processing of an embedded CPU	Sending information through Wifi link	Music reproduced in 2 W speakers	Temperature sensor sample	Inertial sensor sampling at 50 Hz	All the electronics in the left in standby
Running power	*70 mW*	*5 mW*	*330 mW*	*660 mW*	*2 W*	*20 uW*	*500 uW*	*8.3 uW*
Energy required (per min.)	*4.2 J*	*0.3 J*	*19.8 J*	*39,6 J*	*120 J*	*0.000001 J*	*0.03 J*	*0.0005 J*

Table 9. Power and energy required by typical electronic blocks in a device

3.4. FROM HUMAN COMMUNICATION TO ELECTRONICS COMMUNICATION

Communication considerations are also essential, as smart devices usually need to communicate among themselves and with the Internet. Communication between devices is structured in seven layers, called the ISO/OSI model, that are differently implemented by each communication technology and protocol used. Two devices must share all layers in order to effectively communicate. *The designer must understand how electronic communications work to properly design systems with a feasible implementation.* Table 13 shows the analogy between human communication and electronic communication.

HUMAN COMMUNICATION	ISO/OSI LAYERS	ELECTRONIC COMMUNICATION
Physical link between people *Examples*: acoustic waves from speaker to listener; a written message on paper; non-verbal language (hand-eye) *Communication problem:* I cannot hear your voice because I'm deaf or because you talk too quietly	1. PHYSICAL	Ensures physical connection between nodes *Examples*: radiofrequency, infrared, cabled *Communication problem*: Infrared remote cannot command a radiofrequency automatic door
Sound from phonemes, strokes of letters *Communication problem:* bad handwriting or vocalisation	2. DATA LINK	Manage the data flow in and out of a node, ensuring common format of data messages *Communication problem*: data misinterpretation due to insufficiently strong RF signal
Build a conversation among three people while avoiding interruptions *Communication problem*: two persons talking at the same time	3. NETWORK 4. TRANSPORT 5. SESSION	Guarantee node's access to the network, ensuring that messages reach destination and building relationships between nodes in network *Communication problem*: messages not reaching receiver due to high data traffic or message routing problems
Phonemes and letters form words *Communication problem*: Two persons speaking different languages	6. PRESENTATION	Focus on the presentation of data from data link layer in order to provide understandable information *Communication problem*: node receives messages that are not understood
Words form sentences providing meaning *Communication problem*: Two persons who don't understand each other. E.g. Question: What time is it? Answer: it is red.	7. APPLICATION	Serves as an interface between applications of nodes in the network *Communication problem*: node receives messages that are not applicable to its application; e.g., a temperature sensor receives a message asking for humidity value

Table 10. Analogy between human communication and electronic communication

In addition to understanding how electronic communications work, a designer must also know the usual *wireless communication standards* and how their features influence system design (see Table 14).

4. METHODOLOGY FOR CREATING TECHNOLOGY LITERACY

4.1. APPROACH

Collaborative work in interdisciplinary environments is very common in professional life, and industry demands increasingly many *graduates with higher-order thinking skills and soft skills* (Tulsi and Poonia, 2015). In our context, as sourced from the European Higher Education System (EHES) (Sorbonne Joint Declaration, 1998) and the European Higher Education Area (EHEA) (EHEA, 2014) constitution, *Project Based Learning (PBL) methodologies* have experienced a noticeable adoption in industrial design and product development studies (Manchado and López, 2012). The learning methodologies based on the principles of "learning by making" or "learning through experience" are helping to yield better results from the students, in terms of the ratio of effort/achievements (Markham et al., 2003). Most schools, such as those described in Section 2, base their study plans on a combination of subjects, where teamwork and multidisciplinarity help to put into practice theoretical contents, and convert them into skills. However, teamwork abilities and, in general, *soft skills are considered transversal matters* and it is very rare to find courses specifically devoted to them. In fact, education about these topics is more common in master-level courses or in the final years of the programmes, and more frequently these topics are "relegated to courses outside the technical disciplines or to extracurricular courses" (Fernandes et al., 2012).

	Cellular: 3G, 4G, GPRS	WiFi	ZigBee / 6LowPAN	Bluetooth	RFID / NFC
Range (from a whisper to a howl): indicates how distant devices can be, in order to exchange data among themselves or with the Internet.	WAN (few kilometres)	LAN (hundred s of meters)	LAN - WAN	PAN (few meters)	NFC (centimetre s)
Bandwidth (from a telegraph to a mail): indicates the maximum data rate (measured in bits per second) that can be handled. As this determines the quantity of information that can be sent, it has a direct influence on the device's functionality.	Many Mb per second	Many Mb per second	Many kb per second	Few Mb per second	Few kb per second
Topology (from one-to-one conversation to a large meeting): defines how devices interconnect among themselves. Include "point to point" (as two people talking), star (as one person giving a speech to many), or mesh (as in a friend's meeting).	Star	Star	Mesh	Star	Point to point
Energy demand (from a simple greeting to a master class): describes the amount of energy needed to communicate. It follows a simple rule of thumb: the larger range and bandwidth, the more energy consumption.	Few W	Hundred s of mW	Tens of mW	Few mW	None; device harvests it
Cabled equivalency	Fiberglass, cable	LAN Ethernet	Field buses (CAN, KNX, LON, etc.)	USB (using a hub)	USB

Table 11. Main features of wireless communication protocols

One precursor in this sense was the European Project Semester (Hansen, 2015), launched in 1995 and developed into a success in institutions from the Netherlands, Norway, Poland, Portugal, Spain, Germany, France, Finland, Belgium, Austria and Romania. As part of this initiative, some schools offered for a period of years a program in which students of advanced levels, from different areas of knowledge and of varying nationalities, worked together for an entire semester on a unique project, in an experience very similar to a real industrial environment. This was an ideal learning environment even if the process to establish it was challenging, due to the difficulty in: (i) Meeting all of the students' requirements, especially when they were participants in interchange (Erasmus) programs; (ii) Achieving a close participation of industries, which was sometimes problematic due to different schedules, among other factors; (iii) Conducting an individual evaluation of each student; (iv) Managing academic matters such as teachers' dedication, coordination, and schedules.

4.2. DESIGN

In the Industrial Design and Product Development Degree at the University of Zaragoza (Spain), we put into practice some initiatives –still functioning-- to explore learning methodologies in the field of collaborative, cross-disciplinary work. In the first levels of the degree. We implemented the *"Module projects",* in which teams of design students developed a project that incorporated all of the subjects of a semester from different fields of knowledge. In the final courses of the program, we carried out the *"Hybrid module projects",* where we went one step forward, integrating students from two different degrees –representing the two worlds described previously: electronics and industrial design--. The cases presented in this paper correspond to Hybrid module projects. We intended to create a professional-like environment, as close as possible to the real world, where actors from different departments participate in the process of design and development of a product. This took the form of an innovative educational experience of learning through co-working, the aim of which was to develop these professional attitudes sought by industry, with a focus on communication, shared understanding and interdisciplinary work skills (López-Pérez et al., 2013).

Not only the students teams are *hybrid*: the group of lecturers is an interdisciplinary team, as well. These instructors originate from different working environments, disciplines and departments; the two departments involved were the Electronics and Communications Engineering Department and the Design and Manufacturing Engineering Department, both at the University of Zaragoza. In this way, a parallelism can be appreciated between the instructors' and students' levels, both working in a collaborative, interdisciplinary, and iterative fashion. Furthermore, the understanding must be effective with respect to other underlying terms that we have taken into account (see Figure 4), and that makes this a complex process.

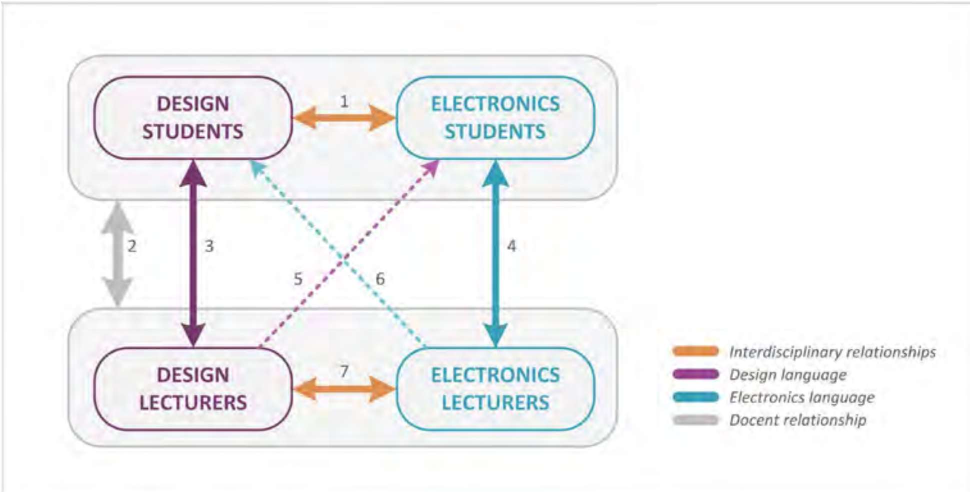


Fig. 4 Interaction dimensions between students and lecturers

Our methodology conception encompasses all of these dimensions that organise into two layers (Figure 4); one is related to the students, and the other to the lecturers. The latter has been developed during nine years of experience, and at present is in a stage of formalisation with a double objective: to describe the level of wisdom needed to face new challenges and to establish a way of working that can be easily learned by new lecturers, hence assuring the sustainability of the methodology. An explanation of both levels of methodology follows.

4.2.1. METHODOLOGY FOR LECTURERS (FIGURE 4, ARROWS 2 TO 5)

As an interdisciplinary group, the lecturers' team is confronted by organisational issues that represent the same difficulties that any other team would encounter. Fluid communication and constant collaboration are needed, and the team has to establish a common ground and shared understanding, as students must also do. The lecturer of electronics needs a reasonable understanding of industrial design methodologies and, conversely, the design lecturer must know about the possibilities and restrictions of electronics technologies. In this sense, the team of lecturers departed from, at one point, their own *islands of knowledge* because they have gained a certain *awareness* of the other disciplines, but they only achieved a real *appreciation* and *understanding* after several years in a way that could be called "teaching-based learning". In fact, the team of lecturers is shown to the students as example and reference.

In addition to their educational function, their roles as facilitators, coaches, and guides for teams of students are heterogeneous by principle (Felder and Brent, 2005). Therefore, a key requirement to supervise each team successfully is the coordination between lecturers, with the establishment of predefined activities that are divided into several categories detailed below.

a. *Preparation sessions (arrow 7):* The methodology is flexible enough to be adapted for each course to the peculiarities of the new groups of students and to tailor *ad hoc* activities that fulfil the educational and methodological needs of each case. Prior to the start of the course, several creative sessions are held to create a new version of the process, including the following matters: (i) *Selecting the topic:* Definition of the subject or the product to be developed. It has to fulfil the educational requirements of both specialties and it has to be stimulating to the students, to motivate teams, and to stimulate their creativity. This is, therefore, a fundamental item in which lecturers contribute their different backgrounds and experiences. (ii) *Scheduling:* The main challenges to implement the methodology are the different timetables and calendars derived from both degrees. This is the first restriction to consider during the subject organisation process. Properly scheduling the development of the project is critical to achieving the final goal of developing functional products at the end of the course module. (iii) *Tailoring the students' teams:* The number of students of each specialty is variable from one year to another, and it is crucial to establish the number of teams and to distribute students within each specialty to each team. (iv) *Other organisational matters:* These include the generation of documents, material procurement, and definition of procedures for meetings and communication.

b. *Educational activities (arrows 2 to 6):* The team's working environment is semi-controlled and is focused through some common milestones. Usually, lessons and practice sessions are given by each lecturer to his or her own students (arrows 3 and 4), but there are at least two seminars for students of the opposite specialty (arrows 5 and 6); there are also certain sessions that are imparted jointly by the group of teachers for the entire group of students. As the learning results consider soft skills, direct and continuous observation of behaviours and achievement of short-term objectives is mandatory. We also evaluate together the product evolution through several group presentations that are held for the product development milestones. All of this is addressed from an overall view, in a continuous close coordination and reciprocity between the lecturers to guarantee an effective feasibility of the product, in both concept viability and electronic functionality; dysfunctions in this guidance may lead to confusion and delays. Frequent activities are the resolution of conflicts and the reorientation of the specifications of the product to meet the learning objectives of both parts of the team.

c. *Summary and feedback (arrow 7):* Over the duration of the course, we perform an internal parallel evaluation about the act of teaching itself, including the programme of the educational modules, their contents and scope, and even the teaching methods. Likewise, as a part of the final report, students are asked to criticise the subject and the methodology itself, from several fronts and methods, both quantitative and qualitative, as explained in Section 5. Therefore, the final part of the methodology for lecturers is an opportunity to detect failures and dysfunctions, and to analyse their causes and relevance. This is also the starting point that leads to the invention of new methodological strategies.

4.2.2. METHODOLOGY FOR STUDENTS

Each student's team's goal is always to develop a viable, realistic, commercial electronic product, even though the specific target and contextualisation change each year. Even if each part of the team has to address sectorial tasks, they have to communicate and collaborate at all stages. The "Hybrid Project" methodology is explained to all students in a first session, where a brief is forwarded to them with the content and all relevant details to be used as a reference during the course. Although the activities and methods can vary depending on the specifics of each iteration. To illustrate the general process, we present above the schema resulting from our technology literacy philosophy.

Phase 1 – Establishment of common ground (arrows 1 to 6). The objective of this phase is that students jump from their *islands of knowledge* to, at a minimum, the *awareness* of the other discipline (Fruchter, 2001). Difficulties arise firstly from communication, due to the differences between their technical languages and the way they understand such concepts as product, technology, user or methodology. Therefore, the first challenge every year is to overcome this barrier by establishing a common ground on several fronts, either soft skills or technical transference, with mixed methods borrowed from both specialties. Specifically, in this case we emphasised technology literacy creation, applying the contents as described in Section 3. This was complemented with the study of the state of the art related to the technology associated with the product, and with user and scenarios analyses.

Phase 2 – Conceptualisation and technology literacy experimentation: product development (mainly arrows 1 to 4). First, teams develop three design concepts of the same product. This is an iterative cycle of communication, development of ideas, and exploration of technological viability, which works in both directions, enriching the process and its protagonists. The advance in knowledge and development is always collaborative, thoughtful and self-critical, as participants have to share and evaluate their respective proposals. Although there is supervision by the lecturers, teams work in an independent manner, thus promoting self-learning. Each team introduces its concepts in a public presentation where the lecturers evaluate each team performance and select the best concept to develop as a complete product. In this stage, students are expected to have evolutionarily developed an *appreciation* of the goals and utility of the other domain. Furthermore, teams fully develop the concept, delving into the technological and technical details until finally defining a real, manufacturable and marketable product.

Phase 3 – Technology literacy assessment: Integration and presentation (mainly arrows 1 and 2). The big moment comes when a prototype is integrated, including aesthetic appearance, electronic prototype, interface and all functionalities being operational. At this stage, the value of the interdisciplinary work is clearly evident, since the results could not have been achieved as an addition of parts developed separately. The integration of each component requires from them greater commitment and engagement efforts, where negotiation, proactivity and common languages are essential. All of these factors contribute to approach a nearly complete *understanding* of the other field. The course concludes with a final oral presentation of the projects and an exhibition of the prototypes. Presentation skills and public speaking resources are also put into practice, as students evolve from the more academic to commercial-like formats (e.g. videos oriented to web product launching platforms, PechaKucha or elevator pitches).

4.3. PARTICIPANTS

Lecturers that implemented the methodology have been the same in both years; two for the electronic students and three for the design students. To strengthen experiment validity, a forth design lecturer has been in charge of the assessment design, its deployment and further analysis. Lecturers involved have been leading innovation initiatives to enhance the capacity of students in the design of electronic products since 2006. Nonetheless, it was not until 2013 that structured analysis began, with specific methodologies of shared understanding bounded with technology literacy activities, and all of these efforts centred in students' starting capabilities. The cases explored in this papers are situated at the transitional period of this change.

The students taking part in the study are electronic and design students developing Hybrid Module Project in collaboration. In 2013, students from different disciplines worked together, but methodologies for technology literacy and shared understanding were not implemented. Observing the results obtained, the described methodology was designed and deployed in 2014. Thus, students of both years had the same background, belonged to the same course and same subjects were involved. Besides the methodology here described and the project topic, docent methodology, learning challenges and course evaluation used in both years has been also the same. Groups were formed randomly including 4 or 5 design students and 1 electronic student. Resulting number of students and teams are as following:

- 2013: 60 students from industrial design and 11 from electronic engineering (some of them from their final year project) formed 11 groups.
- 2014: 59 industrial design students and 12 electronic engineering students, organised into 12 teams.

4.4. IMPLEMENTATION

4.4.1. TOPIC 13: SMART ELECTRONICS FOR ENERGY CONSUMPTION AWARENESS AND INCREASED EFFICIENCY

Students were asked to design devices to reduce energy waste in different environments by means of raising the awareness of the consumer. Students researched how information on environment and consumption habits can be used to provoke consumers' understanding of the economic and environmental impact of their energy use. This should result in the acquisition of the necessary wisdom to address energy needs with minimum waste.

Products developed were:

1. e-COM: Mobile phone app that collects data from consumption of electrical appliances.
2. BAMBU: Humidity supervision in gardens intended to control its irrigation system.
3. gestH2O: Supervision of expended water at hotel rooms that interacts with the guest.
4. Ascension: A system embedded in an elevator that monitors its rides and informs the user about the energy expended and how many calories would have been burned if the stairs had been taken instead.
5. StudyLight: Intelligent post for study room, which supervises artificial light with respect to the presence of a student.
6. Sunlight: Monitors lighting of shop windows depending on outdoor light; features several operating modes.
7. WaterAware: Interactive system that monitors the use of the shower, and provides messages of awareness to the user.
8. Boo: Gadget to be embedded in toilets of schools to provide an emotional message related to the good / bad use of water when the kids wash their hands.

9. **BeeLight**: Interactive light switch intended to train kids to save energy. Also works as a night light.
10. **Ecoirrigation**: Monitoring and control of an irrigation system.
11. **S-light**: Control of lighting and blinds of public spaces depending on outdoor light, to optimise electricity consumption.

Figure 5 shows some of these projects, which can also be viewed at the web of the annual grade-selected projects (Unizar, 2013).

Fig. 5 Sunlight, Boo and S-light projects. Further details at

http://www.egrafica.unizar.es/proyectosemergentes2013/cata.html

The most common functional and conceptual mistakes that the groups made in their products are shown in Table 15. As can be appreciated, all teams failed to solve at least one technological item (communications, energy and sensing). Furthermore, the aspects related to product design but intimately associated with electronic design (size, installation and configuration) were partially met by six teams.

	Number of the product/team											
Common errors:	1	2	3	4	5	6	7	8	9	10	11	Total
Unfeasible communications (range, virtualisation)	■		■			■		■	■		■	55%
Energetically unfeasible (power conditioning, autonomy)		■		■	■	■		■	■			55%
Sensing unfeasibility			■	■			■			■		36%
Size		■						■				18%
Installation and configuration	■			■					■			27%
Total of errors:	*2*	*2*	*2*	*3*	*1*	*2*	*1*	*3*	*3*	*1*	*1*	21

Table 12. Distribution of concept errors in 2013 groups. Coloured cells indicate errors and white cells mean absence of errors.

In the qualitative assessment in 2013, students reported an improvement of their teamwork capabilities, but there were signs of certain clashes between both specialities. Among other issues, students reported that one of the most conflictive points in common work related to the agreement about technological specifications and restrictions. Furthermore, the lecturers' assessment of the projects revealed that collaboration and understanding between electronics and design students had not worked as well as it should have (see Table 16). In fact, even if electronics students had sufficient knowledge to implement every concept without encountering problems of feasibility, this was not reflected in the final designs. *Here, the hypothesis that developed was to establish a better common ground by improving designers' technology literacy, as this could serve as an enabler to better multidisciplinary performance through cross-disciplinary learning, enabling negotiation, proactivity in the discussion and capacity to use electronic language.* Designer students confirmed the propriety of that hypothesis in specific survey answers: 78% agreed that some technological literacy shared with electronic engineers would improve the outcomes of interdisciplinary work.

4.4.2. TOPIC 14: ELECTRONIC GADGET TO MAKE MONEY VIA CROWDFUNDING (WITH COMMON TECHNOLOGY UNDERSTANDING)

A subtype of electronic products are the so-called electronic gadgets, which are not intended to fulfil essential necessities, but to satisfy needs of amusement, learning or technical support for different activities. Gadgets constitute a very attractive range of products, so there is a broad demand from consumers. The aim of the project was to design an electronic gadget that takes advantage of the existing technology, maximising it. It was intended to be used in a defined environment, having a clear identity to be recognised and enjoyed by users in the best possible way. Concepts were encouraged to be creative and innovative since this is a rapidly changing emerging sector. The students were told to regard the development of the products as if they were to be launched in the market. Crowdfunding platforms such as Kickstarter (Kickstarter, 2015) are very suitable for this type of product. Accordingly, students were given this reference and asked to produce a video presentation oriented to such a web platform, and to use it as the basis of their final presentation.

Products developed were:

1. SkatoTRICK: Supervisor system of skateboard tricks. Embedded underneath the board, it should be able to extract data of movements and process them to be analysed.
2. NAE: Emotional bracelet that translates mobile phone messages into tactile sensations on the user skin (vibrations, caresses, etc.).
3. WIW: Weather station that advises what to wear to go outside.
4. MyUP: Wireless alarm clock that controls the light of the room, forcing the user to get out of bed.
5. MOSAICO: Programmable puzzle game.
6. Light Bracelet: Intended to be delivered to the public of musical events such as concerts or raves, it features changing lights controlled remotely from the stage, causing the crowd to interact with artists and music.
7. SURPRISE: Surprise box open / closed programmable.
8. AWARE: Technical aid for canyoning. It consists of a ball that is thrown into a pool to measure its depth.
9. SCORK: A cork intended not only to elegantly pour wine, its main feature is the ability to assess the acidity and, hence, the quality of different types of wine.
10. STRENGTH FISH: Measures the force with which a fish pulls the line from a fishing pole's spool.
11. MeetME: Toy coaster intended to encourage social interaction between people in public bars.
12. Sension: Controls the capacity of a disco venue and the sound volume at the door.

Fig. 7 Aware, Scork and Strength Fish projects. Details in http://www.egrafica.unizar.es/proyectosemergentes2014/cata.html

Some of these projects can be explored at the website of the annual grade selected projects (Unizar, 2014).

	Number of the product / team												
Common errors:	1	2	3	4	5	6	7	8	9	10	11	12	Total
Unfeasible communications (range, virtualisation)		■		■									*17%*
Energetically unfeasible (power conditioning, autonomy)							■		■		■		*25%*
Sensing unfeasibility		■							■				*17%*
Size		■				■					■		*25%*
Installation and configuration			■	■				■			■		*33%*
Total of errors	*0*	*3*	*1*	*2*	*0*	*1*	*1*	*1*	*2*	*0*	*3*	*0*	*14*

Table 13. Distribution of concept errors in 2014 groups. Coloured cells indicate errors and white cells mean absence of errors.

As in 2013, we investigated the functional and conceptual mistakes that the groups made in the final products in 2014, shown in Table 16.

5. DISCUSSION

5.1. ASSESSMENT METHODOLOGY

To evaluate the effectiveness of the new approach deployed in 2014, we consider 2013 as the control group. We followed a quantitative and qualitative mixed method assessment strategy (see Table 15) from both lecturers' and students' perspectives.

We used a multi-instrumental assessment methodology that allowed us to extract valuable information. A *long-term observation* about the *groups' behaviour* was conducted and described in field notes. We also assessed the *quality of the products* developed, both in general terms and in relation to their technological feasibility and innovation. The evolution of *student's grades* was also used in a quantitative comparison. Additionally, individual surveys of both years' students were conducted using semi-structured questionnaires, in order to obtain feedback about their appreciation of the benefits obtained from the experience, from the literacy learning material, and regarding the degree of achievement of the intangible objectives. Finally, *focus groups* and *interviews* with the teams have been held to explore those aspects that we need to detail and to dialog about the daily teamwork.

Additional to the hybrid project with design and electronic students, we also evaluated how designers put into practice concepts in a further electronic project they conducted on their own (without students in electronics).

Assessment Objective	*Perspective*	*Indicator*	*Instruments*	*Reference*
Quality of the products developed by the students	Lecturers	Global innovativeness and technological performance	Observation + Field notes Internal discussions after milestones assessment	Discussion paragraphs
		Concept and implementation errors quantification	Particular indicators valuation and quantitative comparative	Table 15-16, Fig 8
		Evolution of students' final grades	Quantitative comparative	Fig 9 a – b
	Students	Students' perception about innovation of their ideas	Closed question in the survey	Fig 10
		Students' opinion comparing project outcomes with previous works	Interviews and focus groups	Discussion paragraphs
Technology literacy, learning material use, and learning electronics	Lecturers	Material use by students' analysis Students' familiarity with electronics	Observation + Field notes Internal periodic discussions	Discussion paragraphs
		Third level of technology literacy acquired	Observation + Field notes Internal periodic discussions Students' perceptions analysis	Discussion paragraphs
	Students	Students' perception about learning electronics	Closed questions in the survey Interviews and focus groups Open direct questions in the survey	Fig 11 (a-b)
		Change of vision of electronics	Closed question in the survey Open questions in the survey	Fig 12
		Interest in deepening knowledge about electronics	Open indirect questions in the survey	Discussion paragraphs
		Valuation of electronic training provided	Open direct questions in the survey Interviews and focus groups	Discussion paragraphs
Shared understanding among students	Lecturers	Students jump from islands of knowledge to understanding	Observation + Field notes Internal periodic discussions Students perceptions analysis	Discussion paragraphs
	Students	Number of multidisciplinary meetings	Closed questions in the survey	Discussion paragraphs
		Use of tables as a communication tool	Observation + Field notes Interviews and focus groups	Discussion paragraphs

Table 14. Quantitative and qualitative mixed method assessment strategy

5.2. FINDINGS

From the lecturers' observations from 2006, we can state that learning from people of a different discipline by means of a narrow collaboration between equals proved to be very useful and efficient. With the structured qualitative and quantitative assessment strategy in 2013 and 2014, lecturers and students have already confirmed that the 2014 results were more successful at various levels.

5.2.1. QUALITY OF PRODUCTS

The enhancement in the *technological quality of the products* is demonstrated if we attend to the *considerable reduction in error rates* in 2014; one out of three groups did not have any conceptual error in their projects. This can be appreciated in Figure 8, where the results from 2013 and 2014 are compared. There was also an evident *improvement of solving technological feasibilities*: communications (3 times better), energy (2 times better) and sensing (2 times better). Other aspects more related to product design (size, installation and configuration) slightly improved, as expected, inasmuch as technology literacy was not intended to improve such abilities.

Course grades consider a variety of items such as study of the problem, conceptualisation, quality of design and final presentation. Figure 9-a shows hybrid project results (designers and electronic students together) and 9-b presents autonomous project results (only designers after hybrid project).

In general, we observe that, in line with the improved quality of the projects' outcomes, *better course grades* (grades rise by 10% from 2013) were obtained. Analysing the grades in detail, it is remarkable how quality of design was the most improved item (grades rise by 17% from 2013); we consider this very important as it includes functional, technical and formal aspects of final product design, and also because it was the global objective of our work. Figure 9-b moreover indicates that this improvement can be considered to have been internalised by students, as it is maintained in the autonomous project results.

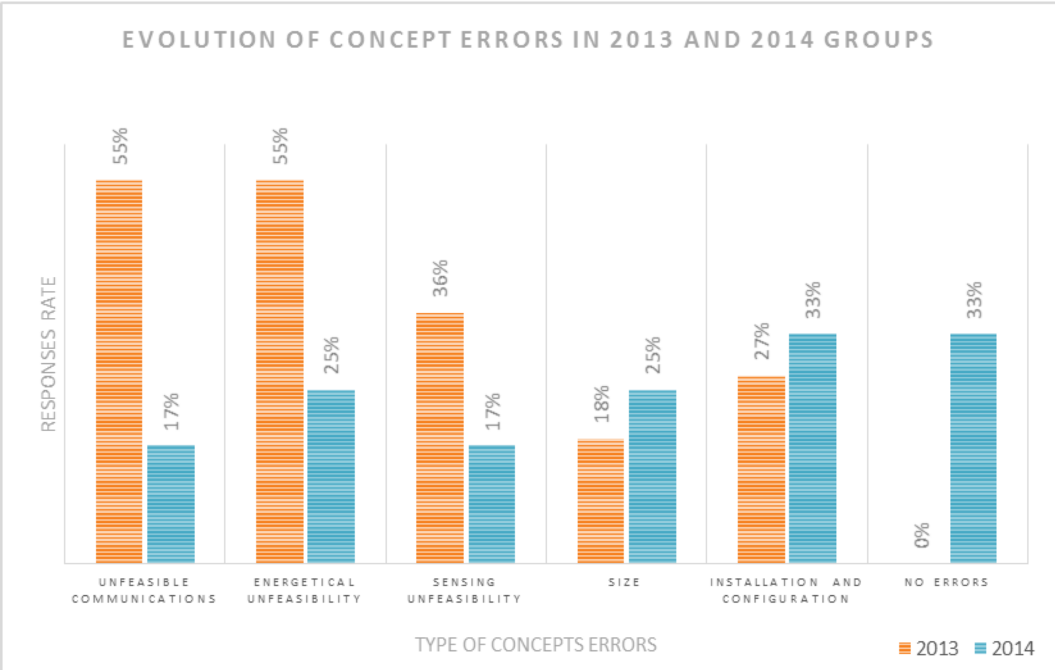


Fig. 8 *Comparison of concept errors in 2013 and 2014 groups*

This improvement evidenced in project outcomes is also coherent with individual students' opinions (from 61% feeling positive or very positive in 2013 to 77% in 2014), as we can see in Figure 10. All of the quantitative inquiries were graded using a Likert scale, with values ranging from 1-5, running from 1: strongly disagree to 5: strongly agree). Moreover, focus groups amplified this perception, being emphasised by the students as crucial points for their successful technological understanding and prototyping.

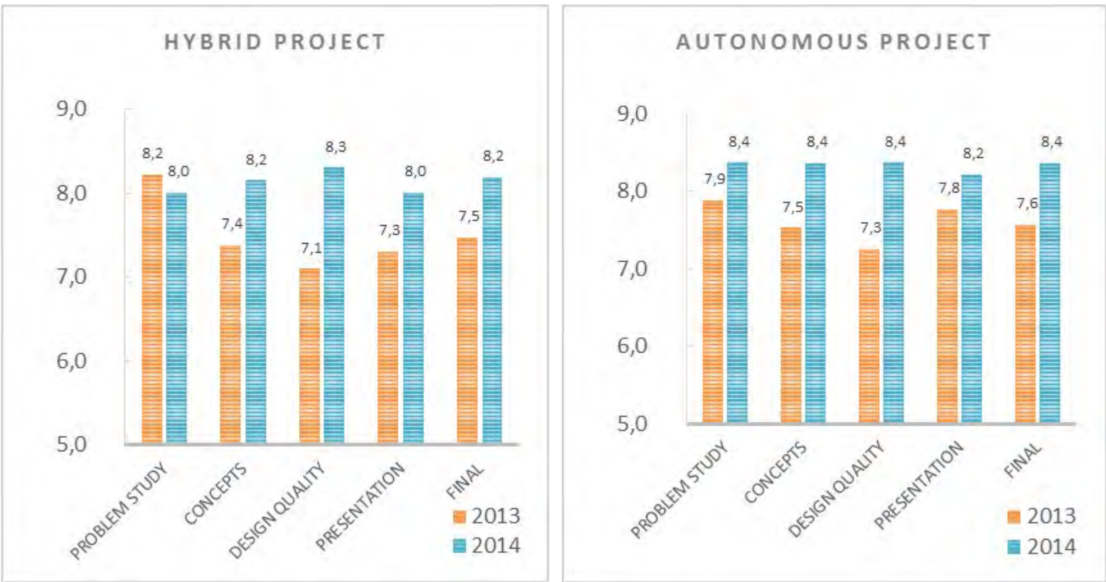


Fig. 9 *Evolution of students' grades (from 0 to 10) in 2013 and 2014 groups for hybrid and autonomous projects.*

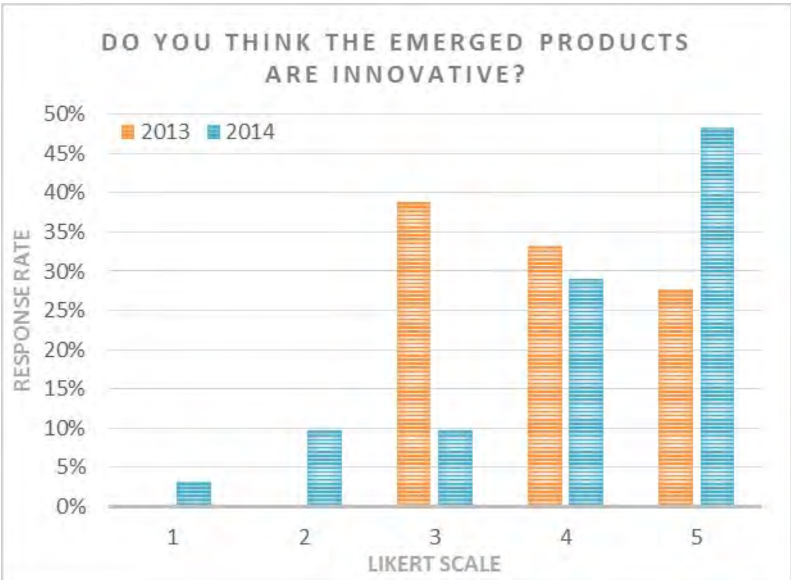


Fig. 10 *Students' responses to the survey question, "Do you think the products that have emerged are innovative?"*

5.2.2. TECHNOLOGY LITERACY AND SHARED UNDERSTANDING

Given that one of our main objectives was to empower designers to work in electronics design with greater confidence, we were interested to know if the students' *perception of learning electronics* was also improved, and if they felt that the technological training provided had been helpful. This issue was solved through various sources that led us to answer positively to that question:

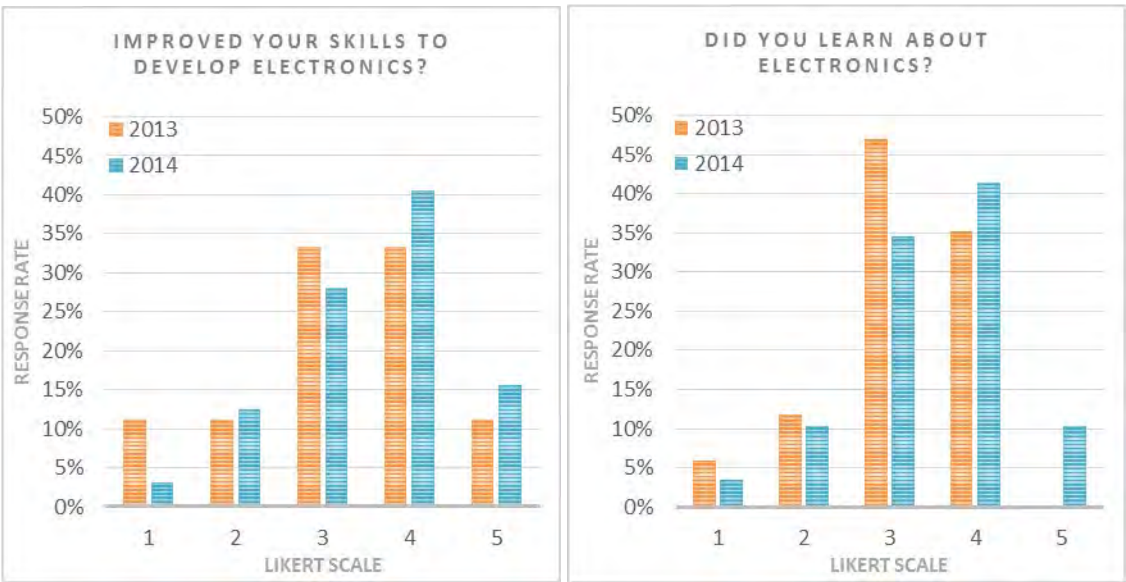


Fig. 11 Students' perception of learning electronics design

(i) Firstly, two questions were posed to designers about their *electronics knowledge after having been trained in the subject* (see Figure 11). The average is high in both years, with the results slightly better in the second year (10% more in 2014 feeling positive or very positive) and the two curves shifted towards the highest scores after having applied the technological instruction. Results in Figure 11-b indicate that the perception of the students about how much electronics they learned is positive, but does not vary much between both years. This is due to the *masking effect produced by the multidisciplinary collaboration,* which implies a learning of electronics by the designers. Working with electronics and with electronic students is an important source of learning, so the scores of 2013 are also high. In fact, qualitative responses indicate that *learning with complementary profiles* is an element that designers have valued as a way to improve their learning results and helped in the establishment of the common ground of knowledge. For example, several students expressed that the conjoint work led them to go further in developing working prototypes with electronic functionalities; this was also expressed in the previous year.

(ii) Furthermore, triangulating the result of Figure 11-b with those expressed in other sources clearly points to a substantial improvement in the vision of designers with regard to the subject of electronics, as we can see in Figure 12.

(iii) This argument is also supported by lecturers' observations and qualitative answers from students in 2014, which attests that this change includes an *explicit interest in deepening knowledge about electronics*, with "more electronics training hours" also "in the laboratory", even going so far as to propose the creation of a specific subject in the design grade. This is a very interesting point, because arising unexpectedly in open indirect questions in the survey, and triangulated with the results in Figure 9, a noticeable *appreciation,* "an interest to understand and support the other disciplines' goals and concepts" is undoubtedly indicated, which is related to Fruchter´s (2001) third dimension of the process of cross-disciplinary learning.

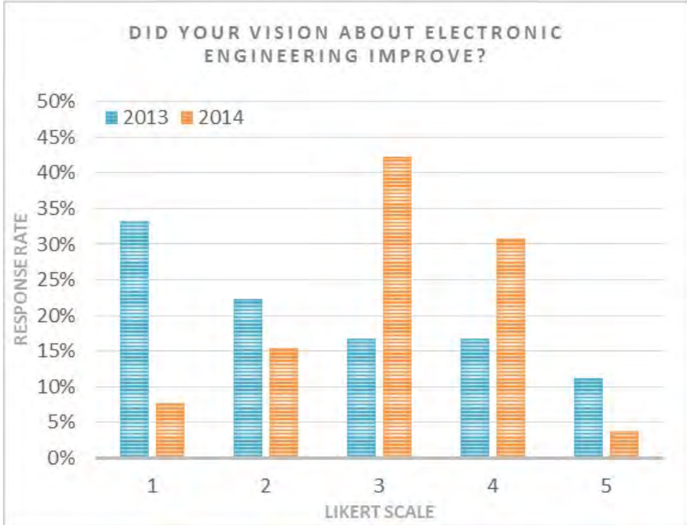


Fig. 12 Change of vision of design students with regards to electronics

Turning now to the tool contents, when asked directly what they valued most about the theoretical electronics training provided, most students highlighted issues related to: (i) ***Structuring of information***, as a guide to help to organise and "clarify ideas before delving into development, as in programming flowcharts", or to "summarise everything related to electronics"; (ii) ***Learning through examples*** "knowing how electronics components work in existing products with a level of complexity similar to that requested by teachers (or, in the future, by customers)"; (iii) ***Knowledge of electronics functioning***, finding it useful to "learn about the technologies that can be used and the differences between them" or to "see clearly the physical contents of electronics devices, and where and how the components interact"; (iv) ***Communication aid*** with their electronics mates, to "understand what they were talking about", and "understand with more clarity their concerns and way of thinking". This constitutes a step forward because, in addition to serving as learning material, it demonstrates shared understanding between disciplines. On the other hand, the first three items (also adding to lecturers' observations) are indicators that most students finished the experience understanding (or having the tools to understand) "the inner-working structure of technology" (Moore, 2011), thus reaching, to a greater or lesser extent, the third level of technology literacy pursued before the experience.

All of the groups used the tables and schemes as foundations for their respective products and contributions to the teamwork. One of the common uses in this sense was to iteratively fill the tables and use the schemes at the same time that they conjointly developed the concepts: "Working in concepts brainstorming the electronics sometimes explained to us why one idea was unfeasible, by considering the tables or the blocks diagram. We all discussed about it and proposed changes. We evolved all of our concepts in this way". This is a very relevant point, because one of the most repeated conflicts in previous years was that electronics students only saw problems in the concepts proposed by designers, and that designers only proposed unfeasible concepts. Students used the material provided as a communication tool, and this was a utility that, despite not having been predicted, supported our goals in a positive, unexpected way. We can align this evidence with the quantitative data resulting from a particular question that we posed the students: to register *how many multidisciplinary meetings they had.* While in 2013, the students met an average of 7 times during the semester, in 2014 they met 12.5 times, an increase of almost 80%. This is a very valuable indicator of the promotion of a closer cooperation among electronics students and designers, and we believe that the technology literacy tool contributed to it. In our experience, the occurrence of fewer meetings indicates that the students have compartmentalised their work and that they get together only to combine these components together. More meetings indicates closer and more effective collaboration, so it is an indicator about the enhancement of common work, discussion and shared understanding among disciplines.

Conversely, it should also be noted that some designers found it difficult to complete the tables, taking the electronics students the lead of this work. This is perfectly understandable, considering the limited time that teachers were able to dedicate to the electronics lessons and given the fact that electronics training was a relevant complement, but not the main focus of the programme. We have also to keep in mind that the use of tables requires an extra effort on the part of the students, and delegating this task to "the expert mate" is tempting. Nonetheless, this issue can be also an indicator that multidisciplinary collaboration is not dispensable in the real world, and the fact is that the majority of the students found it useful. Moreover, we were surprised because most electronics students reported that the model tables have also been useful to them, both with respect to teamwork and to structure their own work.

The experience validates our technological literacy learning material's utility in the design of smart electronic products. We can also stress the future potential of our model tables and constructive schemes: for now, the knowledge and tools were offered to the students in the theory class, they subsequently used it freely in teamwork, and the results have been quite satisfactory. Therefore, we can glimpse that if we provide electronics design guides, the use of which is more closely followed by the teachers, we could obtain even better results. Guides use will depend on the objectives of the subject, the time available, and whether or not collaboration with electronics students exists.

It is noteworthy that the methodology presented in this article broadens the scope of normally addressed competences because it is applied in parallel to students from different degree programmes. Indeed, this is a major difficulty to overcome that requires the strong motivation of the students and the lecturers, as well as flexibility to fit the organisation of an academic institution.

6. CONCLUSIONS

Technological innovations are coupled with meaning changes in market products. In the Internet of Things context, industry needs to respond to a multidisciplinary, pluralistic and society-centric culture that demands cutting-edge smart electronic products and new ways of understanding, using and interacting between humans and technology. Electronics and design engineering are key players in this complex context, where competitiveness and evolution need to integrate different types of knowledge, making interdisciplinarity and co-working strategies imperative.

Nevertheless, in learning institutions the diverse disciplines are still too isolated from others, and this has a negative impact in the working world. In our scenario, this results in the fact that electronics engineers are not usually aware of how much their decisions impact on users' relationships to the product, and designers do not fully understand the technology involved, its full potential and associated limitations. As a result, technologists' lack trust in the designers, and designers lack the resources to make themselves heard.

With the aim to train professionals prepared to share their understanding and capabilities on behalf of a knowledge-based dialogue between these two worlds, an experience of interdisciplinary PBL has been developed over 9 years, involving two different university degrees: the Industrial Design and Product Development Degree and the Electronic Engineering Degree at the University of Zaragoza. More specifically and within this context, in this paper we have described a successful case of applying a new technology literacy learning methodology that has been investigated for two years (2013 and 2014), and has involved 142 students.

Our strategy divided into two convergent directions. On one hand, we apply constructivist theory to create a third level of technology literacy in designers, with the aim that they can understand the inner-working structure of electronics, to mitigate designers' limitations in multidisciplinary teams. We suggest a set of adapted taxonomies to be explained in class and then provided as a guide or checklist to the students (or to be used by professionals). On the other hand, through an *ad hoc* subject methodology based in PBL interdisciplinary teams, we conduct the students from their previous islands of knowledge to a shared understanding between both fields. PBL has been a powerful instrument to frame this technology literacy action within a training of soft skills such as team working, self- and collaborative-learning, group management and confidence in the "different".

The cases examined in this paper demonstrate that our technology literacy contributes to improved smart electronics designs, enhancing the process of design itself at two levels. On one level is the acquisition of the third level of technology literacy in designers, which will allow them to be more involved in the entire process. The other level is the strengthening and facilitation of the shared understanding between the two main visions, which will result in more innovative and competitive products.

These two dimensions lead to a better performance of teams, reflected in the quality of the projects developed, with an enhancement in the innovativeness and the technological quality of the products; a considerable reduction in error rates; an evident improvement solving technological feasibilities; and better overall students' grades. Students' attitudes towards electronics as a topic to be learned have also improved; this has a basis in the improvement both of their perception of having learned electronics and also of their appreciation of the other discipline.

Learning with complementary profiles was an important factor in both years: communication, interaction and collaboration between students that have different backgrounds, character and thoughts, provides them with an effective preparation for the professional world, and with social and personal development. We consider this to be a key issue, as methodology points to integral education of the university student usually centred just in technical training. Also regarding this topic, we can state that our learning tool, used both inside and outside the classroom, was the driver of an improvement in this professional and social development, encouraging shared understanding. The students took advantage of it not only in planned but also in unforeseen uses, allowing us to discover new ways to apply it. Besides its usefulness in teaching activities, it could potentially serve as an instrument to learn about electronics functioning; to structure information; or to communicate adequately with other specialties, among other uses. In any case, we encourage using proposed methodology either as teaching material or as a design guide in the professional world.

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