Contribution to the development of technology-enhanced education in manufacturing and energy generation

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Abstract

In order to revert a global ecological collapse that would jeopardize Earth's capacity to sustain life, international organizations, such as the United Nations, have stressed the need to improve manufacturing methods and energy generation technologies. However, challenges towards the implementation of these methods and technologies vary according to the perspective. Rich countries need to drastically reduce their carbon emissions without abandoning their economic growth and / or decreasing the living standards of their populations. On the other hand, developing economies need to subject their rapid socio-economic development to environmental constraints while facing a severe scarcity of human resources technically competent to introduce methods and technologies necessary to generate local wealth, while reducing the environmental impact generated by productive and energy generation processes. This scarcity is especially dire in rural and informal urban settlement, where the need of local value creation is needed the most.

Given the limited success of current instructional approaches in overcoming specialists' deficits in these societies, new paradigms of education are necessary to support global sustainable development. These paradigms should be based in the integration of economic globalization aspects, rapid development of educational technologies, and didactic methods as a means to generate societal well-being with minimal environmental impacts. This dissertation proposes an Instructional Design Model for Engineering Education (IDMEE) aimed at improving engineering education's quality in developing countries. The proposed model bases its approach in the alignment of so-called educational dimensions to support instruction planners during the planning and delivery of formal and non-formal instruction with a strong technical component. In the proposed model, a strong emphasis has been given to the design of laboratories, appropriate to match specific engineering educational needs of heterogeneous audiences in developing countries.

The model is validated through the design and development of mobile high-end portable laboratories to support developing countries' education in the fields of sustainable manufacturing and energy generation. The design of these laboratories, deemed its physical portability feature as fundamental as a means to overcome technical and pedagogical shortcomings of distant-education alternatives. Demonstrators, realized and documented within the framework of this dissertation include a mobile E-Bike photovoltaic charging station, a portable wind tunnel, and a mobile learning factory for manufacturing. Each demonstrator is designed to address a variety of audiences according to its academic level and training purpose. Through appealing designs and features, as well as intuitive interfaces reducing external supervision, audiences comprising primary and secondary education students for instance, can be motivated to pursue higher education in the fields of engineering. On the other hand, undergraduate and graduate engineers can gain deep technical knowledge in renewable energies and manufacturing, and uneducated audiences can obtain basic knowledge enabling them to generate local value creation networks.

Zusammenfassung

Um einen globalen ökologischen Kollaps abzuwenden, der die Fähigkeit der Erde, das Leben zu erhalten gefährden würde, haben internationale Organisationen wie die Vereinten Nationen die Notwendigkeit betont, umweltfreundliche Fertigungsverfahren und Energieerzeugungstechnologien aus erneuerbaren Quellen zu implementieren. Die Herausforderungen bei der Umsetzung dieser Methoden und Technologien sind allerdings, je nach Entwicklungsstand des Landes, unterschiedlich. Frühindustrialisierte Länder müssen ihre CO2-Emissionen und den Ressourcenkonsum drastisch reduzieren, ohne ihr Wirtschaftswachstum zu gefährden und / oder den Lebensstandard ihrer Bevölkerungen zu verringern. Auf der anderen Seite müssen Entwicklungsländer ihre rasche sozioökonomische Entwicklung den Umweltauflagen unterziehen, wobei sie jedoch kaum über die notwendigen technisch-kompetenten Humanressourcen verfügen. Besonders beträchtlich ist die Knappheit dieses Personals in ländlichen und informellen urbanen Siedlungen in Entwicklungsländern, wo der gezielte Aufbau von Wertschöpfung am dringlichsten ist.

Angesichts des begrenzten Erfolges aktueller internationaler Ansätze bei der Überwindung dieser Bildungsdefizite, sind neue Bildungsparadigmen notwendig, um eine globale nachhaltige Entwicklung zu unterstützen. Diese Paradigmen sollten auf der Integration von ökonomischen Globalisierungsaspekten, einer raschen Entwicklung von Bildungstechnologien und didaktischen Methoden als Mittel zur Erzeugung von gesellschaftlichem Wohlergehen mit minimalem ökologischen Einfluss beruhen. In dieser Dissertation ist das sogenannte Instructional Design-Model for Engineering Education (IDMEE) erarbeitet, das darauf abzielt, die Qualität der Ingenieurausbildung in Entwicklungsländern zu verbessern. Das vorgeschlagene Modell stützt sich auf die Ausrichtung von sogenannten Bildungsdimensionen, um Unterrichtsplaner bei der Planung und Durchführung von formaler und nicht-formaler Ausbildung mit einem starken technischen Bestandteil zu unterstützen. In dem vorgeschlagenen IDMEE wurde ein Schwerpunkt auf die Gestaltung von Laboratorien gelegt, und spezifische technische Bildungsbedürfnisse heterogener Lernergruppen in Entwicklungsländern beachtet.

Das Modell wird durch die Konzeption und Entwicklung von mobilen High-End-Laboren in den Bereichen der nachhaltigen Wertschöpfung und Energieerzeugung validiert. Die physische Portabilität ist eine fundamentale Eigenschaft dieser Laboratorien, um technische und pädagogische Mängel im Vergleich zum Fernunterricht zu überwinden. Zu den im Rahmen dieser Dissertation entwickelten Laboren gehören eine mobile E-Bike-Photovoltaik-Ladestation, ein tragbarer Windkanal, und eine mobile Lernfabrik. Jeder Demonstrator ist dazu ausgelegt, eine Vielzahl von Zielgruppen nach seinem akademischen Niveau und Ausbildungszweck zu adressieren. Durch ansprechende Gestaltung und Features sowie intuitive Schnittstellen können z.B. Schüler motiviert werden, eine Hochschulausbildung im Bereich des Ingenieurwesens zu verfolgen. Andererseits können Studierende an Universitäten tiefe technische Kenntnisse in der Erzeugung erneuerbar Energien und nachhaltiger Produktion erwerben. Ungebildete Zielgruppen können Grundkenntnisse erlangen, die es ihnen ermöglichen, lokale Wertschöpfungsnetze zu generieren.

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AECT	Association for Educational Communication and Technology
aka	also known as
API	Application Programming Interface
APPC	Adaptive Production Planning and Control
BMS	Battery Management system
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAI	Computer-Aided Instruction
CAM	Computer-Aided Manufacturing
CBT	Computer Based Training
CCS	Carbon Capture and Storage
CdTe	Cadmium Telluride
CEDEFOP	Centre Européen pour le Développement de la Formation Professionnelle (French: European Centre for the Development of Vocational Training)
CFC	Chlorofluorocarbons
CIGS	Copper Indium Galium Selenide
CIM	Computer Integrated Manufacturing
CIRP	College International pour la Recherche en Productique (French: International Academy for Production Engineering)
CIS	Copper Indium Diselenide
CNN	Cable News Network
CNC	Computerized Numerical Control
CO_2	Carbon Dioxide
CPL	Cyber-Physical Laboratories
CPS	Cyber-Physical Systems
CSP	Concentrating Solar Power
DAS	Data Acquisition System
DC	Developing Country
DFM	Design for Manufacturing
DGS	Deutsche Gesellschaft für Sonnenenergie
DIN	Deutsches Institut für Normung
DMAIC	Define-Measure-Analyze-Improve-Control
DPAD	Department Policy and Analysis Division
EC	European Commission
EEA	European Environmental Agency
EPA	Environmental Protection Agency
ERP	Enterprise Resource Planning
ESD	Education for Sustainable Development
EU	European Union
FTE	Full Time Equivalent
GDP	Gross Domestic Product
GFN	Global Footprint Network
GIZ	Deutsche Gesellschaft für internationale Zusammenarbeit
GNI	Gross National Income
GOLC	Global Online Lab Consortium
GPE	Global Production Engineering
GWEC	Global Wind Energy Council

HEI	Higher Education Institution
HWAT	Horizontal-Axis Wind Turbines
ICON	Interpretation Construction Design Model
ICSP	In-Circuit Serial Programming
ICT	Information and Communication Technologies
IDM	Instructional Design Models
IDMEE	Instructional Design Model for Engineering Education
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
ILS	Index of Learning Styles
IMF	International Monetary Fund
IOT	Internet of Things
IRENA	International Renewable Energy Agency
IT	Information technologies
IV Curves	Current-Voltage Characteristic
j_{sc}	Short circuit current
K-12	Kinder garden (K) through twelfth education grade (12)
LCA	Life Cycle Assessment
LDC	Least Developed Countries
MDG	Millennium Development Goals
MLF	Mobile learning factory for manufacturing
MOOC	Massive Open Online Course
MPP	Maximum Power Point
MVA	Manufacturing Value Adding
N2O	Nitrous Oxide
NAS	National Academy of Sciences
NCES	National Center for Education Statistics
NMC	New Media Consortium
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Cooperation and Development
OPF	One Piece Flow
OTEC	Ocean Thermal Energy Conversion
PBL	Project- / Problem-Based Learning
PCB	Power Circuit Board
PDI	Power Distance Index
PPC	Production Planning and Control
PV	Photovoltaic
QM	Quality Management
RAS	Reconfigurable Assembly Systems
REN 21	Renewable Energy Policy Network for the 21st Century
RMS	Reconfigurable Manufacturing Systems
RPM	Revolutions Per Minute
RPP	Reconfigurable Process Planning
SAED	Systematic Approach to Engineering Design
SDG’s	Sustainable Development Goals
SEIA	Solar Energy Industries Association
SMART	Specific, Measurable, Attainable, Relevant, Time-bound
SPC	Statistical Process Control
STEM	Science, Technology, Engineering and Math
TF	Transformable Factories

TQM	Total Quality Management
TUB	Technische Universität Berlin
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNWTO	United Nations World Tourist Organization
USD	United States' Dollar
VCM	Value Creation Module
VDI	Verein Deutscher Ingenieure
WB	The World Bank
WEF	World Economic Forum
WESP	World Economic Situation and Prospect
WIP	Work in Progress

1 Introduction

1.1 Motivation

The path to achieve global sustainability is a challenging one as international inequality between individuals and nations is considerable [MIL-05]. On the one hand, populations in developed countries corresponding to close to 18 % of world's population are commonly characterized by high incomes, reliable access to basic, educational and health services, early adoption of technology and products to improve their living standards [OECD-16]. On the other hand, large population sectors in developing countries lack most of these benefits and are commonly marginalized from national economic growth [UN-16]. Through the use of modern Information and Communication Technologies (ICT) however, populations in developing countries acknowledge this wealth disparity and strive to improve their living conditions demanding access to goods and services commonly available in developed nations.

Yet, the grim reality is that, under current production / consumption paradigms, the world is unable to sustain an equal level of development. Since 2007, the Global Footprint Network has reported in its Ecological Footprint Atlas that global population is consuming 1.5 times as many resources as Earth can regenerate. According to the same source, if the entire world population were supposed to live with the same life-standards as the average U.S. citizen for instance, the amount of required earths to support humankind existence would mount to four [GFN-10]. Sustainability has become therefore an urgent requirement and challenge for mankind's survival on earth and for their future development, considering the limits of resources and growth and the unequal distribution of wealth [SEL-12].

Under this premise, the development of roadmaps to achieve global sustainability has become a priority for national governments and international organizations since some decades. The latest and most ambitious agreement in this sense is represented by the Sustainable Development Goals (SDGs) adopted by 193 countries during the United Nations (UN) General Assembly on 25th September 2015. Contained in the UN resolution A/RES/70/1, also known as the 2030 Agenda for Sustainable Development, a set of 169 targets grouped in 17 goals are expected to frame national and international development policies as a means to wipe out poverty, fight global inequalities and tackle Earth's climate change [UN-15]. An overview of the seventeen SDGs is depicted in figure 1.

According to the UN, the SDGs stress "*everything from zero poverty, zero hunger, good health, quality education, gender equality, clean water and sanitation, and affordable clean energy, to decent work and economic growth, innovation, reduced inequalities, sustainable cities, responsible consumption, climate action, and unpolluted oceans and land*". These SDGs will serve as a guideline for every signing country to stimulate concrete actions over a period of fifteen years in areas of critical importance for humanity and the planet [UN-16]. The UN also recognizes that in order to facilitate the achievement of these goals, international partnerships between developed and developing economies are necessary. These collaborations include among others, the mobilization of economic means and the exchange of knowledge to strengthen "*global solidarity, focused in particular on the needs of the poorest and more vulnerable*" [UN-15].

Figure 1: UN's Sustainable Development Goals [UN-15]

Tackling the issues addressed by the UN in its SDGs requires the contribution of a broad range of knowledge areas acting in an interdisciplinary manner to create solutions for the world's most difficult problems on a political, institutional and system level.

Sustainable solutions are especially needed in value creating areas such as manufacturing and energy generation / transmission, responsible of almost 50 % of hazardous gas emissions into the atmosphere [EUS-13]. Abating these figures will require implementation of modern and environmentally friendly technologies, which in turn are a result of blending scientific research, education[1] and practical solutions. The training[2] of engineers, scientists and managers in the fields of manufacturing and energy procurement able to understand the complex interdisciplinary interactions between techno-social systems and natural environment, should therefore be considered priority while establishing national and international sustainability policies [JAW-13].

Yet, the training of engineers in most developing countries has been historically challenging due to chronical deficits in terms of available teaching faculty and infrastructure [JHA-07] [SZI-15]. UNESCO data show that, while developed countries count between twenty and fifty scientists and engineers per 10,000 inhabitants, the average in developing countries ranges three to nine such specialists [UNE-10]. This rate worsens when considering the so-called Least Developed Countries (LDC) [UNE-10].

Among international developing agencies, there seems to be a consensus that the lack of engineering capacities in most developing countries is hampering the improvement of their socio-economic living conditions. In 2014, UNESCO estimated that 2.5 million new engineers and technicians were still required in sub-Saharan Africa to achieve the development goals of the organization [UNE-14]. The challenge for these economies UNESCO adds, not only relies in educating engineering specialists with way lower infrastructural resources, but also in retaining and regaining graduates trained in national and international Higher Education

[1] Education refers to a broadly inclusive term referring to a process of fostering cognitive, physical, social, emotional or moral growth and development in individuals or groups. It is goal directed, implies a values system and may proceed in a formal, non-formal, or informal manner [COL-03].
[2] Training refers to the instruction that is planned and focused on the acquisition of skills and knowledge for a specific task or purpose. In contrast to education, training is undertaken for extrinsic purposes and practical ends, e.g. career preparation, while education is intrinsically valuable and is lifelong and continuous [COL-03].

Institutions (HEI) [UNE-10]. More recently, a report of WaterAid showed that billions of dollars of foreign aid fail to reach desperately needed energy, water and sanitation projects every year due to the lack of local engineers [WAI-15]; [MAT-16].

It may be concluded therefore, that the accomplishment of the targets of the UN's SDGs largely depends, in the capabilities of developed and developing countries to produce and keep high quality engineering specialists, who help tackle global underdevelopment through sustainable approaches.

1.2 Research aims

1.2.1 General objective

The general objective of this dissertation is to present a formal instructional framework aimed at supporting engineering instructors during the planning and conduction of high-quality formal and non-formal instructional events[3]. The proposal will be centered in the development of an Instructional Design Model (IDM), characterized by the alignment of the four core educational dimensions of "What", Who", "How", and "By which means" comprising teaching content[4], target audience[5], didactic principles[6], and educational technologies[7] respectively. The suggested IDM is intended to serve as a means to support formation of human resources capable to contribute to the accomplishment global sustainability. Given engineering's technical nature, implementation of technology-based training will be prioritized by including a methodological approach to align the selection, or the design and development of educational technologies and laboratories to specific learning theories[8], learning styles[9] and didactic models[10]. Through the development of mobile, high-end laboratories in accordance to the proposed IDM, a special focus will be given to the improvement of formal and non-formal education in the knowledge fields of sustainable manufacturing and energy generation in developing countries. Engineering education improvement in these fields is relevant as a means to contribute to the achievement of the SDGs described below:

- Goal 4 (Quality education): The goal makes explicit reference to the need of enhancing local teaching competences in developing countries and to ensure that "*all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development*". In this sense, the IDM to be presented considers the principles of universality and customization to develop local human resources in developing countries to act as knowledge multiplicators.

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[3] Instructional events are lectures, seminars or exercises conducted to deliver instruction.
[4] Referred to as the subject of instruction. Also understood as what is to be taught.
[5] Referred to as a specific subset of learners addressed by the instructional event. Also understood as who will be taught.
[6] Referred to as the application of learning theories, learning styles and didactic models proposed by psychologists, pedagogues and engineering educators to enable efficient knowledge conveyance. These concepts are further specified in chapter 3.
[7] Referred to as technological resources used to facilitate and improve learning processes.
[8] Psychological theoretical frameworks intending to explain how cognitive processes take place.
[9] Personal preferred modes of learning influenced by intellectual preferences, culture or environment [COL-03].
[10] Principles, strategies, methods and mechanisms of instruction between learners and teacher.

- Goal 7 (Affordable and clean energy): The goal stresses the need to "*expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries*". The presented IDM is validated through the development of courses and laboratories to support instruction[11] in the fields of photovoltaics and wind energy in developing countries. The courses will aim to enhance acceptance and local development of these technologies.
- Goal 9 (Industry, innovation and infrastructure): The goal puts a strong emphasis on the development of sustainable industrial capabilities in developing countries as a means to generate economic growth and societal wellbeing. The presented IDM will be validated through the development of courses and technological infrastructure to support instruction in the field of sustainable manufacturing. In this case, a formal instructional event based on a hands-on approach to take place in a mobile learning factory for manufacturing has been developed to fulfill industrial needs in developing countries.
- Goal 12 (Responsible consumption and production): The goal seeks to increase the resource consumption efficiency through methodological and technological means (e.g. through reduction, recycling, and reuse). Developing countries are to be supported to "*strengthen their local scientific and technical capacities to move towards more sustainable patterns of consumption and production*". For this purpose, the presented IDM will be validated through the development of courses and technological infrastructure to support instruction in the field of sustainable manufacturing. In this case, a non-formal instructional event will be developed to improve rural and informal urban communities' education as a means to support their economic diversification and reduce their economic dependence on primary sectors such as agriculture and forestry.
- Goal 17: (Partnerships for the goals): The targets of this particular goal are divided in technology, capacity building, finance, trade, and systemic issues categories. The first two categories are especially relevant for this dissertation including targets such as:
    - *"Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favorable terms, including on concessional and preferential terms, as mutually agreed".*
    - *"Enhance international support for implementing effective and targeted capacity-building in developing countries to support national plans to implement all the sustainable development goals, including through North-South, South-South and triangular cooperation".*

Particular educational challenges faced by developing countries will be thoroughly analyzed in order to provide technological and methodological alternatives to instructional approaches that have proven insufficient to reach impoverished rural and informal urban communities. The concept of physical mobility to counter educational shortcomings of distance-education methods will be presented.

1.2.2 Methodology

The improvement in the education of sustainable manufacturing and energy generation in developing countries is to be achieved through the following methodological approach:

- Conduction of an analysis of conventional knowledge transfer practices from developed to developing countries with special focus on the areas of sustainable manufacturing

[11] Instruction refers to the guided lessons and materials used to teach a subject. It is characterized as a systematic approach to impart knowledge or developing skills. Synonym: Teaching [COL-03].

and energy generation. The intended assessment will allow the identification of gaps, as well as advantages and disadvantages of existent knowledge transfer methods.

- Analysis of existing engineering education frameworks in developing countries as a means to achieve a better understanding of their infrastructural and teaching human resources, as well as education systems[12]. The assessment will evaluate elements such as teaching / learning infrastructure, local availability and quality of teaching staff and learning materials, as well as the locally available formal and non-formal education systems.
- State-of-the-art review concerning relevant learning theories[13], didactic models[14], and educational technologies[15], as a means to understand how learning takes place and how diverse educational technologies can be implemented to support cognitive processes[16]. An important component of this research comprises systematic approaches to organize instruction known as Instructional Design Models [17](IDMs).
- Proposal of an educational technology-based Instructional Design Model to support engineering education. A strong focus on methods to design and develop appropriate educational technologies according to particular educational needs will be given.
- Validation of the proposed model through the design and development of mobile laboratories to support the conduction of sustainable manufacturing and energy generation courses to improve training of human resources in developing countries.

1.3 Disambiguation of "Developing Countries"

Due to the special focus of this dissertation, a concrete definition of the term "developing countries" is in order. There is no universal consensus when it comes to designate a country as "developed" or "developing". International organizations classify countries in different ways under consideration of different factors. The International Monetary Fund (IMF) classifies countries in advanced, emerging, or developing economies, for instance, while the World Bank (WB) classifies them in either high income, upper middle income, lower middle income, and low income according to the country's gross national income (GNI) per capita [NIE-11]; [TWB-13]. The United Nations in turn, use factors such as income, education, healthcare and life expectancy to divide countries in either developed, developing, or least developed countries (LDC) [DPA-12]. For the sake of coherence while addressing the individual targets of the UN SDGs, UN's classification has been used throughout this study while referring to "developing countries".

[12] The term education system generally refers to public schooling, and more commonly from kindergarten through high school programs. Schools or school districts are typically the smallest recognized form of "education system" and countries are the largest. Simply put, an education system comprises everything that goes into educating public-school students at the federal, state, or community levels [ABB-13].

[13] Conceptual psychological frameworks describing how information is absorbed, processed, and retained during learning [ORM-12]. Some of the best-known theories include behaviorism, cognitivism, constructivism and experiential learning theories.

[14] Principles, strategies, methods and mechanisms of instruction between learners and teacher [FLE-96].

[15] The study and ethical practice of facilitating learning and improving performance by creating, using, and managing appropriate technological processes and resources [JAN-13].

[16] Cognition is a broad term used to distinguish the abstract, reasoning components of mind/brain from other psychological functions such as affect/emotion, sensation and the like. Hence a cognitive process describes the act people use in perceiving, reasoning, understanding, and judging the environment and the information they receive [COL-03]

[17] Instructional Design Models are systematic methodological approaches to accomplish learning objectives by means of structured instructional events. In more abstract terms an *instructional design model* is a kind of abstract design rule for a given instructional design approach or a given pedagogic strategy [EWK-16].

This classification is provided by the World Economic Situation and Prospect (WESP) publication of the Development Policy and Analysis Division (DPAD) of the United Nations Secretariat (UN / DESA) [DPA-12]. According to the publication, DPAD's classification is based on information provided by the five United Nations regional commissions, the United Nations Conference on Trade and Development (UNCTAD), World Tourism Organization (UNWTO), the International Monetary Fund (IMF), the World Bank (WB), the Organization for Economic Cooperation and Development (OECD), and national and private sources. A list of developing countries according to WESP in shown in table 1.

Table 1: UN's classification of developing countries per region [DPA-12]; [DESA-15]

Africa **16 % of world's population**		**Asia** **58 % of world's population**	**Latin America and the Caribbean** **9% of world's population**
North Africa	Southern Africa	East Asia	Caribbean
Algeria	Angola	Brunei	Barbados
Egypt	Botswana	China	Cuba
Libya	Lesotho	Indonesia	Dominican Republic
Mauritania	Malawi	Malaysia	Guyana
Morocco	Mauritius	Myanmar	Haiti
Sudan	Mozambique	Papua New Guinea	Jamaica
Tunisia	Namibia	Philippines	Trinidad and Tobago
Central Africa	South Africa	Republic of Korea	Mexico and Central America
Cameroon	Zambia	Singapore	Costa Rica
Central African Republic	Zimbabwe	Taiwan	El Salvador
Chad	West Africa	Thailand	Guatemala
Congo	Benin	Vietnam	Honduras
Equatorial Guinea	Burkina Faso	South Asia	Mexico
Gabon	Cabo Verde	Bangladesh	Nicaragua
	Cote d' Ivoire	India	Panama
East Africa	Gambia	Iran	South America
Burundi	Guinea-Bissau	Nepal	Argentina
Comoros	Liberia	Pakistan	Bolivia
Congo	Mali	Sri Lanka	Brazil
Djibouti	Niger	Western Asia	Chile
Eritrea	Nigeria	Bahrein	Colombia
Ethiopia	Senegal	Iraq	Ecuador
Kenya	Sierra Leone	Israel	Paraguay
Madagascar	Togo	Jordan	Peru
Rwanda		Kuwait	Uruguay
Somalia		Lebanon	Venezuela
Uganda		Oman	
Tanzania		Qatar	
		Saudi Arabia	
		Syria	
		Turkey	
		United Arab Emirates	
		Yemen	

Within this dissertation, a special emphasis will be put in proposing approaches to enable and improve engineering education in developing countries' rural and informal urban areas. The reason is simple, despite clear evidences of steady global urbanization trends indicating an increase of urban population from 30 % in 1950 to 54 % in 2014, population in developing regions such as Africa and Asia remain mostly rural with 40 and 48 percent of their respective populations living in urban areas in 2015 [DESA-14].
Moreover, even when considering urban populations, many developing countries have recognized difficulties in managing the migration effect from rural to urban areas resulting in over 70% of urban growth currently happening outside formal planning processes and 30 % or urban populations in developing countries living in informal urban settlements commonly known as slums [KEL-10]; [OLA-15]. In most cases, the lack of settlement control on behalf the public administration leads to a deprivation of services such as education in these communities, leading to a high number of poor and uneducated community dwellers, which in turn leads to chronic underdevelopment or social unrest.

1.4 Dissertation structure

The present dissertation is comprised by seven chapters briefly described in figure 2.

	Analysis	**Results**
Chapter 2: Sustainability and two relevant knowledge areas.	• Sustainability definition. • Manufacturing and sustainable manufacturing. • Sustainable energy generation. • Current sustainability challenges in developing countries.	• Developing countries (DCs) suffer from a lack of specialists in sustainability related fields due to a deficit on education resources (staff, equipment, and literature).
Chapter 3: State of the art.	• Learning theories. • Learning styles in engineering education. • Didactic models. • Educational technologies. • Instructional models' design methods.	• Review of significant concepts and elements in education. • Identification of appropriate pedagogic approaches for engineering education and suitable technologies to support education in DC.
Chapter 4: Research gap.	• DCs lack quality education in sustainability relevant fields. • Knowledge transfer from developed to developing countries is insufficient. • Low accessibility of educational technologies in DCs.	• Instructional models and educational technologies to support education in DCs are needed.

Chapter 5: Instructional model for engineering education.	• Definition of model's core components: content, target audience, pedagogic methods and educational technologies. • Definition of model structure.	• Proposed Instructional Design Model for Engineering Education (IDMEE).
Chapter 6: Concept validation.	• Planning of three courses in sustainable manufacturing and energy generation for DCs. • Determination of required educational technologies.	• Design and development of laboratories to support education in sustainable manufacturing and energy generation for DCs. • Validation through conduction of prototype courses.
Chapter 7: Conclusion.	• Review of own contribution.	• Development of an instructional framework to support educators during the planning and conduction of high-quality engineering instruction aiming global sustainability.

Figure 2: Dissertation structure

Due to their relevance to the present dissertation, chapter two will introduce the knowledge fields of manufacturing and renewable energy generation. Divided in two sections, the chapter intends to familiarize the reader with the aims, processes and technologies pertinent to these fields as a preamble to analyze their sustainability potentials. Realizing the enormous challenge to describe the broad field of manufacturing in a succinct sub-chapter, the first section provides an overview of the most common elements and disciplines comprising modern industrial production. Some of the topics covered in this section include the classification of manufacturing and assembly processes, the planning of production systems and operations management. These topics are later retaken in section 6.4 as learning elements of the proposed practical course on sustainable manufacturing introduced in the chapter "Validation". The relevance of sustainability in manufacturing is also described in this section, which finalizes with a review of the challenges developing nations will face in the upcoming decades to cope with their productivity-growth perspectives.

Chapter two's second section commences with a renewable energy technologies' outline including an overview of their energy generation principles, physical conversion systems and components, as well as their current energy contribution to the world's energy mix and degree of deployment. Similar to the previous section, topics such as potential contribution of fossil-free energy generation towards the achievement of sustainable development targets, and existing challenges for their implementation in developing countries, including specialists' deficits, will be covered.

Chapter three will provide an extensive state-of-the-art analysis concerning classic and modern learning theories and styles, didactic methods, educational technologies, as well as methods for the design of instructional design models used to support modern primary, secondary and tertiary education. A special focus will be laid at their implementation as a means to support engineering education, which implies a thorough review of available technological means capable of improving practical learning in laboratories for students of all ages.

In chapter four, a comprehensive analysis of the state-of-the-art review in engineering education will be conducted. The need for an Instructional Design Model for Engineering Education as a means to conceive instructional events that support high quality engineering training based on virtual and physical educational technologies will be addressed. As a means to contribute towards the achievement of UN’s SDGs, the dimensional specifications of the suggested model should support the harmonization of the instructional event’s learning objectives with its learning outcomes under consideration of social, economic, infrastructural and cultural considerations. Finally, the implementation challenges of such a model in developing countries due to their human resources and infrastructural deficits will also be addressed.

In chapter five, an Instructional Design Model for Engineering Education to support engineering education will be proposed. The presented model will have a strong practical focus as a means to prepare future engineers to cope with technical and methodological challenges experienced in real life. The sequential four-dimensional model takes into account factors such as instruction’s content (“what”), target audience (“who”), pedagogic approach (“how”), and educational technologies (“by which means”) to design and elaborate engineering instructional events appropriate for all formal education layers and even non-formal education. In order to cope with infrastructural challenges proper of rural and informal urban regions in developing countries, the approach will make use of the latest development in educational technologies for the realization of mobile laboratories that facilitate cost-efficient, high-quality practical education in the fields of engineering. It will be argued that the mobility characteristic of these devices has a significant potential to contribute towards the achievement of global sustainability, as it enables the conduction of high-quality formal and non-formal instruction in rural and informal urban communities in developing countries.

Chapter six describes the validation of the proposed model through the design of instructional events to support education in the fields of sustainable manufacturing and energy generation in developing countries. The validation includes the development of a mobile E-Bike photovoltaic charging station, a portable wind tunnel, and a mobile learning factory for manufacturing to support instruction even in infrastructurally underdeveloped regions contributing thus to the achievement of the UN’s SDGs 4, 7, 9, and 12. Preliminary results of the conduction of test courses carried out at the facilities of the Technische Universität Berlin with participants originating mostly from developing countries will be additionally presented.

Finally, chapter 7 will wrap up the conclusions of the study, its limitations, as well as future research perspectives.

2 Sustainability and its impact in manufacturing and energy generation

The term sustainability has, since its inception during the UN Brundtland commission on the 20th March 1987, proven to be one of the core elements while setting priorities in the political agendas of most of the world's countries. According to the results of this commission embodied in the document "our common future" also known as the Brundtland report, the term "sustainable development" was defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [BRU-87].

The two key concepts of sustainable development were, according to the report "the concept of needs, in particular the essential needs of the world's poorest people, to which they should be given overriding priority; and the idea of limitations which is imposed by the state of technology and social organization on the environment's ability to meet both present and future needs" [BRU-87].

This definition, though deliberately vague in its reaches and implications marked the start of serious global attempts to reconcile economic interests of developed nations with the need of development in poor and developing nations under the umbrella of what until then was considered as "a common environment". The definition served also as cornerstone for the development of thorough approaches towards the determination and quantification of the earth's environmental limits while supporting human life. Soon after, during the 2002 World summit of sustainable development, the standard definition was elaborated further by explicitly naming and including what currently is broadly accepted as the three pillars of sustainability, namely economic development, social development and environmental protection [UN-02].

Since then, UN conferences have taken place on a regular basis in order to set international standards, limits and targets to socio-environmental indicators provided by science to achieve a sustainable development on a global level. The latest UN climate change conference held in Paris in 2015 finalized with formal agreements on behalf of the 193 participant countries, to sign a pact concerning the reduction of carbon emissions and global warming to "well below 2°C above pre-industrial levels by 2030" [UN-15]. Furthermore, since January 1st, 2016, seventeen Sustainable Development Goals (SDGs) came into force as part of the UN's 2030 Agenda for Sustainable Development. These SDGs, aimed to replace and enhance the original Millennium Development Goals (MDGs) as a global strategy to achieve sustainable development worldwide, include targets and action plans concerning key areas such as alleviation of poverty, education, access to clean energy, national economic growth, improvement of industrial production processes, and market consumption behaviors among others. Although not binding by nature and in some cases somehow ambiguous, these global targets were ratified by heads of state of over 185 nations and are expected thus to permeate national and international development policies in the upcoming years [UN-16].

The importance set by the UN in the SDGs 7, 9, and 12 are better understood by analyzing emission reports from regional and international environmental agencies. According to EUROSTAT, an organic directorate of the European Commission, in 2012 a staggering 46 % of greenhouse gas emissions within the EU were caused by energy generation & transmission processes as well as by manufacturing activities [EUS-13]. Figure 3 presents greenhouse emissions' shares in the European Union in 2012.

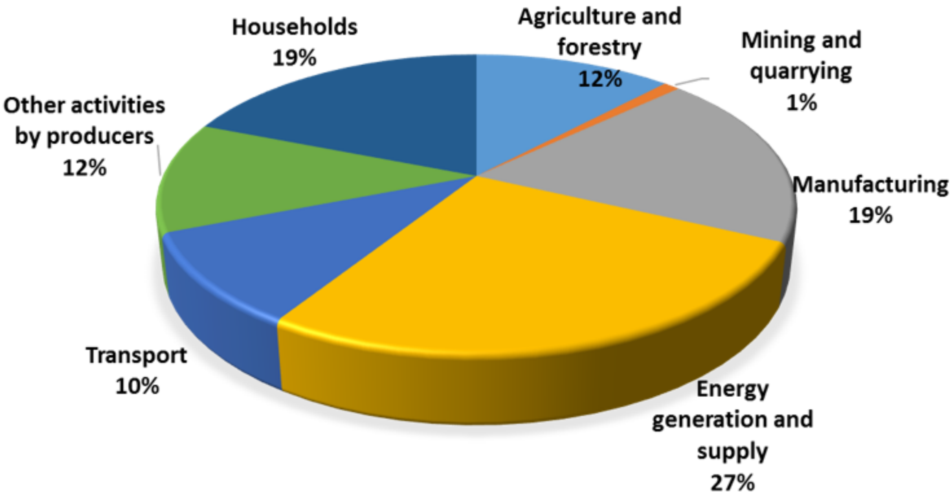

Figure 3: Greenhouse gas emissions by industries and households. Year 2012 [EUS-13]

The objective of the present chapter is therefore to introduce two fields of study with remarkable relevance while achieving the SDGs and international agreements on sustainable development. The first of these fields, namely manufacturing comprises industrial production processes and systems aimed at transforming raw materials into finished goods. The second refers to the fossil-free generation of energy achieved through renewable energies.

2.1 Manufacturing

2.1.1 Definition

The International Academy for Production Engineering (CIRP: French) define manufacturing as "*the entirety of interrelated economic, technological and organizational measures directly connected with the processing / machining of materials, i.e. all functions and activities directly contributing to the making of goods*" [CIR-04]. Manufacturing is characterized by its value-creation or value-adding nature. Value is created / added through the physical transformation of input materials into output materials [HEY-14]. Value in turn, is understood as an objects' potential of being useful [WEN-87]. In a finished product, it can be defined as a monetary reflection of and owner(s)' / buyer(s)' desire to respectively retain or obtain it [NEA-99].

2.1.2 Relevance

The degree of a nation's industrialization positively correlates to its economy [KAU-10]. Most economists accept that this correlation is governed by Kaldor's "economic growth laws" stating that:

- There is a strong relation between the growth of manufacturing output and the growth of a national Gross Domestic Product (GDP).
- An increase in the rate of growth of manufacturing output leads to increases in labor productivity in that sector (Kaldor-Verdoorn Law).
- The productivity in the non-manufacturing sectors increases as the rate of growth of manufacturing output increases.

Manufacturing's impact on a given economy is reflected in several ways by creating strong forward and backward linkages across most national and international income generation sectors. According to [LAV-12], some of the most visible effects of manufacturing on the socio-economic development of a country are:

- A strong economic contribution to national GDPs: When it comes to its direct economic impact for instance, manufacturing contributes with up to 15 % of the combined European GDP [EC-15] and 12.7 % in case of the U.S. GDP [NAM-14]. The contribution of manufacturing in global economies ranges from 3 % in Chad to 30 % in South Korea [TWB-14]. Despite halving its global GDP contribution in the last 65 years, manufacturing's GDP share remains one of the biggest in developed economies [MAY-12], which suggests that developing economies' economic growth is largely linked to their capabilities in beefing up their manufacturing sector.

- Generation of direct and indirect jobs: In terms of job generation, manufacturing continues to be a significant employment provider. Whereas direct employment tends to be relatively moderate, lying between 10 and 20 % of the total national job base, the sector provides the highest indirect employment ratio in linked sectors [MAY-12]. This "multiplicator" effect has been documented in several national and international reports with the U.S. Bureau of Economic Analysis (BEA) stating that for each USD worth of final demand in the U.S. market, manufacturing generates 1.48 USD in other services [GOL-14].

- Knowledge and technological spillover effects: Another well-studied side effect of a strong industrial sector is the intersectoral knowledge and technological spillover a country observes as a result of massive investments in research and development usually sponsored by manufacturing companies [LAV-12]. Park estimates that the social returns to manufacturing R&D are two to six times bigger than the private returns in the manufacturing sector alone [PAR-04].

- Structural transformation: Manufacturing fosters what economists describe as structural transformation. Defined as the evolution of an economy from traditionally low productivity activities, such as conventional agriculture, to activities with higher productivity rates, such as manufacturing or services, this structural transformation allows a diversification on national income sources and technologically develops regional and national technical infrastructure [SZI-12a].

- Alleviation of balance of payment constraint: By increasing national competences in producing surpluses in a given sector "x", developing economies alleviate their commercial balance with more developed economies [LAV-12].

- Potential contribution of manufacturing on poverty alleviation: Research studies have empirically established a link between growth of manufacturing and poverty reduction mainly through direct and indirect creation of jobs. However, the literature is still inconclusive and imprecise when it comes to define a concrete relationship between both indicators mostly due to a huge and complex amount of variables [LAV-12].

2.1.3 The Value Creation Module (VCM)

Seliger (2007) claims that value creation in manufacturing takes place through the combination of five factors within so-called value creation modules. These factors comprise "product", "process", "organization", "equipment" and "human" elements, which unified describe any value-creation activity. By considering economic, social, and environmental criteria, these value creation modules offer an opportunity to change manufacturing paradigms from a profit-oriented shareholder perspective to a more sustainability-oriented stakeholder perspective [SEL-07]. The concept of value creation modules works at different levels of aggregation (see figure 4). Individual nodes comprising single productive units, e.g. workplaces, cells, factories, form interwoven networks under consideration of vertical and horizontal integration dimensions. Assuming a common understanding and sustainability strategy, global value creation networks exhibit a big potential to reduce extreme differences in some of the main areas of human living such as energy, production and mobility [SEL-07]; [SEL-10].

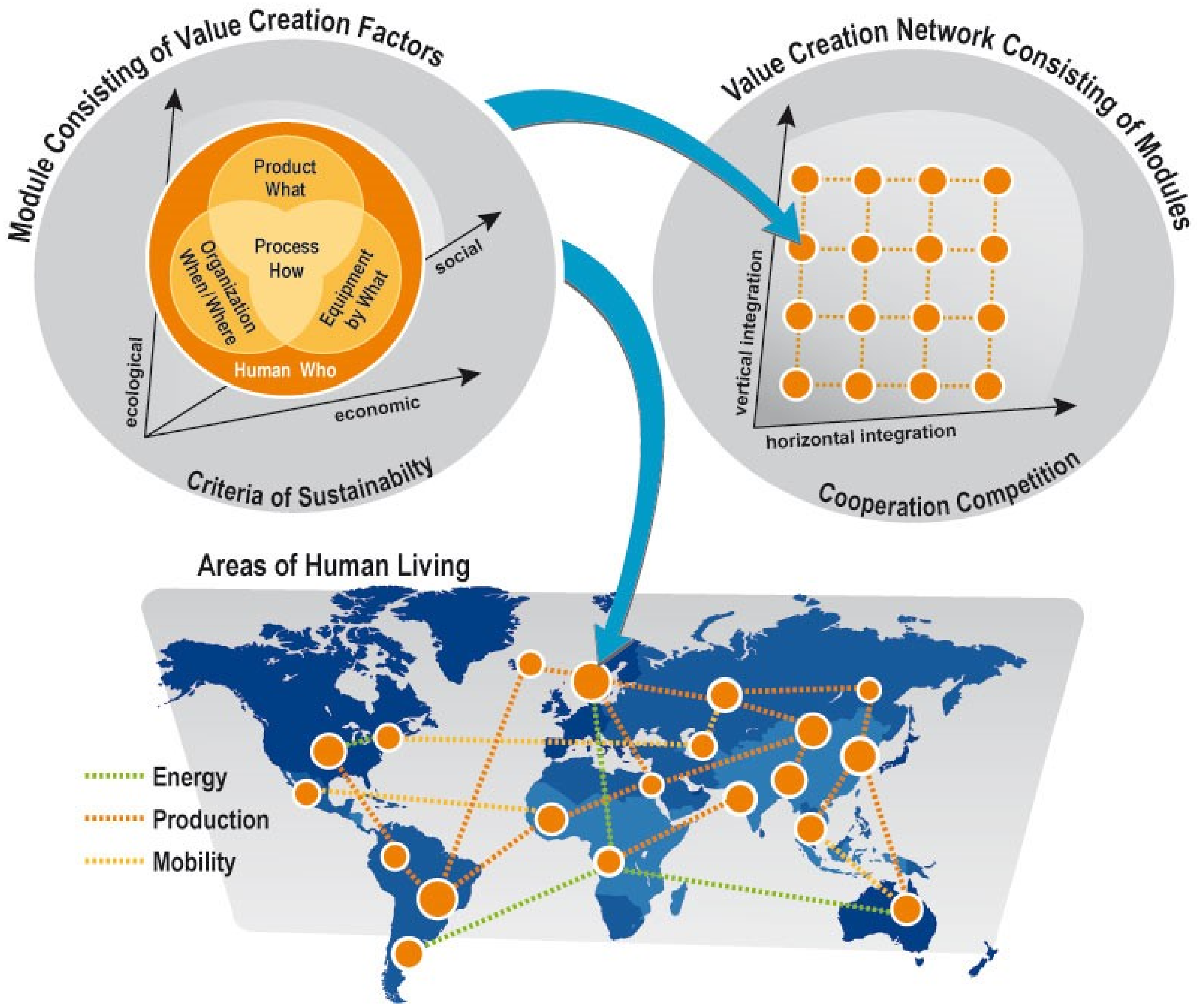

Figure 4: Value creation factors, modules and networks [SEL-10]

Key for the purposes of this dissertation is the analysis of the value creation factors as sustainability enablers and baseline for education in the field of manufacturing. A thorough analysis of the individual value creation factors is therefore in order.

A value creation module (VCM) consists of five factors, namely product, what is being produced; process, how is it being produced; equipment, by what; organization, when / where; and human, who is producing. Individual sustainability contribution of a VCM is determined by the economic, environmental and social impacts perceived by its stakeholders. The economic dimension is commonly evaluated by parameters such as profit, market share, research and development expenditures. The social dimension in turn considers parameters such as staff qualification, remuneration, proportion of women. Finally, the environmental dimension commonly takes into account issues concerning resource consumption, CO_2 emissions and energy efficiency criteria [SEL-07]; [SEL-10]. Through their interaction with one or many value creation factors, disciplines associated to manufacturing contribute in distinct manners to enhance the sustainability of VCMs. Disciplines with high relevance to this dissertation will be succinctly introduced in the next sections.

2.1.3.1 Process (How)

Regardless of its manifold areas of influence, manufacturing's core remains the technological processes that give form and functionality to a final product. Processes add physical value to finished or semi-finished products in different ways determining therefore "how" a product is being produced. Most common value-adding processes in the shop floor correspond to either manufacturing or assembly processes.

Based on the physical processes by which the configuration of a material structure is altered, the National Academy of Sciences (NAS) divides manufacturing processes in five types, namely mass change, phase change, structure change, deformation, and consolidation processes [NAS-95]. The German Institute for Standardization (DIN: German) in its norm 8580, divides in turn manufacturing processes in six main groups, namely primary shaping, forming, separating, joining, coating and change of material properties. Technologies and operation standards are then specified further in subsequent DIN norms. DIN's classification of manufacturing processes and some of its sub-norms are depicted in figure 5.

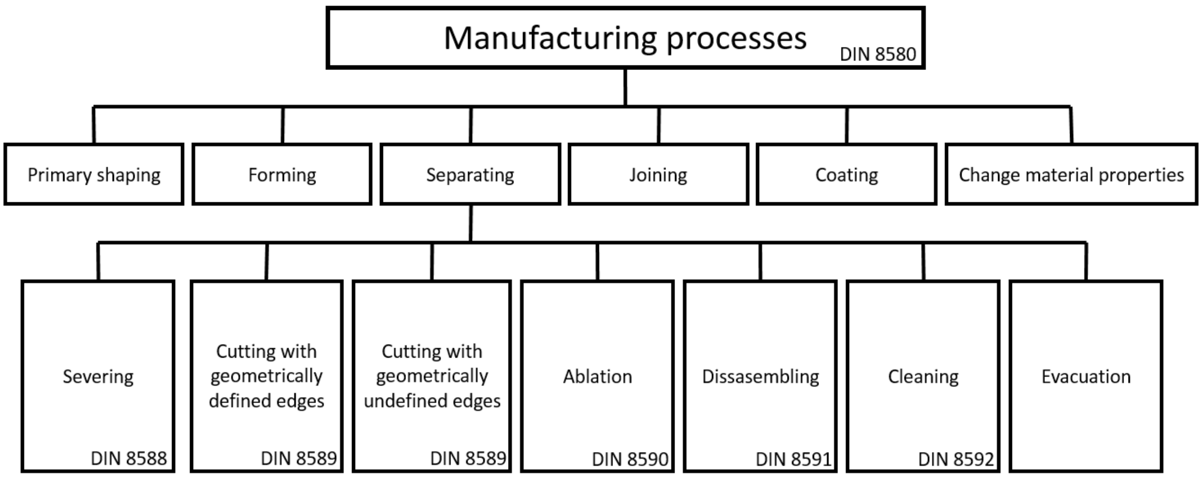

Figure 5: Classification of DIN 8580 and sub-norms of the separating process [DIN-8580]

On the other hand, most finished products require some sort of assembly process while joining multiple components. Assembly processes are defined as activities that serve the ultimate purpose of joining geometrically defined subcomponents into a final product where amorphous operating and ancillary materials are commonly required [WIE-15]. Assembly processes commonly consist in positioning or mating product components, which originally didn't belong together by means of fixtures, mechanical fasteners, shrink and expansion fits, welding, and adhesives [HU-01]. The association of German Engineers (VDI: German) in its guideline 2860 presents a taxonomy of assembly processes according to the type of physical activity involved in it. The taxonomy, reproduced in figure 6, includes joining, handling, checking, adjusting and special operation processes.

Depending on the type of product and / or the production method utilized, assembly is conducted either in assembly lines with multiple stations and workers assigned to each station, or in assembly cells, where multiple activities are conducted by a single worker. Due to the historically cost-intensive, high-labor-content operations involved in them, more automation has been brought in the last decades into assembly processes [BRL-07].

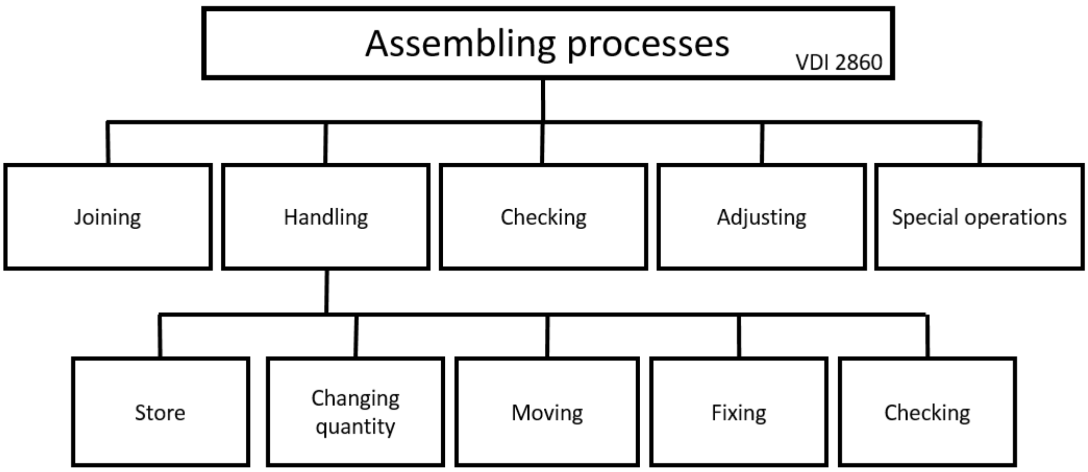

Figure 6: Assembly operations according to VDI guideline 2860 [VDI-2869]; [WIE-15]

2.1.3.2 Equipment (By what)

The spectrum of the machinery responsible of conducting the manufacturing and assembly operations is broad and mostly differentiated through its working principle, geometry, weight, media supply, and emissions. Spur and Stöferle provided an outline, reproduced in figure 7, of manufacturing technologies commonly employed according to DIN's 8580 taxonomy.

Machines for primary shaping	Machines for forming	Machines for separating	Machines for joining	Machines for coating	Special Machines for changing material properties

• Continuous casting machines
• Centrifugal casting machines
• Die casting machines
• Injection molding machines
• Electroforming machines
	• Presses
	• Hammers
	• Rolling mills
	• Bending machines
	• Drawing machines
		• Separation machines
		  • Shears
		  • Cutting Presses
		• Cutting machine tools
		  • Turning machines
		  • Milling machines
		  • Drilling machines
		  • Grinding machines
		  • Honing machines
		  • Lapping machines
		  • Machining centers
		• Physicochemical process machine tools
			• Welding machines
			• Soldering machines
			• Riveting machines
			• Bonding machines
			• Screwing machines
				• Galvanization machines
				• Painting machines
				• PVD plants
				• CVD Plants
				• Ion plating machines
					• Nitriding automat
					• Hardening furnace
					• PVD plants
					• CVD Plants
					• Ion accelerator plants

Figure 7: Classification of manufacturing machinery [SPU-86]

Automation in turn is facilitated by automation systems and components such as sensors, actuators and controllers incorporated into open or closed production loops [EBE-08]. Reasons to introduce automation in assembly processes include the increase of productivity, reduction of labor costs, mitigation of labor shortages effects, reduction of routine tasks, increase of workers' safety, improvement of product quality, reduction of manufacturing lead times, accomplishment of tasks that cannot be conducted manually, and reduction of manufacturing costs due to labor expenditures [RIL-96]; [EBE-08]; [EEP-16].

Further examples of equipment commonly applied in modern VCMs correspond to Information and Communication Technologies (ICT) responsible of supporting or executing planning, control or operative processes. Nodes of communication in manufacturing include:

- Production and inventory control systems such as Enterprise Resource Planning (ERP) software.
- Internal control systems such as drives, sensors and controllers responsible of monitor and control production variables like motor temperatures, spindle speeds, and coolant flow rates.
- Simulation software to conduct analyses of manufacturing systems through the formulation of hypotheses, realization of mathematical models and virtual visual representations. The objective of simulation systems is decision taking processes within the factory under consideration of effectiveness, efficiency and profitability criteria [ISE-16].

Finally, material handling systems and devices such as conveyors, forklifts and cranes, as well as precision instruments for calibration and checking processes rounds up the conventional equipment found within VCMs.

2.1.3.3 Product (What)

From a pure manufacturing perspective, a product is an item resulting from an activity, operation or process, particularly from a manufacturing process [CIR-04]. Every product is made at a cost and sold at a price, which depends on market conditions. Each product has a lifecycle and ideally an afterlife phase, in which it has to be reinvented [TET-16].

Products are normally designed and developed by manufacturing enterprises according to their business strategies or as a reaction towards market demands [STO-99]. The study field dealing with the creation of new products and their physical and virtual prototypes is known as product design. Product design is the methodological approach concerned with the efficient and effective generation and development of ideas that leads to new products to be launched into a specific market [MOR-09]. Numerous product methodologies exist in the literature. Some of the most popular methods in higher education the British Standards BS 7000 series “Design Management Systems”, Pugh’s “Total Design” [PUG-91], and the Engineering Design method from Pahl and Beitz [PAH-96]. Product design and manufacturing or assembly processes in the shop floor are closely connected and interdependent. At the systems level, both need to be coordinated to reduce costs and maximize productivity. At the business level, new products need to map existing production environments to avoid unnecessary disruption and expenses [STO-99].

Interrelations between product and manufacturing processes are covered in specialized fields of study. Design for manufacturing (DFM) is a design methodology in which manufacturing (and / or assembly) input is used at its earliest stages in order to conceive parts and products that can be produced more easily or more economically. Examples of variables to be accounted for include tooling costs, process controllability, production cycle times and safety concerns. [POL-01].

Environmental considerations in product design are addressed by the study field of Ecodesign. Ecodesign is conducted in early stages of the product planning and its main objective is the reduction of environmentally adverse effects of products throughout their life cycles [ISO-14062]; [YIM-07]. The approach makes use of well-known methods such as the Life Cycle Assessment (LCA) to analyze potential environmental impacts of the manufacturing of a product throughout its life from cradle to grave. These impacts, presented as outputs of the analysis, are divided in categories such as soil and water pollution, CO_2 emissions, energy consumption, and resources consumption. [ISO-14040]. Ecodesign has been considered a strong enabler of sustainability practices in Manufacturing with its implementation being enforced by the European Parliament over the European industry in its 2005/32/EC directive [EP-05]; [YIM-07].

2.1.3.4 Organization (When / Where /How many / How long)

Organization within a VCM involves the planning, monitoring and controlling of manufacturing activities within and outside the shop floor. Frameworks and parameters ruling these activities depend mostly on the manufacturing company’s business strategies. These manufacturing strategies, formally addressed for the first time by Skinner in 1969, refer to the choice of the most beneficial set of manufacturing capabilities for a business unit and the investment needed to build that set of capabilities [WAR-96]. By mean of these strategies, top and middle management are able to delineate company’s objectives aligned to its manufacturing competences [SKI-69]. Skinner claimed that in most of the cases, decision-making implied a tradeoff, in which a business unit deliberately relinquishes to market sectors to focus in its core competence.

Although Skinner's tradeoff decision model has been in some instances challenged by later authors arguing that the nature of tradeoff relationships is contingent upon the approach [FED-90], the relevance of his contribution lies in pointing out decision dichotomies in production in general. Some of Skinners tradeoff decision elements are depicted in table 2.

Table 2: Tradeoffs in manufacturing strategy [SKI-69]

Decision area	Decision	Alternative
Attitude towards market	Product introduction	Push or pull
Plant and equipment	Span of process	Make or buy
	Plant size	One centralized plant or several smaller ones
	Plant location	Locate near markets or locate near materials
	Investment decisions	Invest mainly in buildings or equipment or inventories or research
	Choice of equipment	General-purpose or special-purpose equipment
Production Planning and control	Frequenty of inventory taking	Few or many breaks in production for buffer stocks
	Inventory size	High inventory or low inventory
	Degree of inventory control	Control in great detail or in lesser detail
	Quality control	High reliability and quality or low costs
	Use of standards	Formal, informal or none at all
Labor and staffing	Job specialization	Highly specialized or not so highly specialized
	Wage systems	Many job grades or few job grades; incentive wages or hourly wages
	Supervision style	Close supervision or loose supervision
	Industrial engineers	Many or few such specialists
Product design / engineering	Size of product line	Many customer specials or few specials or none at all
	Technological risk	Use of new processes unproved by competitors or follow-the-leader policy
	Engineering	Complete packaged design or design-as-you-go approach
Organization of management	Kind of organization	Functional or product-focus or geographical or other

One of the main strategical decisions for a manufacturing enterprise is the determination of production methods, defined as processes and techniques used to manufacture a product [KAU-10]. The basic forms of production methods are:

- Single unit production: Concentrating in the fabrication of unique items such as prototypes, experimental products or highly customized articles, which most probably won't be produced ever again by the company

- Lot / batch production: A determined number of similar articles is produced in batches. Fixtures and other methods are used in working cells and production lines to aid a speedy and accurate fabrication or assembly. A high production flexibility is required to switch between product families with a minimum loss on productivity.

- Mass production: a large, sometimes undetermined, number of standard products are produced in high-volume runs by specialized employees incorporating principles of interchangeable production. Product flexibility is limited as machines and processes are geared for a non-stop production of same components creating a highly sensitive-to-disturbances system. On the other hand, a clear advantage of the method is a reduction of the costs-per-piece due to economies of scale.

Once a strategic roadmap has been developed to engage a specific target market, manufacturing facilities need to be set by means of factory planning methods in order to materialize and satisfy production goals of a company. Factory planning consists mainly in the identification of boundaries of a manufacturing site, namely its production and auxiliary equipment, its technical building services, its physical location, and its internal organization and setup [SEL-15]; [WIE-15]. These boundaries spanning across the complete facility determine to a great extent the structure of a factory in terms of setup, manufacturing capabilities, as well as its resources and energetic consumption. Numerous factory planning methodologies exist in the literature. Most of these methods follow a project management-based discrete sequence of phases connecting planning, realization and optimization [SCO-13]; [SCH-11]. Some examples are the approaches proposed by [ROC-83], [KET-84], [AGG-90], [GRN-09], [TOM-10], [SCH-11], and [WIE-15]. The Association of German Engineers in its guideline 5200 also define a methodology consistent of seven consecutive phases shown in figure 8.

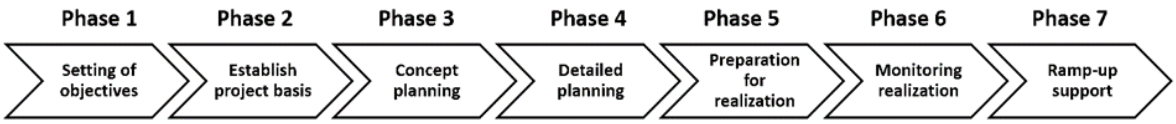

Figure 8: Seven phases of the VDI 5200 Method [VDI-2869]

Planning of shop floor layouts in accordance to manufacturing strategies and philosophies is a decisive element of factory planning. Layout decisions are centered in the best placement of manufacturing, assembly and handling stations under consideration of capacity and space requirements, manufacturing environment, flows of information, moving costs and times, and product physical characteristics. Due to its innumerable variables, layout planning is no exact science and has been referred to as “more of an art” [HEI-09]. Four main layout types, depicted in figure 9 are nonetheless common in the industry [BOE-09]; [YOU-09]; [GRO-10]. In a fixed location layout, the workstations are located around a product, which is difficult or costly to move. A process layout refers to a setup of machines separated in departments where similar machines or similar processes are brought together. Product layouts are typical setups for mass production where machines or workstations are lined-up according to a specific product’s fabrication sequence. Finally, in a cellular layout, groups of machines dedicated to the production of specific product components or products families are segregated in cells [NAH-09].

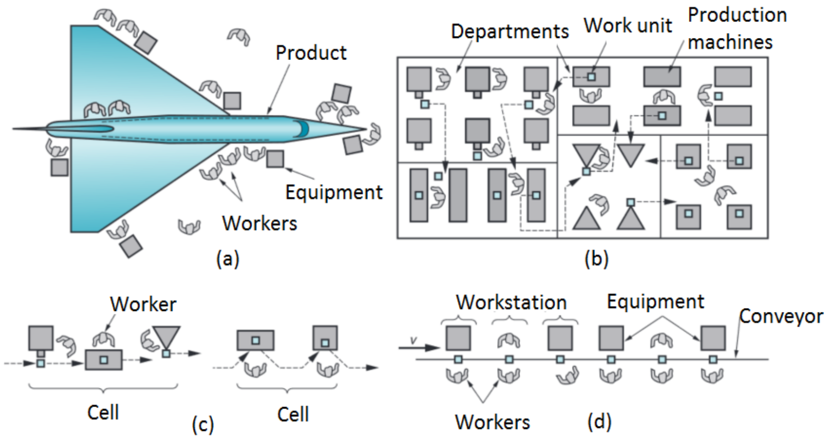

Figure 9: Types of layouts: (a) fixed-position layout; (b) process layout; (c) cellular layout; (d) product layout [GRO-10]

In order to cope with constantly changing market demands, manufacturing enterprises are obligated to rapidly adapt their infrastructure and capabilities to new production methods and layouts. Flexibility and changeability of manufacturing sites belong to the most important features during the planning stages of a factory. Chryssolouris considers flexibility as one of the four main strategic manufacturing attributes along with cost, quality and time [CHR-96]. Flexibility is defined as a manufacturing company's capability of producing a number of distinct products in a shop floor environment where opportunities for production variability exist [RAO-95]. A set of eight types of flexibilities within a factory - machine, process, product, routing, volume, expansion, operation and production flexibility - was suggested for by Browne in [BRW-84]. A different perspective of viewing flexibility was offered in [BUZ-82] considering only two types of flexibility, namely "*the ability of the system to cope with external changes (e.g. jobs to be processed) and the ability to cope with internal change (e.g. breakdowns)*".

Changeability, also known as re-configurability is defined in turn as the characteristics to economically accomplish early and foresighted adjustments of the factory's structures and processes on all levels in response to change impulses [ELM-09]. Changeability responds to external drivers such as volatility in the markets or a company's strategic change. According to ElMaraghy, reconfigurable factories allows changeable capacity by physically modifying the elements of a production system by adding and / or replacing in it machines, modules, handling systems or complete lines [ELM-09]. The difference between flexibility and changeability is that traditionally, flexibility is interpreted as the ability of a system to change its behavior without changing its configuration. Conversely, reconfigurability is interpreted as the ability to change the behavior of a system by modifying its physical and logical configuration [TOL-06].

The organization factor within a VCM includes also the introduction of Production Planning and Control systems (PPC). A PPC is a techno-managerial system of organization responsible of forecasting, planning, directing and implementing production in the shop floor. It controls the material supply, the manufacturing processes' schedules, internal and external logistics and in general the material flow throughout the value adding activities [KOH-14]. In the last forty years, PPC have greatly benefited from the introduction of computer-based monitoring and managing systems. The term Computer Integrated Manufacturing (CIM) was made popular in the eighties as Information Technologies (IT) helped industrial enterprises to rationalize their production and developed processes to increase their process efficiency.

Finally, another manufacturing field relevant for the organizational structure of a VCM is *Quality Management (QM)*. QM is a broad field in manufacturing responsible of the monitoring, control and achievement of quality standards with regards to products, processes and auxiliary services of manufacturing sites. Quality itself has been defined in numerous ways by different sources. Arguably one of the most common definitions states that quality is the degree to which a set of inherent characteristics, of a product or process, fulfill requirements [ISO-9000]. Depending on its implementation stage, QM can be divided in quality planning, quality assurance, quality control, and quality improvement [ROS-05]. Evolving quality concepts are concentrated in specific formal frameworks and philosophies which have been developed throughout time. Two of the best known are:

- Total Quality Management (TQM): The process quality emphasis is drawn from the suppliers up to the end-customer. The approach, progressively developed since the 1920's, but credited to W. Edwards Deming is characterized as a philosophy which applies equally to all parts of the organization and stresses the responsibilities of every member of staff within the organization [HEI-09].
- Six Sigma methodology: Six Sigma makes use of technological and statistic inputs aimed at eliminating defects, driving toward six standard deviations between the mean and the nearest specification limit, in any productive or service-oriented service [ISI-16]. The methodology defines its own iterative model "Define-Measure-Analyze-Improve-Control" (DMAIC) to reduce process variation up to a rate of 3.4 issues per million. Six Sigma integrates well studied quality tools into its model to achieve long lasting improvements in the value creation chain. Some of these tools include process mapping, check sheets, Pareto analyses, 7M tools, Statistical Process Control (SPC), Ishikawa Diagrams and Kaizen events.

2.1.3.5 Human (Who)

The human factor is omnipresent in a VCM. Most of value adding and supporting activities throughout the entire value creation chain still depend on human participation and intelligence. The role of humans in manufacturing can be both, positive due to his / her capacity to be creative and solve unexpected problems, and negative due to inherent mankind's fallibility enhanced by environmental factors such as lack of qualification, tiredness, and boredom. [HAM-11]. Study fields such as work place design, human factors and ergonomics seek to improve employees' personal development and wellbeing within and outside the manufacturing site.

Ergonomics and Human Factors, can be respectively defined as the study of people at work and the study of human-machine systems with an emphasis on the human aspect [LEH-12]. Specialists in these fields are commissioned with the design of simple and complex work systems under consideration of the capabilities and limitations of human beings. In the case of ergonomics, two subdivisions, namely occupational ergonomics and cognitive ergonomics are common. The first refers to the determination and dimensioning of manual tasks in accordance to physical efforts underwent by operators. The second focuses on the design of devices that support decision-making processes [ISE-16]; [THO-10]; [VEE-92].

Occupational Health and Safety (OHS) on the other hand, is defined as the science of anticipation, recognition, evaluation and control of hazards arising in or from the workplace that could impair the health and wellbeing of workers [ALL-08]. In manufacturing, OHS measures involve strategies to eliminate hazards in the first place and separating workers from hazardous areas in the second. Common sources of injury or intoxication are high-speed working stations, fumes emissions, environment contamination and biologic hazards.

2.1.3.6 Trends in manufacturing

Due to its complexity and broad field of influence, manufacturing concrete trends are hard to specify. However, some core directions in the further development of the field are worth of mentioning. Over the past years, manufacturing has evolved from a labor-intensive set of mechanical processes to a sophisticated net of intertwined information technology based processes [SHI-12]. Industry 4.0 or the so-called "fourth industrial revolution" refers to a further developmental stage in the organization and management of entire value creation chains and networks based on four elements [DEL-14]:

- Vertical networking of smart production systems, smart factories and smart products.
- Horizontal networking through the generation of global value creation structures.
- Through-engineering grasping the entire value chain and the product life-cycle.
- Acceleration through exponential (IT) technologies

In this regard, industry 4.0 will be supported by the development of completely new computing devices based on new developments in semiconductor technologies, global information technology economies, and through the development of advanced materials with internal structures with superior properties that facilitate transformative changes in manufactured products [SHI-12].

Two other emergent technologies are noteworthy. The first is the rapid development of additive manufacturing technologies defined as a layer-based automated fabrication process of scaled 3D objects directly from a 3D CAD data without using part-depending machine tools [GEB-12]. The second technology is synthetic biology, which can be understood as the design, construction and characterization of improved or novel biological system using engineering design principles [ZHA-13].

The most relevant trend for this dissertation however, is the integration of sustainability philosophies and principles in manufacturing, which will be presented in the next section.

2.1.4 Sustainable manufacturing

Paradigms existing since decades assuming unlimited natural resources and / or an infinite regenerative nature's capacity are unacceptable anymore [GAR-12]. With a global population to date of over 7.3 billion [DESA-15], the number of produced goods demanded by consumers' markets all over the globe increase dramatically, and with it, the need for natural resources. This demand increase is nonetheless non-uniform as world regions, specifically those populated by industrialized countries, are characterized by a higher purchasing power and thus a higher consumption of finished goods. In its last ecologic footprint atlas (2010), the Global Footprint Network classifies world's countries as "biocapacity creditors" and "biocapacity debtors" according to the deficit-reserve ratio of resources' availability. A biocapacity debtor, such as most developed and leading developing nations, is defined as a nation that imports biocapacity through trade, liquidating national ecologic assets or emitting carbon dioxide waste into the atmosphere, while an ecological reserve exists when a country's biocapacity exceeds its population's consumption of resources [GFN-10].

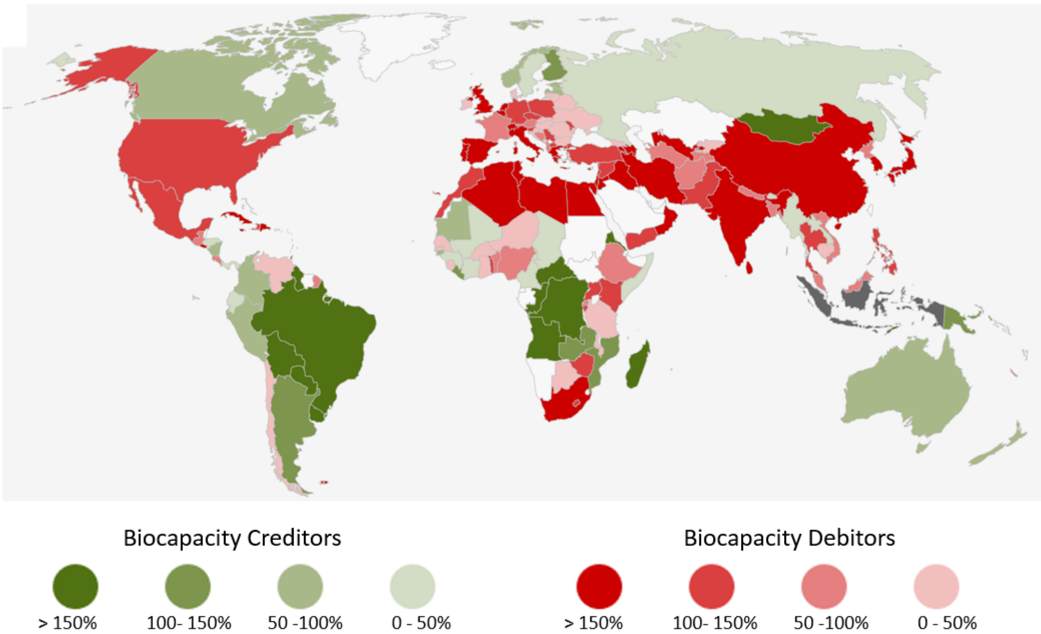

Figure 10: Ecological deficit / reserve per country. Year 2010 [GFN-16]

Phenomena such as globalization adds up to the challenge of achieving a heterogeneous sustainable development. With developing economies striving to achieve the life standards of richer countries, concerns about the capabilities of the earth to sustain the demand of raw materials arise. The Global Footprint Network (GFN) reported that already in 2007 a resources' overshoot of 50 % had been experienced as direct consequence of human productive activities, which means that the equivalent of 1.5 Earths were consumed by mankind at the time. If the entire world population were supposed to live with the same life-standards as the average U.S. citizen however, the amount of required earths to support humankind existence would mount to four Earths [EWI-11].

The sustainability paradox in manufacturing consists therefore in considerably increasing the life standards of the global population, while at the same time drastically reducing the consumption of natural resources and hazardous anthropogenic gas emissions. The challenge to find globally consensual agreements is even higher when considering opposing priorities of developed and developing economies. Seliger described the unbalance between "saturated" and "hungry" markets as a divergent perspective between both sectors. On the one hand, industrialized societies need to decrease their resource consumption without sacrificing their quality of life; while on the other; developing economies need to increase their living standard without drastically increasing their natural resources consumption [SEL-12].

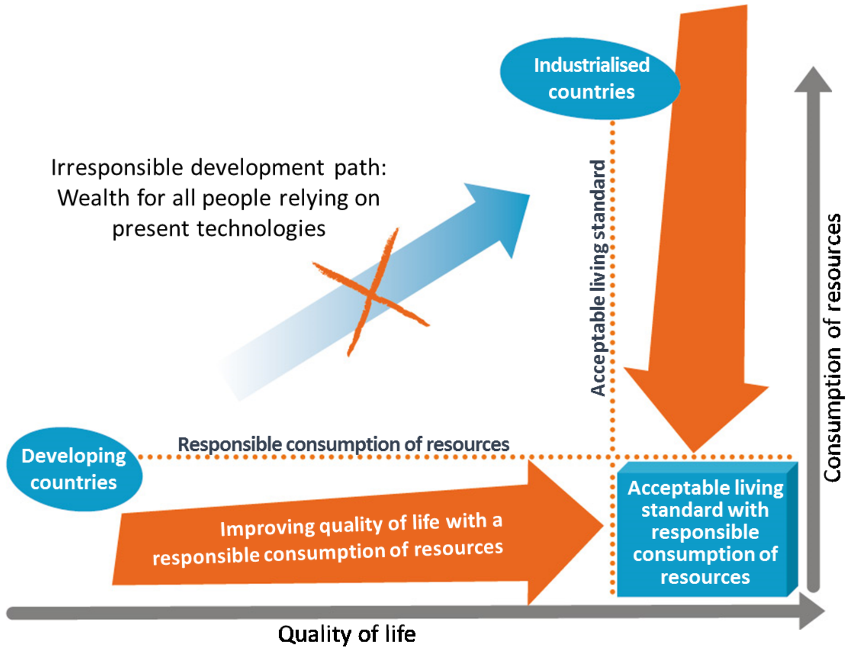

Figure 11: Sustainable development paths for developing and industrialised nations [SEL-12]

Manufacturing engineers of today are therefore conferred with the task of modifying existing production and consumption paradigms of entire societies by means of technological and methodological means, facing in many cases change resistance on behalf on some population sectors [DES-09]. This resistance to adopt sustainability as a way of life will wane as closer alignment and coherence across education and sustainable development sectors are globally met. This involves restructuring formal and non-formal curricula to adopt a sustainability focus along entire national education systems [BOK-14]. Another critical condition to achieve societal sustainability acceptance is the improvement of education's quality. More research, pedagogical and technological innovation, as well as instruction's monitoring and evaluation contributes to incentivize individuals to accept, adopt and demand cleaner technologies as a means to create value [BOK-14]. Literature suggesting approaches on how to integrate sustainability paradigms in manufacturing education is constantly growing. Most of it centers in the integration of social and environmental competences into higher education curricula. A comprehensive review of it will be presented in section 3.5.1.

2.1.5 Challenges for developing countries

Progress and socio-economic development have been achieved in most developing economies mostly due to changes in global economy and globalization [UN-13]. This trend will continue in the next decades as developing economies will grow three times faster than developed countries representing up to 65 % of global economic growth in 2020 [BOU-13]. This growth although uneven across the spectrum of developing nations, has been observed even in the world's least developed countries (LDC), which have seen their share in world's population but also their contribution in global manufacturing value adding (MVA) increase in the last years [DESA-13]. Concretely, the United Nations Industrial Development Organization reported that from 2000 to 2010, the share of LDCs in world population grew from 11.1 to 12.5 percent, while their share in world MVA advanced from 0.3 to 0.5 percent [UNI-12].

However, this development has been accompanied by consumption and production patterns with a huge environmental impact. Regeneration efforts in turn are scarce and in some occasions even seen as hindrance towards rapid profit [DESA-13]. In its report "Trends in Global CO_2 Emissions", the Netherlands Environmental Assessment Agency (NEAA) compares for instance worldwide CO_2 emissions generated through the consumption of fossil fuels and the production of cement, considered as one of the most pollutant industries worldwide. According to the report, contrary to the curbing trend experienced in most developed countries, a substantial yearly global emission increase has been observed in the last decade in fast- growing developing economies such as India and China [OLI-13].

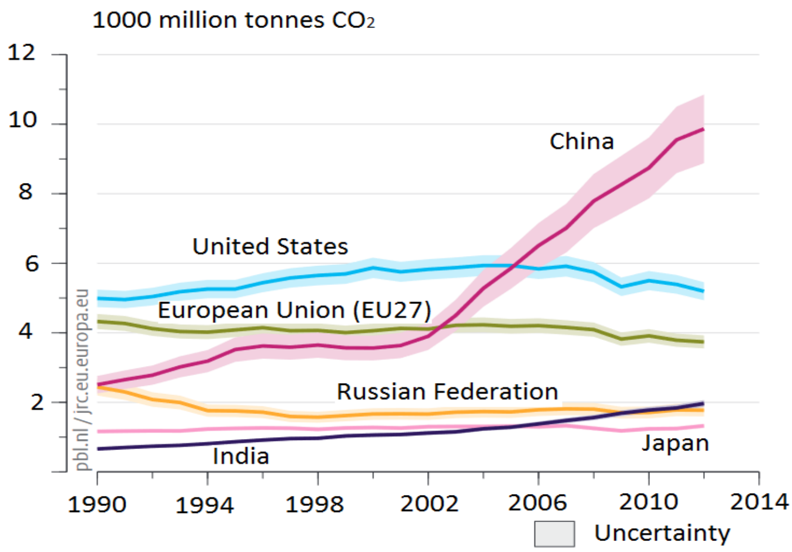

Figure 12: CO_2 emissions from fossil fuel and cement production. Year 2013. Adapted from [OLI-13]

Moreover, rapid economic development experienced by most developing nations has had limited impact in the living standards of their rural and underdeveloped urban populations. According to UN's department of economic and social affairs, over one billion people still live below the extreme poverty line, which can be only explained by a continuously enlarging gap between overwhelming poor majorities and elite minorities [UN-13]. Some developing economies are additionally facing particular challenges including a rapid but structurally disorganized urbanization, which originates basic services scarcity as well as social integration and transportation issues [GEY-11]; an ageing population, result of sinking child birth rates which threatens the biggest developing countries with getting old before getting rich [GOI-10]; and massive brain drain, evidenced by the fact that 86 % of the patents filed by citizens of developing economies occur during their stay in host countries [THE-15].
Challenges faced by developing countries in order to accomplish a more sustainable development through manufacturing can be therefore roughly classified in global and indigenous challenges.

2.1.5.1 Global challenges

Developed and developing countries share some educational roadblocks to overcome while modifying their curricula according to environmental and socio-economical needs of modern societies. For starters, manufacturing is a vast field that combines and intertwines a series of independent disciplines and specializations to materialize and commercialize all kinds of products and even services. Finding a balance between technical, managerial and environmental competences and skills to be conveyed to future manufacturing engineers, all within a limited timeframe, is a complex task that has been thoroughly studied in academic milieus. Approaches to cope with this challenge from a higher education perspective have been proposed in sources such as [SWE-02], [ROS-07], [JIA-11], SEL-11], and [JAW-13]. Other sources however, claim that manufacturing education cannot be limited to higher education instances and consider the integration of manufacturing content in primary and secondary stages of educational systems a priority. According to these sources, Science, Technology, Engineering, Math (STEM) educational content introduced in early education stages should contribute to: (a) Improve the quality of teaching, and (b) attract more students into manufacturing by promoting the availability of creative, and high-tech jobs in the branch [SME-12].

Secondly, manufacturing itself has always been a challenge due to its dynamic nature as it barely restricts to current practices [PET-89]. Well established manufacturing technologies of today find themselves very soon challenged by brand new technological approaches that prove to be more reliable, profitable, and environmentally friendlier [NGA-15]. Innovation in manufacturing occurs at almost every level; products, processes, machine tools, philosophies and auxiliary services [OSU-02] and can happen at transformational, radical or even disruptive paces [TID-05]. Under this context, vocational institutions and universities are understandingly having difficulties to cope with industrial demands due to limited financial resources, as well as outdated faculty, literature and equipment.

Determination and integration of these industrial demands is another big challenge by itself. In recent years, the academia has been reiteratively accused of failing to establish communication channels with the industry, missing therefore the opportunity to take advantage of the knowledge generated in actual production facilities [OSU-09]. In response, so-called “learning factories”, in most of the cases result of collaborations between HEI and global conglomerates, have been lately introduced as a catalyst for industry-academia interactions. Their impact is still limited however as their implementation is not globally widespread [OSU-09]; [MAV-11]; [ABE-15].

2.1.5.2 Indigenous challenges

Apart from the global challenges described above, developing countries have particular societal, institutional, infrastructural and political issues to overcome before being able to match developed economies and their manufacturing capabilities to achieve a sustainable development. Some of them include unreliability of long-term growth projections, lack of an industrial culture, a chronic struggle to train specialists in the area due to the lack of qualified lecturing staff, obsolescence of teaching materials and infrastructure, as well as limited integration of typically large sectors of population, mostly rural, in manufacturing [PET-89]; [JHA-07] [SZI-15]. The scope of the present research demands a more intensive review focus on these educational and infrastructural shortcomings.

Education system: Most developing countries are characterized by an endemic educational underdevelopment that hinders the formation of manufacturing specialists and therefore local value creation and innovation. Richard Jolly, a former director of UNICEF has been cited claiming that “*virtually, every serious commentator agrees that major reforms within the Third World education is long overdue*” [TOD-12].

The problem, economists have claimed, lays largely in the fact that the planning of educational infrastructure at primary, secondary and tertiary levels in developing countries is primarily determined by short-term political agendas, often unbound to development and economic criteria [TOD-12]. Todaro and Smith claim that due to an ill- strategic planning and poor management, social costs of education[18] in developing countries tend to drastically increase, while its societal benefits [19] is decreasing as students climb the education ladder (see figure 13). This is explained when considering that resources invested in building schools in a non-strategical manner are usually funneled from innovation and development programs responsible to improve and generate local technological and economic development. The end result is a very limited offer in high-specialization jobs for a relative large number of graduates in the field [TOD-12].

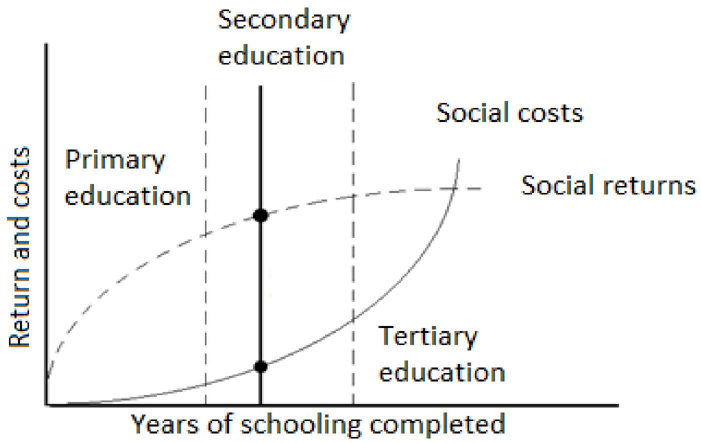

Figure 13: Social returns and costs of state education in developing countries [TOD-12]

On the other hand, the struggle for differentiation has created a market niche for elite minorities in developing countries who are able to afford private costs of education. High-class private schools and universities offer in most of the cases better education, a higher social status perception, and a broader access to well-remunerated jobs, which exceed by far the marginal costs of post-secondary education (see figure 14) [ASL-14].

Studies have demonstrated that, within this context, the educational systems of many developing nations sometimes act to increase rather than to decrease income inequalities. The reason for this effect is that the poor majority is effectively denied access to high specialization jobs due to a deficient post-secondary education, triggered in turn by state policies prioritizing quantitative over qualitative parameters of education [TOD-12].

[18] Social costs of education refer the opportunity cost to society as a whole, resulting from the need to finance costly educational expansion at higher levels when this funds might prove more productive in other economy sectors

[19] Social benefits of education refer to the benefits a society gets through the education of an individual, such as the benefits of a more literate society or the economic output from his/her activities.

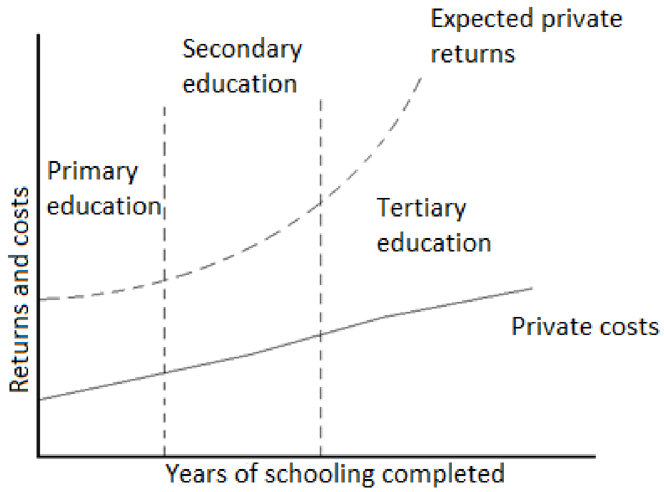

Figure 14: Social returns and costs of private education in developing countries [TOD-12]

Limited industrial culture: As described in 2.1.2, economists have empirically determined a correlation between the industrialization degree of a country and its economic growth. Szirmai's "engine of growth argument" demonstrate that in the last decades, countries which have achieved the highest increase in per capita incomes have also experienced a dynamic growth of manufacturing output and manufactured exports. On the other hand, "*the poorest countries are invariably countries that have failed to industrialize and still have very large shares of agriculture in GDP*" [SZI-12b].

To a great extent, Szirmai credits the dependence of poor countries on agriculture to a historical colonial division of labor. According to this paradigm, developing countries are responsible of the procurement of primary products and minerals, while developed countries create technological means to gain value from the incoming resources in order to produce goods and feed their export-based economies [SZI-12b].

A country's evolution from an agriculture-based economy to manufacturing one implies an innovation and technological progress, which can be achieved in the middle term through foreign and domestic direct investment, transfer of appropriate technology and management knowledge [DAB-00]; [HOO-16]. Most importantly, it has also been concluded that there is a positive effect of manufacturing growth in developing countries with a highly educated workforce [SZI-12-b].

Manufacturing education in developing countries has therefore to fulfill two objectives. Firstly, developing countries are required to prioritize the formation of highly trained specialists in large and medium national technology hubs to incentivize: (a) Foreign Direct Investment (FDI) and thus the transfer of knowledge and technology, and (b) development of native innovation and value creation. In this sense, international development agencies and manufacturing guilds have proposed the integration of technical, social and economic competences and skills into comprehensive competency models to serve as curricula-design bedrock for manufacturing programs in developing countries.

The Advanced Manufacturing Competency Model (AMCM) developed by the U.S. Department of Labor is an example of such proposals. Depicted in figure 15, the competency model introduces a knowledge typology to be conveyed to future manufacturing specialists in a sequential manner, reflecting the increasing level of specialization in the manufacturing profession [SME-12]. The first two levels of the model specify generic fundamental principles required in the manufacturing profession, which are however not exclusive of the field. Competences such as the understanding of interdisciplinary work, and basic concepts of science and mathematics are some examples. The middle layers are production specific competences to be conveyed to manufacturing generalists ranging from operators to industrial engineers. Content of these layers focus in developing competences such as team work, understanding of production processes and quality assurance. Finally, the last two layers define competences to be acquired by personnel with advanced manufacturing and management responsibilities.

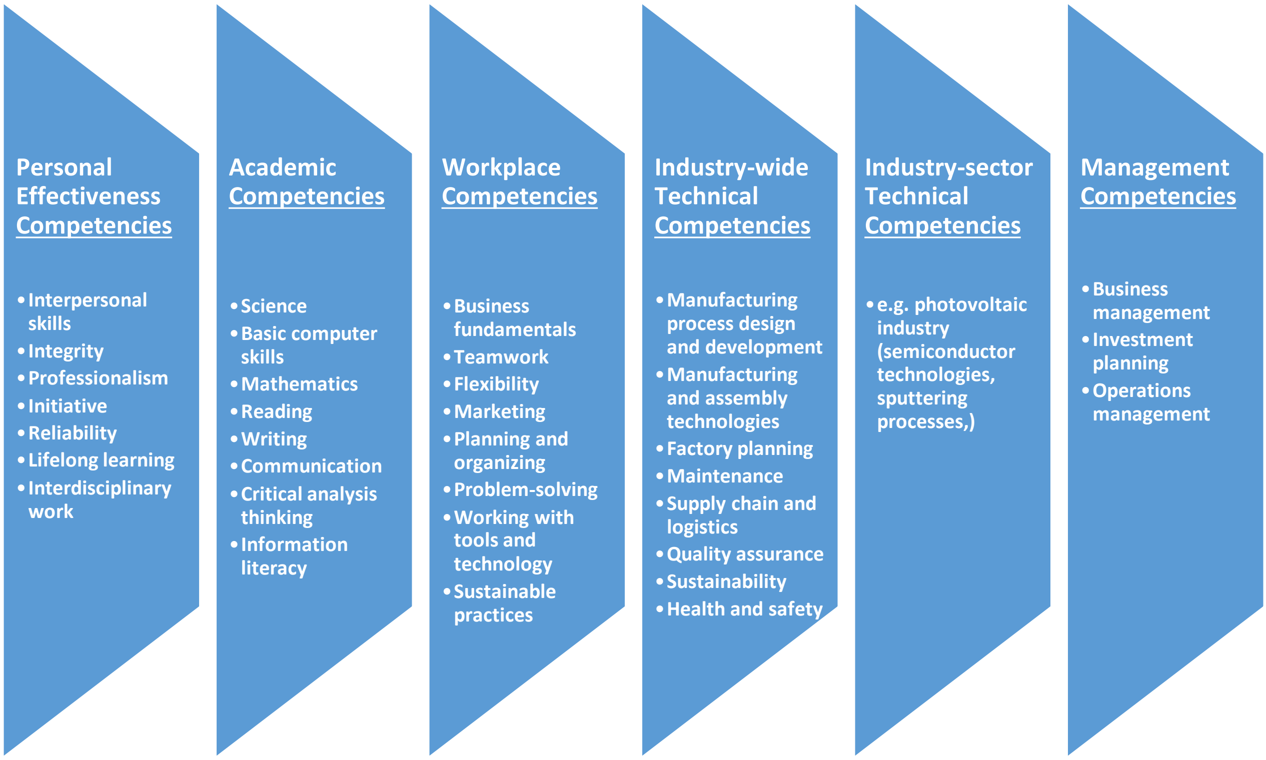

Figure 15: Advanced Manufacturing Competency Model. Adapted from [SME-12]

On the other hand, developing countries are in the need to integrate their large, mostly under-educated, rural populations as active links in advanced value creation chains by fostering the development of rural manufacturing enterprises with access to national and international markets. The World Bank, the U.N. and other research institutions have stressed the potential benefits of small rural manufacturing enterprises as economic triggers of national development. The same sources claim that the primordial precondition to develop these enterprises is to overcome the scarcity of local managerial skills and technological input [ELN-89].

Human resources and infrastructure scarcity: Most researchers agree that to a greater or lesser degree, developing countries suffer from insufficient and under-qualified human resources to implement, develop and disseminate technological and methodological solutions to generate value locally [ELN-87] [TWB-00]; [JHA-07]; [AKA-10]. Bridging the technologic and economic gap between developed / rapidly industrializing nations and developing countries, depends to a great extent on the capabilities of these nations to train and keep their own manufacturing specialists. This is lighter said than done. Currently, most developing countries suffer from a scarcity of specialists willing to teach new generations of manufacturing professionals, and a lack of proper training infrastructure especially in their rural areas [JHA-07] [AKA-10]. Main cause of this phenomenon is little governmental expenditures in higher education and low industrial employability caused in turn by strategic national decisions to invest in service sectors, e.g. tourism and banking. With little manufacturing output, a vicious circle is generated in which a lack of employment possibilities inspires little interest to pursue a career in production. Table 3 below depicts a comparison of the enormous differences between developed and developing countries in terms of education expenditures and highly specialized human resources. The data shown corresponds to the year 2011, year in which information was lastly available for all presented countries.

Table 3: Human resources and output indicators – 2011 [UNE-15a]; [TWB-16]; [ROD-13]; [VDI-12]; [SAR-14]; [NAK-11]; [CHO-11]; UNE-15b].

	Developed countries			Developing countries				
Indicator	**Germany**	**Japan**	**U.S.**	**India**	**Mexico**	**Bangladesh**	**Ethiopia**	**Sri Lanka**
Government expenditure per tertiary student in PPP (US$) [UNE-15a]	9.521	8.076	9.813	2.778	6.209	420	3.592	1.820
Technicians (per million people) [TWB-16]	1407	588	n/a	100	73	65	44	91,62
High technology exports (% of manufactured exports) [TWB-16]	15,25	17,97	19,96	7,18	16,93	0,17	2,73	1,02
Scientists and engineers (per million people) [VDI-12]; [NAK-11]; [SAR-14]; [ROD-13]; [CHO-11]; [UNE-15b]	17.700	18.312	21.097	n/a	10.080	44	91	191

In conclusion, in order to build the bedrock in which socio-economic development is built, developing countries need to improve their capabilities to integrate all echelons of society to high productivity activities and local value creation. Members of currently underdeveloped rural and informal urban communities need to be offered the means to develop economically and socially without needing to migrate to urban areas in their countries or abroad. Achieving this, requires in the first place a noticeable quality improvement throughout entire education systems in developing countries, and secondly, access to high-end education means and technologies to cope with modern industrial needs.

Developed countries have lately made substantial efforts to contribute in accelerating this process. The terms “knowledge transfer” or “technological capacity building” are quite common to describe partnerships between developed and developing countries aimed at increase technical capabilities of the latest. Simply transferring knowledge and instrumentation is however not enough to help developing countries to build their own productive infrastructure [HAR-04]. As pointed out by the 17th SDG, a sustainable approach requires the understanding of local needs and potentials, as well as the integration of local human and institutional partners to uphold the results of the effort. A review of traditional collaboration schemes between developed and developing economies will be presented in section 2.3.

2.2 Renewable Energies

While considering manufacturing as sustainability enabler due to its potential to trigger socio-economic development through the generation of value creation modules, it is also of the utmost importance to take into account that a global sustainable development without the establishment of low-carbon economies is unachievable [MCK-09]. Nowadays, one of the most heated debates among world leaders turns around determining viable pathways to decouple global economic development from fossil fuels responsible of the generation of 27 % of world's greenhouse gas emissions via combustion of coal, oil or gas [EPA-16]. Several authors claim that one of the most important and complicated questions regarding the achievement of a real global sustainable development is whether economic growth and environmental protection are mutually compatible [JUK-13] as modern life without energy is inconceivable and almost 80 percent of energy is produced by fossil fuels [IEA-15].

In this sense, the introduction of cleaner energy generation technologies has been promoted by academic circles, environmental groups, as well as national and international development agencies as an alternative to fossil fuels. Most of these technologies rely on harnessing energy from renewable natural sources and are commonly known as renewable energies

Renewable energies, also known as renewables, means all forms of energy produced from renewable sources characterized in most of the cases by a low emission of anthropogenic greenhouse gas emission during its generation [IRE-09]. According to the International Energy Agency (IEA), world's net renewables power capacity in 2013 accounted for 22 % of world's total electricity generation. By 2020, this figure should rise to 26 % [IEA-15]. The International Renewable Energy Agency (IRENA) estimated that under favorable conditions of human resources availability and low-cost bio mass sources, the energy generation share of renewables in the manufacturing sector could reach 30 % by 2030 [IRE-14b].

The main renewable energy technologies, prioritized according to their contribution to the overall renewable power generation in 2013 are: hydropower (64.4 %), wind energy (20.25 %), photovoltaic power (8.76 %), bioenergy (5.6 %) and geothermal power (0.77 %) [REN-15]; [IEA-15].

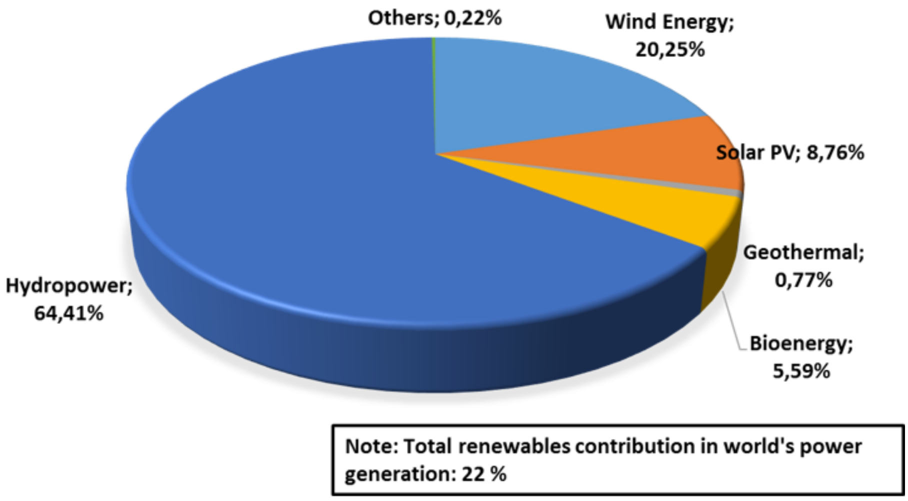

Figure 16: Share of renewable energy technologies within total renewables world's power generation. Year 2013 [REN-15]; [IEA-15]

The importance of renewable energies lies largely in their potential contribution towards the abatement of CO_2 emissions currently generated by conventional fossil-based energy sources. According to international organizations the market of renewables is also the fastest growing in the energy sector with over 45 % of net additions to world's energy capacity [IEA-15]. This growth has additionally led the renewables industry to become a key sector when it comes to job generation on a global level, playing thus a major role in the economic development of nations [PAO-13]; [REN-15]. Sustainable growth of renewables is guaranteed in the next decades mostly due a growing price competitiveness, a long-term certainty, and energy security [PHI-15].

The impact renewable energies are having over global environmental indicators is clearly measurable. In this sense, the Renewable Energy Policy Network for the 21st Century (REN21) reports in its Report on Renewable Energies that:

- Despite rising energy use, for the first time in four decades, global carbon emissions associated with energy consumption remained stable in 2014 while the global economy grew. This stabilization has been attributed to increased penetration of renewable energies and to the improvements in energy efficiency [REN-15].
- The utilization of renewable energies, measured in terms of its total cumulative capacity, has more than doubled in the last decade with photovoltaics leading the development statistics [REN-15].
- Europe remains an important market and center of technological innovation. Yet developing markets are nowadays taking the lead in terms of new installed capacity with China leading the rankings for the third consecutive year and economies like Brazil, South Africa and India closing in. A clear market development has also been registered in regions in Asia, Latin America and Africa [REN-15].
- Altogether, renewable energies are now contributing with over 22 % of the world's electricity generation and, depending on the policies and objectives issued in the upcoming years by the members of the global community, this figure is expected to increase dramatically in the next decades [REN-15]. According to reports from the National Renewable Energy Laboratories for instance, with currently available technologies, up to 80 % of total U.S. electricity generation in the U.S. can be achieved by renewables in 2050 [NRE-15b].
- In the last decade, the global investment in renewable energies and fuels grew from 45 billion USD in 2004 to 270 billion USD in 2014 [REN-15].

2.2.1 Technologies

An overview of the most important renewable energy sources and technologies will be presented in this section with a special focus in photovoltaic technologies and wind energy.

2.2.1.1 Solar power (Photovoltaics)

The most direct, economic and flexible way to transform sunlight into electricity is conducted through the so-called photovoltaic effect. The phenomenon, defined by Goetzberger as the emergence of an electric voltage between two electrodes attached to a solid or liquid substrate upon shining light was first observed by Henri Becquerel in 1839, and since then has evolved into a practical application field known as photovoltaics [GOE-05].

Solar cells represent the fundamental unit of photovoltaics. A cell usually consists of a "p" doped silicon wafer on one side and a "n" doped wafer on the other, to which electrical contacts are added to collect the generated current [GOE-05].

According to its semiconductor material, solar cells can be divided in roughly three types, namely crystalline wafer-based silicon cells, thin film cells, and nanostructured organic cells.

- Crystalline silicon cells: Covering close to 90 % of the world's market share, these 200 microns-thick silicon-based wafers cells represent by far the most common, and also most efficient PV technology so far [DGS-13]. These types of cells are in turn subdivided in two kinds depending on the orientation of their silicon crystals:

    - Monocrystalline silicon cells: Until now, the most efficient solar cells are monocrystalline based [FRA-15]. This kind of silicon characterized by a continuous and unbroken crystal lattice and relatively few impurities influencing its semiconducting properties is also the most expensive kind of semi conductive material used by solar cells producers. The reason for this is mainly the high manufacturing costs which includes in most of the cases crystal forming by means of the Czochralski (CZ) process and wafer's "squaring – off" processes out of cylindrical ingots [GOE-05].
    - Polycrystalline silicon cells: Polycrystalline silicon consists essentially in multiple randomly-oriented monocrystalline grains. A loss of efficiency is therefore experienced because light generated charge carriers, e.g. electrons and holes, can then recombine while hitting the boundaries of the material forming grains. The amount of impurities present in polycrystalline silicon is also much higher than the amount of impurities found in monocrystalline silicon, which leads to a decrease in the lifetime of the carriers and the material's efficiency as a whole [SCM-01].

- Thin film cell technology: The second type of solar cells is based on a thin layer of semiconductor material applied to a low-cost substrate such as glass. Manufacturing processes of these cells involve physical and chemical vapor deposition, sputtering, and electrolytic baths. Thin film cells are less efficient than their wafer based counterparts, but are less resources- and energy-consuming, making them economically and environmentally more attractive. There are different types of thin film cells depending on the semiconductor deposited onto the substrate:

    - Amorphous silicon (a-Si): exhibiting non-crystalline structure, amorphous silicon is only suitable as semiconductor if bonded with hydrogen atoms. Its electrical properties are therefore unstable and rather inefficient for large scale applications [HAE-12].
    - Cadmium Telluride (CdTe): with a band gap energy close to the maximal theoretical efficiency, cadmium telluride cells are by far more efficient and stable than their amorphous silicon counterparts. Yet cadmium is environmentally hazardous which difficult their disposal and its end-of-lifecycle handling [HAE-12].
    - Copper Indium Gallium Selenide (CIGS): Being considered as environmentally friendlier, and almost as efficient as Cadmium Telluride based cells, CIGS-

based PV cells are unfortunately much more expensive since they are composed by Indium, a rare element in nature [HAE-12].

- Nanostructured organic solar cells: Still mostly under laboratory development, nanotechnologies involving inorganic and organic materials such as nano-structured Copper Indium Diselenide (CIS) and dye-sensitized nano-crystalline cells will be commercially available for large applications in the near future [DGS-13].

With solar cells as fundamental units, the most visible component of a photovoltaic system is the photovoltaic module. Photovoltaic modules are units composed of an array of solar cells connected in series or parallel and encapsulated in a protective laminate. Crystalline silicon PV modules are commonly composed of an array of 36 stringed cells with operating voltages from 12 to 20 V and an output range of 50 to 200W [HAE-12], common module sizes range from 0.6m x 1m to 1m x 2m. In the case of thin film modules, most models have dimensions of 1.2m x .6m for CdTe and CIGS modules, or 1.3m x 1.1m for a-Si modules [DGS-13].

PV modules of different technologies have different power conversion efficiencies. The efficiency refers to the percentage of incident solar irradiance upon a PV module that is converted into electricity. Efficiencies of the diverse PV technologies are well monitored by commercial and academic circles and even though the improvement is constant, it can rarely be defined as breakthrough.

Apart from PV modules, a PV system constituted as a useful powering unit comprises:

- Charge controllers: Electronic devices designed to prevent standalone battery banks from overcharging and excessive discharge [LUQ-03].
- Inverters: Electronic devices that convert low DC voltages generated by a PV array into a high, typically 230V, AC voltage that can be either fed to the public electricity grid or to AC electrical appliances.
- Battery array: Depending on the application, a PV system can include a set of batteries to store power during charging times such as daylight hours, so that it can be used during periods of low- or non-existent daylight, e.g. at night.

Photovoltaics is a fast-growing market. In 2015, the PV Market Alliance estimated global photovoltaic installations of at least 51 GW worldwide. This figure represents a 25 % increase with respect to the installed capacity in 2014. The biggest market growths have been observed in the U.S., China and Japan [TPV-16]. The Solar Energy Industries Association (SEIA) reported in 2015 a 34 % growth with respect to the installed capacity in 2013 in the U.S. The market behavior in the country grows steadily fostered by plummeting PV prices due to improvement in technologies and manufacturing processes [SEI-16].

2.2.1.2 Wind energy

Wind energy is the result of implementing aerodynamic principles to harness moving air's kinetic energy and transform it into useful power. The transformation process is conducted by wind turbines comprising up to 8000 electromechanical components. The most important are depicted in figure 17. Depending on the wind speed a wind turbine is chosen to work on and its output capacity, conventional wind turbines may have rotors with more than 60 m in diameter atop of 80 m towers, yet lately industry has reported the development of offshore windmills with blades of up to 100 m in length sitting on top of a 170 meter high tower [BUR-01]; [SCL-13]. Power output capacities on modern windmills range from 250 Watts to 7 MW [GWE-15b].

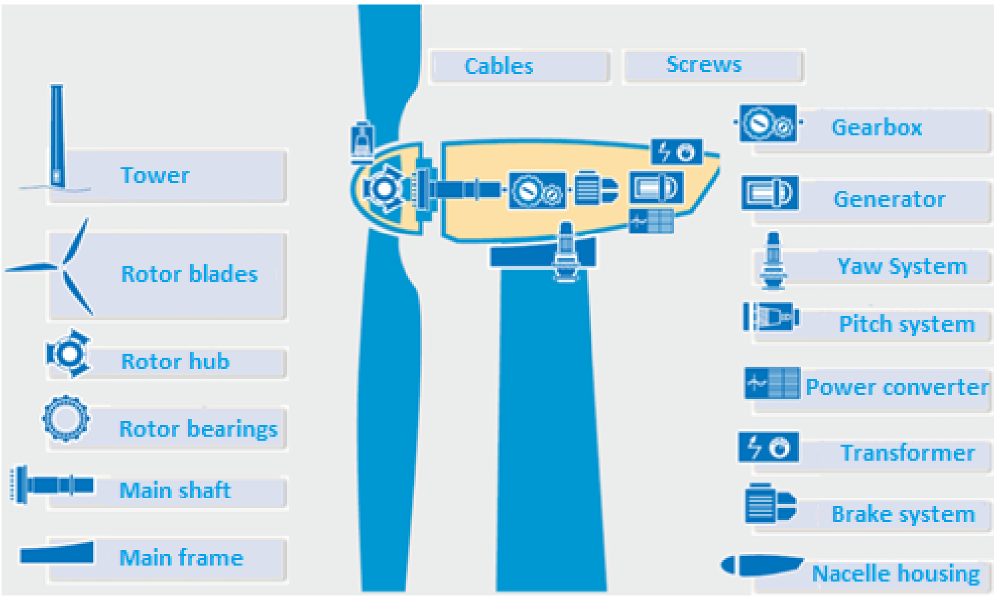

Figure 17: Main components of a wind turbine. Adapted from [WID-15]]

Wind turbines are turbo-engines with variable outputs depending on the operational area in which they act. According to the law of conservation of energy, the turbine's output energy, in form of electricity, equals the kinetic energy of the wind minus intrinsic losses of the system.

The wind kinetic energy is represented by the following mathematical expression:

$$K = \frac{1}{2} \rho A v^3$$

where:

K = Kinetic energy of air flow per time unit
ρ = Air density
A = Area of the circumference drawn by the turbine blades
v = Air speed

Graphically, wind's kinetic energy can be understood as the energy contained in a cylindrical mass of air with a specific density and diameter determined by the turbine radius as depicted in figure 18 [BOY-04].

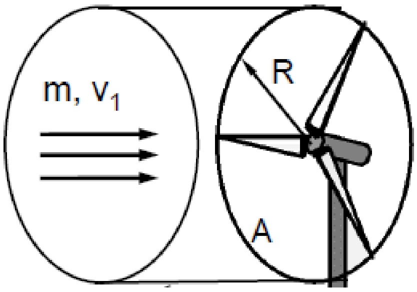

Figure 18: Kinetic energy represented as air tube [LIE-15]

The energy output of the wind turbine on the other hand, depends on its power coefficient, also known as efficiency and it is given by the following expression.

$$P_W = \frac{1}{2}\rho A v^3 C_P$$

where:

P_W = Turbine's power output
C_P = Turbine's efficiency

C_P is a dimensionless figure which represents the turbine's capacity to turn wind's kinetic energy into some other type of energy such as rotational energy, or electricity if a generator is attached to the turbine. This power coefficient is limited by Betz's law to a theoretical maximum of 59.26 %.

According to international organizations such as the Global Wind Energy Council (GWEC) and REN21, the installed capacity of wind energy worldwide reached 370 GW in 2014. According to the same sources, wind power could reach 2000 GW of worldwide installed capacity in 2030 supplying up to 17-19 % of global electricity [GWE-15a]; [REN-15].

2.2.1.3 Other renewable energies

Hydropower: Hydropower is by far the biggest contributor of net energy production within renewable technologies and will remain as such in the foreseeable future. The IEA estimates that by 2050, world's hydropower installed capacity will reach 2000 GW and a global electricity generation of 7000 TWh per year, which would represent preventing 3 billion tons of CO_2 from fossil energy sources. The biggest growth for hydropower according to IEA, will come from large projects in developing economies especially in Africa, the Asia Pacific region and Latin America [IEA-12b].

Advantages of Hydropower are manifold. Firstly, the technology is reliable, flexible and proven since over a century. With prices ranging from 0.03 – 0.15 USD per kWh depending on the worlds region, costs of energy generation are comparably low to other renewable energies. Hydropower generates no CO_2 other than those emitted during the construction of its infrastructure. Additionally, and also quite relevant is the fact that potential hydropower can be stored, which means, hydropower energy can be used to level energy fluctuation between power grids compensating losses from other sources [GAA-11]. Hydropower has also its downsides, especially when it comes to large sized plants, as it has been proven that they affect water availability in downstream stages and might affect whole ecosystems or human settlings [GAA-11].

Operation principles of hydropower plants are based on their energy storing capabilities, or size of its reservoir. Hydropower with no, or very limited, reservoirs are called “Run of River” plants and their energy production depends entirely of the size and power capabilities of a turbine powered by the flow of running water. On the other hand, hydropower plants with large reservoirs have the possibility to concentrate large amounts of water bodies in a higher location, commonly upland or mountain regions. The water in the reservoir is delivered to the turbine through a series of tunnels and penstocks with water being controlled by gates or valves [MUN-12].

<u>Bioenergy:</u> Bioenergy or biomass energy relies on organic material to produce energy. Present at least since mankind used wood to cook its food or keep itself warm, bioenergy is one of the first humanity energy sources [REW-15]. According to the IEA, bioenergy accounts today for roughly 10 % of world’s primary energy supply, with its main contribution allocated in the inefficient use of wood and crops for heating and cooking purposes in Least Developed Countries (LDC). However, according to the same source, modern bioenergy supply methods will help the technology to position itself as one of the leading energy suppliers in specific energy demanding areas. IEA predicts for instance that biomass energy will be able to provide up to 27 % of worlds transportation fuel by 2050 [IEA-12a].

<u>Solar thermal energy:</u> Solar thermal energy can be divided in two technological categories, active / passive solar heating and solar thermal engines. Passive and active heating systems can be defined as either discrete solar collectors heating water or spaces by means of the circulation of an active fluid, or as passive construction elements such as glazing and insulation materials integrated in a building to reduce its space heating / cooling energetic consumption [BOY-04]. Solar thermal engines on the other hand, refers to the utilization of large scale, high temperature devices to produce useful mechanical work. This work is commonly utilized to generate electricity through steam turbines.

Active solar thermal technologies are technologically simple devices comprising heat transfer elements, insulation and in most cases a frame. Energy, in form of heat, is harnessed by a selective coating absorber out of sunlight radiation and then transferred to a liquid carrier that either distributes the heat in an open space or keeps it. Solar thermal engines on the contrary are far more complex systems involving a large number of heliostats or highly polished mirrors that commonly reflect and concentrate solar radiation in a specific focus point to produce steam and electricity through a conventional thermodynamic cycle. These technologies, often referred to as Concentrating Solar Power (CSP) are still relatively uncommon if compared with technologies such as photovoltaic. In 2015 a total of 4.5 GW of installed capacity with 11GW more in the pipeline have been reported by energy monitoring agencies [CSP-15]; [BOY-04].

<u>Geothermal energy:</u> Geothermal energy is the utilization of earth’s internal heat as usable energy. Earth’s internal heat is generated from radioactive decay of uranium, thorium, and potassium isotopes. Additional to the radiogenic thermal energy, other sources of heat such as the primordial energy of planetary accretion have been determined to contribute to Earth’s inner temperature [DIK-13]. The exploitation of this potential energy comprises a series of field studies including the analysis of the geothermal system, area where the energy reservoir is located, fluid analysis of the resource and electrical conductivity, propagation velocity and density. Geothermal resources of over 150°C are suitable for electricity production, lower

temperatures are utilized for many other types of applications such as heating and cooling [DIK-13].

Geothermal power plants produce electricity through steam extracted from geothermal systems and energy reservoirs. Conventional geothermal power plans can be divided in dry steam, flash steam and binary steam types [NRE-15a].

Ocean power generation: Finally, technologies with relatively current low contribution to the energy generation mix but with future potential in the area of renewables include ocean power technologies. Ocean power technologies fall in one of three categories:

- Tidal energy: Subdivided in turn in tidal range, tidal current and hybrid technologies. Tidal energy's principle is based in the potential energy generated between rise and fall of tides resulting of the gravitational interaction between sun, earth and moon. Until 2014 only five projects have been developed commercially generating a combined power output of 520 MW [IRE-14c].
- Wave energy: Wave energy turbines convert kinetic energy of waves into electricity. Three main technological categories exist; oscillating water columns; oscillating body converters; and overtopping converters [IRE-14d]. Each technology has a different working principle that depends on factors such as water depth and distance to the shoreline [FAl-09]. Currently the technology has been limited to pilot and demonstration project without a single commercial plant in operation.
- Ocean Thermal Energy Conversion (OTEC): The principle of OTEC lies in using the temperature difference existing between warm upper layers of seawater and cold deep seawater to generate steam used to drive turbines. So far, the largest OTEC plant delivered 1 MW. Several other plants are currently under different levels of development [IRE-14a]

2.2.2 Relevance

Main arguments brought while delineating national and international policies ruling the introduction of renewable energies in the respective energy mixes revolve around four premises: Reduction of anthropogenic greenhouse gas emissions, diversification of energy sources, promotion of economic growth and job creation [DUS-14].

2.2.2.1 Climate change

The injection into the atmosphere of anthropogenic gas emissions, consistent mostly of carbon dioxide (CO_2), chlorofluorocarbons (CFC) and nitrous oxide (N_2O), changes the disposition of incoming solar radiation and outgoing heat radiation enhancing the natural greenhouse effect of the planet. Direct consequence of this phenomenon is the increase of global temperatures [SOR-10]. Exact repercussions of this temperature rise are variable according to the extent of its increase and are also somehow unpredictable. However, experts warn that temperature increase is expected to be on the order of two to five degrees Celsius by the time CO_2 emissions double preindustrial concentrations. Under these conditions, ocean levels will rise up to one meter in the next century due to melting glaciers, leading to loss of life and land in coastal areas. Further consequences according to researchers include increase of hurricanes and tropical storms due to higher sea surface temperatures, stronger rainfall and modification of rainfall patterns followed by long dry seasons, harsher conditions for agriculture, and extinction of plant species due to changing habitats [JAK-13]; [FUC-07]; [WWF-12].

Since the signing of the Kyoto protocol, numerous national and international efforts have been launched to curb the environmental impact of greenhouse gas (GHG) emissions. The European Union for instance, in its 2020 climate and energy package, enforces a set of binding regulations to its members to achieve climate and energy specific targets, commonly known as the 20-20-20 objectives. These environmental targets, to be achieved at the latest in 2020, were endorsed by the EU in 2007, and focus on:

- A 20 % reduction of the EU's GHG emissions compared to 1990;
- A 20 % share of renewable energy sources in the EU's gross final energy consumption;
- A 20 % saving of EU's primary energy consumption compared to projections [EU-15].

The European Environmental Agency reports that the first target was virtually achieved already in 2014 and that targets two and three were on track be accomplished until 2020 [EEA-14]. The EEA estimates that the use of renewables in 2012 resulted in the avoidance of approximately 326 Mton[20] of gross CO_2 emissions, with 23 % of those savings registered in the non-trading sectors, e.g. manufacturing [EEA-15].

2.2.2.2 Diversification of energy sources

The decoupling of fossil fuels as main energy source has been identified as pillar energy policy element of several economies. According to some research studies, the motivation of diversification depends on the development level of the country. On the one hand, developing countries see in renewables a mean to achieve national and international environmental goals, to address a constantly growing energy demand, or to reduce dependence on imported fossil fuels. On the other, developed countries' focus seems to lie in increasing energetic supply's reliability, reducing energy costs, and achieving internationally agreed emission curbing targets [REC-15]; [MUL-11]. Based on calculations of the EEA for example, 116 Mtoe[21] fossil fuels, mostly coal, were substituted by renewables in 2013 when compared to the energy production in 2005. The total is equivalent to an EU-wide coal consumption reduction of over 13 % [EEA-15].

Concerning the previous aspect of gas emission abatement, diversification of energy sources also contributes to achieve the reduction of the environmental impact generated the one way or another by almost every energetic source. According to Li, "*the dominance of a single energy source and system, no matter how ''perfect'' it might be at a time, would be unsustainable in the long run*". The broad range of renewable energy technologies, facilitates the compensation of technological drawbacks through the implementation of alternative technologies according to geographical, social and economic preconditions [LI-05].

2.2.2.3 Economic development

From the macroeconomic perspective at a global level, IRENA concluded that doubling the share of renewables in the global energy mix by 2030 would increase the global GDP by up to 1.1 %, mainly due to capital investment of conglomerates throughout the entire value chain [IRE-16a]. Economic benefits would also reach welfare gains for the population including productivity increase through electrification, as well as better heat and transport systems. The

[20] Meassurement Ton
[21] Million Tons of Oil Equivalent

monetary impact is hard to calculate as factors such as economic impact on consumption, social impact based on expenditure on health and education, and environmental impacts with respect to materials consumption need to be considered [IRE-16a].

From the microeconomic perspective, implementation of renewable energies, due to their decentralized nature, have the capacity to trigger circulation of capital within local communities developing their economies and infrastructure. Many studies have reported substantial impacts in the productive diversification in small communities, which shifted from a pure agriculture-based economy to the utilization of endogenous resources to generate value creation chains. Several similar conclusions have been reached by many other researchers [LIM-09]; [DER-09]; [DEI-11].

2.2.2.4 Job creation

As the renewable energies industry grows, so does the demand of specialists in the diverse technologies on a global scale. In [IRE-15b], IRENA concludes that until 2014:

- An estimated 7.7 million jobs, excluding large hydropower, were reached in 2014. This represents an increase of 18 % with respect to the previous year.
- A trend could be nonetheless identified with more jobs in the sector shifting towards Asian markets especially in the manufacturing sector.
- With respect to individual technologies, PV and wind energy occupied first and third place with 2.5 million and 1 million jobs respectively.
- The current ten largest renewable energy employment countries are: China, Brazil, United States, India, Germany, Indonesia, Japan, France, Bangladesh and Colombia (see figure 19).

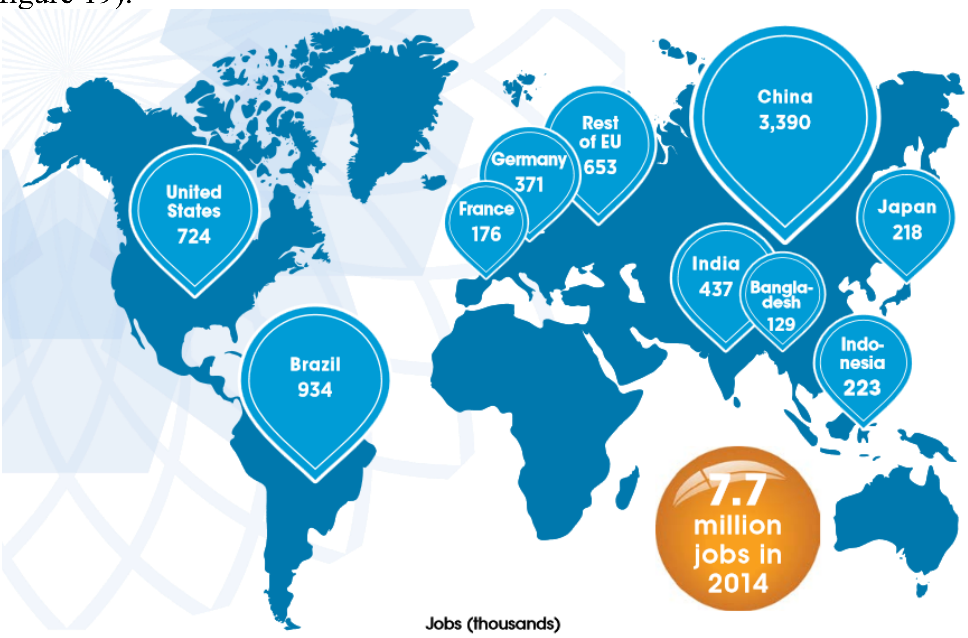

Figure 19: Global jobs in renewables [IRE-15b]

Now, considering the 9.8 million jobs that the oil and gas industry generates in the U.S. alone, the global figure on renewable energy job positions has still a long way to oust fossil fuels as economic pacemaker in the energetic sector. The challenge is even bigger while taking into account that the sector is growing far faster than the specialists market and the training capabilities of specialized centers or higher education institutions. Developed and leading developing economies alike have in this sense recently reported a significant deficit in photovoltaic and wind energy specialists [EWE-10]; [MWG-10].

The job creation potential therefore is undeniable. Not only the sector is growing at an uncommon speed, but it is also a labor-intensive sector, which creates more jobs per USD than conventional electricity generation or manufacturing fields. Renewables use also primarily indigenous human resources so that the local communities are highly benefited with each investment [IRE-16a].

2.2.3 Challenges for renewables implementation in developing countries

The scarcity of skilled personnel in the field of renewable energies and its impact concerning the accomplishment of targets regarding the increase of renewables contribution to national and international energy mixes have been described in the last section. However, the biggest concern of researchers and renewable agencies is not the current deficit of human resources specialized in the field of renewable energies, but the notorious lack of education programs and teaching infrastructure to form them [KEC-15]; [KAN-15].

Kandpal suggests that tackling the problem on a global scale will require a judicious mix of formal and non-formal education in the field. In the concrete case of developing economies, the author argues that non-formal education should play a more important role in the dissemination and embracing of the technologies by rural and informal urban populations. Only then, renewables would be accepted by communities opening business and investment possibilities in these areas [KAN-15]; [JOS-07]; [MWA-06]; [CHD-02]; [BRM-13].

In the case of formal education, teaching curricula are to be modified to integrate concepts of sustainability and renewable energies up from primary school levels. Secondary, technical and higher education programs should build upon these basics in order to form experts, who will serve as practitioners or multiplicators of the acquired knowledge (see figure 20). A detailed description on suggested content elements for each education level can be found in [KAN-15]; [NEW-91]; [ZOG-08]; [HAN-06].

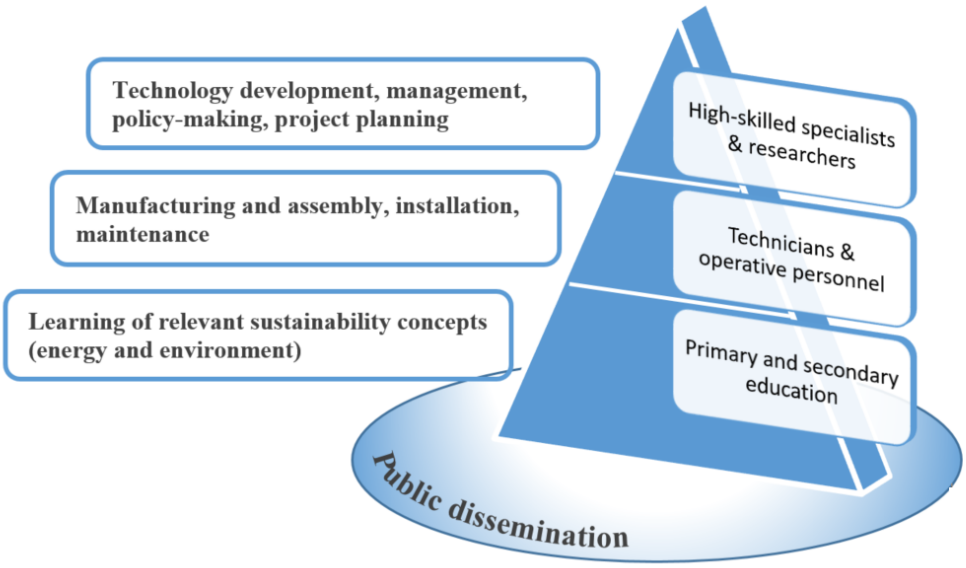

Figure 20: Renewable energy relevant curriculum content per education stage

The improvement of formal renewables education in developing countries faces several challenges, which have been thoroughly documented in sources like [THM-08]; [BEN-04]; [IRE-15a]; [WIL-10]; [NEG-12]; [KAN-15]; [IRE-12]. Some of the most important issues are briefly described below:

- Public acceptance: Currently, large sectors of the population in developing countries need to be made aware of the importance of responsible energy procurement and consumption in order to diminish negative impacts on the environment. Mindsets of consumers that see in renewable energies an unreliable or expensive energy source need to be changed through what Benchikh calls technical, economic, ecological and political credibility [BNE-04].
- Links to employment and employability need to be established: Dissemination of renewable energies needs to be accompanied by visible direct and indirect job opportunities in local value chains, or at least demonstrate potentials to self-employability. Achieving this not only fosters local economic development but also acceptance of the technologies per se.
- Lack of teaching professionals in the field: Due to the relative late introduction of renewable energies in developing economies, experts in the field who act as knowledge disseminators are scarce and quite often lack academic competences to transfer knowledge adequately.
- Lack of lecturing material: A severe scarcity of literature and teaching aids such as computer software has been encountered in many developing countries. Moreover, without a solid basis on experts in the field, knowledge transfer occurs usually based on teachers' expertise or biases.
- Inadequate or inexistent laboratories: Hardware infrastructure in the field or renewables at primary, secondary and higher education levels are either inexistent or insufficient to carry out qualitative experiments. Existing equipment consists mostly of imported specific purpose devices with limited update and upgrade potentials. Support infrastructure for the installation of larger laboratories, such as space, power supply, cooling, or maintenance is reportedly also scarce.

To try to cope with the deficit of local education programs in the field of renewables in developing countries, several international initiatives and projects have taken place in recent years supporting transfer of knowledge, technological cooperation, policies advice and investment measures from developed nations. Some examples include UNESCO's Global Renewable Energy Education and Training Programme (GREET) [UNE-09a], the Transfer Renewable Energy and Efficiency (TREE) [RENAC-12], Capacity Building on Integration of Large Amounts of Renewable Energy in Electricity Grids (ReGrid) [RENAC-14], and Capacity Development on Renewable Energy and Grid Integration (CapREG) [RENAC-15] programs financed by the German Ministry for Environment, Nature Conservation Building and Nuclear Safety (BMBF), and IRENA's Renewable Energy Learning Partnership (IRELP) [IRE-16b].

2.3 Knowledge transfer partnerships

The seventeenth UN's SDG stresses the need to secure global partnerships and cooperation as a means to achieve global sustainability. North-South partnerships are encouraged to mobilize science, technology and innovation knowledge to underdeveloped regions as a means to foster their socio-economic development, while at the same time find the means to build local human resources to secure self-sufficiency in the near future. Knowledge transfer in sustainability relevant fields such as manufacturing and energy generation is a common demand in UN's requests of collaboration and will therefore be reviewed in detail in this section.

The definition of knowledge transfer, aka capacity building, is context-dependent and also determined by the referred author. However, it is broadly accepted that the term refers to transfer of knowledge that is conducted between parties with big knowledge or technological disparities [UNC-14]. Strictly speaking, knowledge transfer can occur informally among individuals through traditional and modern ICT without the need of involved parties to engage in direct contact, e.g. a video in YouTube can transfer knowledge to undisclosed recipients without the need of a formal framework agreement. This section however, is centered in describing the four most common inter-institutional methods to exchange knowledge between education institutions and fund providers in industrialized countries, and learners or partner institutions in developing countries.

- **Human resources of developing countries are educated in foreign higher education institutions**: According to UNESCO's and OECD's estimations, around 4.3 million students were conducting their studies outside their home countries in 2013 [OECD-13]. By 2020 this figure is calculated to reach seven million. This flow of international students has been supported by megatrends such as globalization, establishment of English as international communication language, as well as national and international funding strategies. Figures of the OECD show an unbalanced share of student exchange "with almost three times as many foreign students enrolled in tertiary education in OECD countries, as there are OECD citizens studying abroad. Of those, 83 % are enrolled in G20 countries, while 77 % are enrolled in OECD countries" [UNE-09b]; [OECD-13].

  As a result, many higher education institutions in developed countries and some elite higher education institutions in developing countries have profited from the influx of foreign students by introducing tuition fees as a means to keep up with increasing costs of education that cannot be covered by government tax revenues, effectively adopting a private higher education model. Students in turn benefit on the one hand from education possibilities not available in their home countries and on the other from international exchanges and degrees perceived as economic success factors in their countries of origin [UNE-09b].

  From the sending country's perspective, the aim of the approach is to shorten communication channels between knowledge owner and knowledge receiver. The approach also potentially allows learner's access to the latest state-of-the-art technologies and learning infrastructure. The so-called "brain-drain" or "high-skill migration" effect is nonetheless a side effect, which is hard to estimate due to conflicting stances between studies. Some authors warn against long-term loss of highly educated workforce that hinders local infrastructural development, while others claim outpacing benefits to the sender country due to the generation of positive network externalities [NAU-12]; [GRE-62]; [DOC-14].

- **Building upon existing institutions, strategies and tools:** In this case, available teaching infrastructure and faculty of universities and training centers in developing countries is updated and modernized with funds and technological resources, including remote education approaches, provided by international development agencies, as well as higher education institutions from industrialized nations. Students from developing economies are therefore not any more forced to leave their country to obtain the chance to receive high-quality instruction. The biggest advantage of this approach is that the collaboration's outcome between industrialized and developing countries, in this cases improved facilities and teaching staff competences, remain in the developing country serving local learners. An additional advantage is the sense of national ownership and leadership as the curricula development is mostly carried out according to national / regional needs and frameworks. Supporting countries or associations link these needs to available funds and resources in order to draw an action plan along the local partner institutions under consideration of their existing capacities and knowledge [UNE-06].

Crisp suggested that upgrading existent facilities in developing countries can be conducted on a top-down or a bottom-up organizational manner [CRI-00]. The former implies the donor institution to support its local partner by the setting of guidelines, policies and / or strategies a local institution or agency requires to follow to achieve concrete targets. Resources to achieve these objectives are then provided either by the donor agency or a third party. The bottom-up approach on the other hand, consists in the development of basic capabilities in almost every area within the local institution under the premise that developing a core well-trained individuals decreases reliance in external consultants and increase the chances of an effective further conduction of the activities once the funding ceases [CRI-00].

- **Teaching the teacher approach**: Also known as "train-the-trainer" this approach concentrates in the education of multiplicators or agents from developing countries who are trained either locally or abroad by foreign experts with the sole objective of enabling local dissemination of knowledge. The particularity of the approach is that the focus of the training activities lies in enabling a human resource to become a teacher and not necessarily a practitioner. Thus, competences transmitted go beyond technical aspects of the knowledge field to be instructed, commonly including pedagogy facets as well [AST-08].

  Teaching venues for train-the-trainer activities vary according to learning preconditions and available didactic means. Activities conducted in the learner's country present the opportunity to immediately introduce local elements into the training program but often require local particularities to be taken into account, which could be alien to the transferring entity, e.g. local language and customs. Another disadvantage is the potential lack of technological infrastructure required for an adequate transfer of knowledge, which is quite often the case while educating human resources in complex technological fields. Training activities conducted in the facilities of a foreign knowledge provider on the other hand, commonly offer specialized didactic and technical infrastructure to facilitate a successful knowledge transfer. Additionally, international languages, mostly English, helps to standardize didactic methods and documents. On the downside, direct implementation conditions are in most of the cases unknown to the foreign trainer [MWG-10].

- **Setup of local training centers:** Training centers are defined in this context as specialized teaching facilities focused in the development of concrete academic and non-academic competences such as sales, installation, and maintenance. This way, personnel from manufacturing and renewable energy companies, and independent contractors receive professional instruction from local specialists in well-equipped local facilities.

  With financial support of national and / or international sponsoring agencies, training can be centralized in a specialized unit settled in a recipient country. This unit will then integrate local and foreign experts and expertise to develop not only human but also their teaching facilities according to the demands and needs of the recipient country. The optimal physical location of the centers needs to be determined according to socio-environmental conditions that facilitate the experimentation in the knowledge area and its implementation in the field, but will always be located close to the final beneficiaries' communities [MWG-10].

Benefits of knowledge transfer to developing economies, conducted under the framework of serious partnership and under fair socio-economic conditions is generally regarded as mutually beneficial for every involved party. Developing countries, usually the knowledge recipients, obtain knowledge and technologies to develop own physical and knowledge infrastructures without carrying the economic burden associated to R&D activities. Developed economies, usually the knowledge providers, earn foreign market benefits and political relevance [COP-70]; [HAR-04]. Knowledge transfer approaches presented so far exhibit particular advantages and disadvantages when it comes to their implementation and lasting results. A brief overview of those is presented in table 4.

Table 4: Advantages and disadvantages of knowledge transfer methods

Partnership	Target learners	Knowledge fields	Advantages	Disadvantages
Education in foreign HEI	Undergraduate and graduate university students	Engineering, management, exact sciences, marketing, political sciences	• Direct contact to technology and knowledge carriers • Access to high-end laboratory infrastructure • Access to all value chain links, e.g. manufacturers, planning companies, and installers • Building of international networks • Potential positive effects of brain drain	• High costs for studying abroad • Limited immediate benefits for local communities • Limited influence in study content. Origin countries' needs not necessarily covered • Series of prerequisites to be covered, e.g. Language skills, and high grades • Potential negative effects of brain drain
Building upon existing institutions	K-12 students, undergraduate and graduate university students, technicians.	Elementary science courses, engineering, management, exact sciences, marketing, political sciences, technical fields	• Sense of ownership from the local institution through the inclusion of local stakeholders • Customized design to fit local necessities and market • Local language of instruction possible • Development and improvement of local infrastructure • Potential benefits for higher stages of education	• Short term collaborations • Project Sustainability is challenging • Limited to local impact
Train-the-trainer	Professionals to be trained as instructors, mostly for adult teaching	Strong focus on technical and specialization fields, e.g. installation; electricity, assembly, planning, and design	• Potential large regional impact with low resource investment • Second stage of instruction in local language • Potentials to integrate local necessities and knowledge • Specifically suitable to abate low instructors' availability	• Very limited contact to high-end laboratories, and infrastructure • Ephemeral bonds to sponsor agency or country • Limited and very focused technical impact. • Quality of dissemination dependent of individuals
Local training centers	Professionals and technicians	Strong focus on technical and strategical fields, e.g. Vocational training, policy-making, academic research	• Strong development of local, regional and national capabilities • Development of local infrastructure • Motivates national and international capital investment in the sector • Strong international and inter-institutional bonds • Customized design to fit local necessities and market. Local language	• High investment costs • Bureaucratic processes • Dependent on local, regional or national support

Knowledge transfer methods presented so far share some characteristics. For starters, their approaches are either individual or institution-centered, bounding to a great extent their knowledge dissemination effect to the primary knowledge or technology recipient. In the case of students educated in foreign HEI, the main beneficiary is clearly the learner. Chances of local further dissemination are slim as graduates of foreign HEI might decide to temporarily or permanently remain in the host country, or aspire to high job positions in companies in their home countries [DOC-14]. On the other side, the dissemination factor achieved through the improving of existing education institutions and the setup of new training centers has a local character determined by their physical location. Their location in turn largely depends on the accessibility to public infrastructure and human resources required for their functioning commonly available in formal urban settlements. Dissemination impacts in rural and informal urban communities are therefore also fairly limited in this case.

An exception seems to be the train-the-trainer approach. In principle, trainers can be considered as unbound to any specific institution or geographical constraints. Trainers are owners of their knowledge and its dissemination is their way of living, which means that rural and informal urban audiences are not excluded as knowledge recipients. However, in this case, knowledge transmitted by trainers can be limited in its depth without access to physical infrastructure to support technical education common in engineering fields.

A further similarity of the presented methods consists in the education stages they most commonly addressed. The OECD estimates that 92 % of foreign students registered in HEI in developed countries study a tertiary education program [OECD-13]. The same way, collaborations among education institutions and the setup of occupational training centers in developing countries lookup to address learners of late-secondary and tertiary education stages to build up competences for immediate implementation in their respective labor markets [MWG-10].

Hence, in this dissertation it is claimed that current knowledge transfer methods between HEI in industrialized and developing countries are insufficient when it comes to contribute towards the achievement of global sustainability due to their limitations to reach large population sectors living in developing countries' underdeveloped rural and informal urban communities. It is also claimed, that the current knowledge transfer methods are strongly focused on delivering formal instruction in tertiary stages of education, largely neglecting earlier education stages acknowledged in previous sections as fundamental to the SDG achievement. When it comes to engineering education, this dissertation argues that knowledge transfer approaches have to be backed by a strong technical component, which enable contact to state of the art educational technologies and laboratories. Figure 21 graphically represents current knowledge transfer method aims and the identified gap.

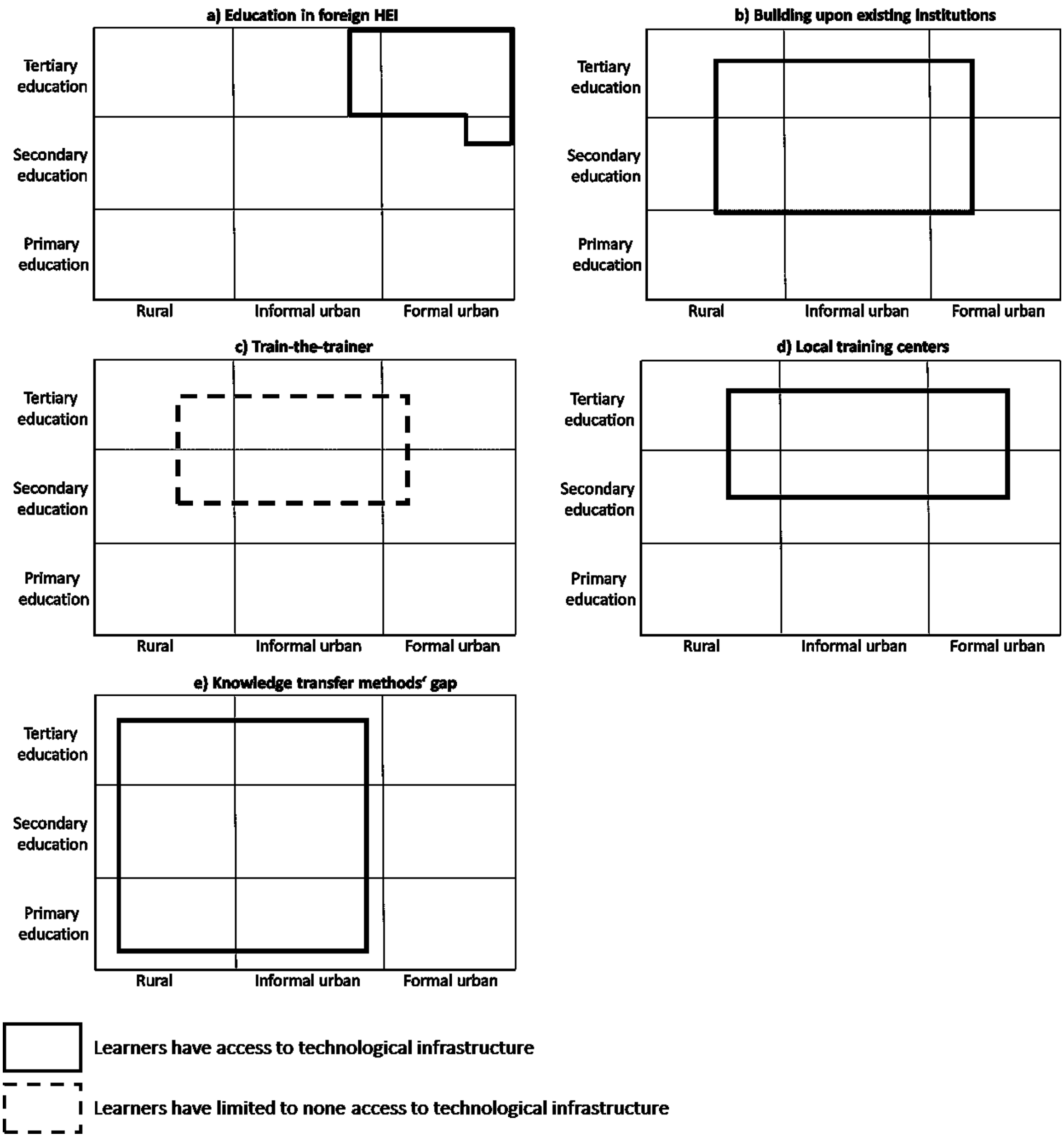

Figure 21: Knowledge transfer method's aims and gap

3 Education

Education is a broad, inclusive term referring to the process of facilitating the acquisition of knowledge, skills, competences values, beliefs and habits through formal[22], non-formal[23], and informal[24] means. When formal, it normally aims to achieve balance between the individual needs and the societal needs [COL-03]; [WIK-16]. The term education is commonly interchanged with the term instruction. However, pedagogues agree the latest is delimited to the acquisition of knowledge occurring exclusively under formal or non-formal contexts [SRI-06]. Education is also closely related to terms such as capacity building, defined as development of a country's human, scientific, technological, organizational, institutional and resource capabilities [UNE-06], and training, which however is centered in developing skills rather than knowledge [BAN-14].

Education usually takes place under the guidance of educators, yet learners can also educate themselves [DEW-16]. Its two most important concepts are learning, which refers to the cognitive process taking place in the knowledge recipient by which she or he assimilates new information, and teaching, centered in the knowledge provider. The means and methods by which knowledge is conveyed from owner to recipient are known as pedagogy or didactic [COL-03].

Education began as an informal process with parents teaching their children and masters teaching their disciples. Formal education began in the middle ages usually governed by religious institutions [LAH-78]. Nowadays, most common education systems worldwide are comprised by primary, secondary and tertiary levels of education. In many western countries, the term K-12 is often used when referring to the education taking place from Kindergarten till the twelfth degree of education, in most cases coinciding with the last degree of secondary education. The right to education has been recognized by the United Nations in its International Covenant on Economic, Social and Cultural Rights [UN-66]. Education has been identified by the UN, further development organizations and national governments as spearhead element towards the achievement of international development targets to enable a global sustainable development such as the Sustainable Development Goals [JOS-07];[UN-16].

In this chapter, relevant education concepts such as learning theories, didactic models, educational technologies, instructional design models, as well as learning outcomes and taxonomies, will be thoroughly analyzed to create a baseline for the development of didactic approaches to facilitate engineering education in developing countries.

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[22] Formal education refers to the hierarchically structured, chronologically graded 'education system', running from primary school through the university including specialized programmes and institutions for full-time technical and professional training [COO-74].

[23] Non-formal education refers to any organized educational activity outside the established formal system - whether operating separately or as an important feature of some broader activity - that is intended to serve identifiable learning clienteles and learning objectives [COO-74].

[24] Informal learning refers to the truly lifelong process whereby every individual acquires attitudes, values, skills and knowledge from daily experience and the educative influences in his or her environment - from family and neighbors, from work and play, from the market place, the library and the mass media [COO-74].

3.1 Learning theories

"The task of transplanting learning theory into practical applications would be greatly simplified if the learning process were simple and straightforward. Unfortunately, this is not the case. Learning is a complex process that has generated numerous interpretations and theories of how it is efficiently accomplished" [ERT-93].

The sentiment above, expressed by Ertmer and Newby more than twenty years ago, summarizes the conclusions found in large part of classic and modern literature concerning learning theories. The question *"how does human beings learn?"* has occupied the minds of philosophers and scholars since early days when Plato (427-347 B.C.) and Aristotle (382-322 B.C.) respectively proposed the theories of rationalism and empiricism.

According to rationalism, knowledge is derived from human's reason with little to no recourse of senses. Plato claimed that knowledge is innate and is only recalled, disambiguated, or "rediscovered" through reflection. The role of senses constitutes exclusively raw material for reasoning with the mind being innately structured to provide meaning to incoming sensory data [SCU-12]. Empiricism on the other hand, maintains that experience is the only source of knowledge. Aristotle distanced himself from his mentor claiming that human beings are born with no innate knowledge and all information learnt is product of their sensory interaction with their environment [SCU-12b].

Since then, philosophers, psychologists and pedagogues such as Descartes, Kant, Locke, Berkeley, Dewey, Watson, Skinner, Pavlov, Piaget and Kolb have proposed contemporary learning theories, which, despite concurring in fundamental aspects of the definition of learning, such as the fact that learning is acquired and not "rediscovered", differ in the way the cognitive process takes place. Some of the most widely accepted learning theories are introduced below.

3.1.1 Behaviorism

The psychological theory, initially proposed by John B. Watson at the beginning of the 20th century, links every human or animal behavior to a concrete stimulus or set of stimuli. According to Watson, behavior is predictable and even subject to be controlled if the stimulus unleashing it is known. From a behaviorist perspective, learning can be defined as "*an improvement in the performance of a subject as a function of a reinforced practice*" [KIB-67]. A behaviorist learning approach therefore would aim to control students' responses the same way as physical scientists look to control natural phenomena [WAT-24]. Key learning elements for behaviorists are the stimulus, the response and the association between both. Especially relevant is the latest as it provides information on how to make, strengthen and maintain a desired conduct. The structure of the learner's knowledge and the mental process necessary to use it is in turn irrelevant [WIN-90]. For pure behaviorists, a learner is considered therefore as a reactive entity with little interest in discovering his / her environment by him / herself. Memory in turn is limited to what can be recounted through punishment and reward [ERT-93].

In the Sixties, B.F. Skinner proposed the disengagement of behaviorism as exclusively a set of responses to stimuli that considered a person as a machine or automaton reacting blindly to an event. Skinner introduced for the first time concepts such as "*consciousness, feelings and states of mind*" as elements to be included in the model by which a learner would acquire new knowledge [SKI-74]. However, the dependence on external stimuli remained unchanged.

Behaviorist learning tactics rely in prescribing strategies aiming to strengthen the desired stimulus-response association. This includes the use of cues, repetition, and reinforcement [WIN-90]; [ERT-93]. After the first half of the 20th century, the implementation of behavioral theories gained technological support through the massification of impersonalized tutoring programs and devices. In 1954, Skinner popularized educational devices known as "learning machines". These devices consisted mainly of a program and a mechanical device that systematically guided the user through a series of "fill-in-the-blank" questions and assessed him through an answer-reinforcement algorithm. If the answer was correct, the learner would receive feedback and get reinforced by moving on to the next question. If incorrect, the student was encouraged to study the topic in order to be reinforced later [WLE-10]. The devices served later as predecessors of popular and currently widespread computerized teaching programs [BEJ-12].

Despite its success in transferring task-based learning, it is generally agreed that behaviorism is inadequate to explain the acquisition of high-level knowledge such as language development, problem solving, inference generating and critical thinking [SCU-12].

3.1.2 Cognitivism

In the late 1960s, psychologists and pedagogues disenchanted with behaviorist theories concerning independent thinking and its shortcomings while explaining complex problem-solving and language development processes, developed a theoretical learning framework centered in the understanding of inner mental activities that trigger and facilitated learning [SNE-85]. The term and principles of this learning theory are credited to Neisser, who in [NEI-67] first acknowledged the intervention of cognition, or thinking, in autonomous learning processes. Opposite to behaviorists, who considered thinking as an induced behavior, cognitivists ascribe knowledge to learning strategies and previous stored information known as schemas. These schemas are continuously enriched by sensorial inputs, processed by the mind and stored for later use [NEI-67]. Cognitive theories centers in how the information is acquired by the learner, how is it stored and especially how is it used in the future. The learner occupies thus an active role in the knowledge acquisition process [ERT-93].

For cognitivists, cues alone are insufficient to achieve learning of complex knowledge. Strategies of this theory focus in encouraging the learner to modify, develop, and use appropriate learning strategies. The use of analogies, metaphors, framing, outlining, mnemonics, concept mapping, and advance organizers have been reported by researchers as especially effective to train associative mental learning processes [REI-89]; [WES-91].

While designing an instructional method, cognitivists stress the importance of taking into account the information that the learner already possesses, to determine the best way to enrich the original knowledge and finally provide feedback that allows the utilization of this newly acquired knowledge in the future [STR-00].

3.1.3 Constructivism

Constructivism is a psychological theory contending that individuals form or construct much of what they learn or understand [BRG-04]. Constructivism is mainly based on Jean Piaget and Lev Vigotsky's theories on intellectual and human development, which argue that knowledge is a result of life-long constructive processes in which the individual organizes, structures and restructures her or his experiences in light of existing schemes of thought [BOD-86]. By accepting the premise that knowledge is generated by the individual itself, constructivist researchers acknowledge that to a great extent, knowledge is subjective and a product of individual mindsets. Research is therefore focused in how knowledge is better constructed instead of how knowledge is acquired [SCU-12]; [SIM-012].

Some similarities between cognitivism and constructivism theories exist, yet their divergences are notorious especially when it comes to the role of the subject during the learning process. According to Duffy and Jonassen, *"both, cognitivists and constructivists view the learner as being actively involved in the learning process, yet the constructivists look at the learner as more as an active processor of information; the learner elaborates upon and interprets the given information"* [DUF-92]. Leonard adds: *"cognitivism is not concerned with the willfulness, creativity, and autonomy of the learners that constructivism considers in its focus on the learning processes. (...) In constructivism, learners build their own meaning from new knowledge that they help construct. In cognitivism, learners have their knowledge built by someone else, an expert whose job it is to convey as best as possible the mental construct that describes the objects being studied"* [LEO-02]. Constructivists disagree with behaviorists and cognitivists when it comes to defining knowledge as "mind-independent", and subject to be "mapped" in a human brain [ERT-93].

Constructivist approaches towards learning include the commonly known "learning-by-doing" or placing the learner into a situation where ho or she is able to accurately portray a framework encountered in the field of study being learned. Constructivists concede that the ability of learners to successfully assimilate knowledge gained through experimentation depends to a great extent on previous experiences and is therefore of little use in early stages of learning. Jonassen describes three stages of knowledge, namely introductory, intermediate and advanced. According to him, a constructivist approach is more suitable for the latest while the former two are better supported by objectivistic approaches such as behaviorism or cognitivism [JON-91].

3.1.4 Experiential learning

Popularized in the early Eighties by David A. Kolb in [KOL-84], experiential learning bases its theses in the work of education pioneers such as Kurt Lewin, John Dewey and Jean Piaget. As an offshoot of constructivism, experiential learning situates experiences, and the reflections upon them, as core of any learning process [UNE-16a]. Contrary to constructivist ideas however, experiential learning's does not necessarily seek to create experiences in order to generate knowledge, but rather aims to understand the manners in which experiences motivate learners and promote their learning preferences [MUG-11]. According to [BRO-83], experiential learning is used with two connotations. The first one encourages students to "*acquire and apply knowledge skills and feelings in an immediate and relevant setting*", which involves some sort of previous contact with the field of study being analyzed. The second one however, stresses the necessity to learn from whatever "*occurs as a direct participation in the events of life*".

Kolb's experiential learning, depicted in figure 22, is based in the so-called cycle of learning. According to Kolb, the cycle starts with a given experience or event taking place in an individual's life. During the second step of the cycle, this individual reviews and reflects upon the causes and effects of this event. During the third step, the individual is able to draw conclusions regarding the particularities of the event, understanding its principles and effectively learning out of that particular experience. Finally, the learner can put in practice the knowledge acquired during the first event while experiencing a similar situation in the future

[KOL-84]. The concrete learning process is defined by Kolb as *"the process whereby knowledge is created through the transformation of experience"* and argues that learning…:

- is a process, not an outcome,
- is driven from experience,
- requires the learner to resolve conflicts through dialect,
- carries a more holistic and integrative view,
- requires the individual to interact with its environment,
- creates knowledge [KOL-84].

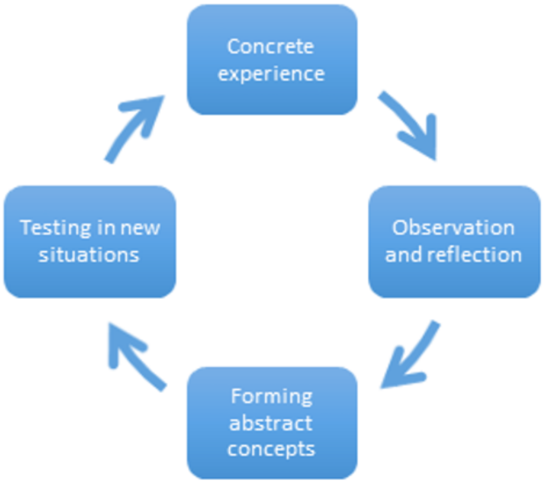


Figure 22: Kolb's cycle of learning [KOL-84]

3.1.5 Connectivism

Connectivism is a new learning theory largely focusing in modified mental processes and communication paradigms originated by the use of modern information and communication technologies. According to connectivism theorists, knowledge exists as an entity "out there" and the learner simply "connects" to it through external means and information networks. Connectivism was proposed as a new learning theory by George Siemens in 2004, as the educational potential of Internet and mobile devices was unfolding. It has been used to explain changes in learning patterns and characteristics of young children, who according to Siemens, seem to have gotten their minds "rewired" through the interaction with modern Information and Communication Technologies (ICT) since early ages [SIE-04]. Recent psychiatric studies seem to confirm this theory, at least to a certain extent. According to a study of the University of California, Los Angeles (UCLA), Magnetic Resonance Imaging (MRI) revealed that experienced web users showed a higher brain activity in areas of the prefrontal cortex, responsible of problem solving and decision making, than Internet newbies [CHM-08]. According to [CAR-10], the evidence provided by this study suggested that "the distinctive neural pathways of experienced Web users had developed through the internet use".

According to connectivists, an efficient knowledge transfer relies mainly not in inner cognitive processes but in the knowledge carriers. Sharples et al. have suggested in [SHA-05] that digital conversation including words, images, videos, and multimedia have become the new drivers of learning. Tools such as YouTube, wikis, and social networking platforms support nowadays' learning processes as books did in the past by creating frameworks for learning networks in which information is accessed privately and ubiquitously [BEL-11].

3.2 Didactic models

Didactic models comprise principles, strategies, mechanisms and management of instruction between lecturer and learner/s. In [FLE-96], Flechsig described what according to him were the twenty most representative models for instruction. Table 5 summarizes them below:

Table 5: Didactic models according to Flechsig [FLE-96]

Model	German Term	Description
Case study	Fallmethode	The method consists in the recreation and analysis of real-life (sometimes also imaginary) event for training purposes. The model makes use of an inductive approach commonly utilized in business, law and medical schools [BOT-12].
Computer-based training (CBT)	Individualisierter Programmierter Unterricht	The CBT method consists in the education through the utilization of mostly offline training programs on a computer.
Debate	Disputation	Meaning the exchange of arguments and counter-arguments from opposing perspectives on a common topic.
Distance learning	Fernunterricht	Defined as education which demands no physical presence from learners in a classroom. Originally conducted through physical correspondence, distance learning is nowadays executed over the Internet.
Educational conference	Lernkonferenz	Large gathering of students, usually with a duration of one or more days, in which participants exchange expertise and knowledge by means of presentations or symposiums.
Educational dialog	Lerndialog	Thorough discussion between two individuals, usually a learner and a field expert, regarding a concrete subject.
Educational network	Lernetzwerk	Defined by Flechsig as the *"activity in which learners generate new knowledge, especially innovative practice areas, and put it to the disposition of colleagues mutually and unselfishly mostly via written communication"* [FLE-96]. Currently, education networks use Internet as ideas exchange platform.
Educational workshop	Werkstattseminar	Field experts and an audience gather in a compact, single event to discuss latest developments and trends on a specific topic.
Exhibition / Presentation	Lernausstellung	The method consists in the transfer of knowledge taking place in public areas with a particular relation to a specific subject, e.g. museums, fairs.
Field work	Erkundung	In terms of education, field work or field study refers to the introduction of learners in natural / institutional environments as a means to acquire information through observation and data analysis.
Frontal teaching	Frontalunterricht	Frontal teaching refers to the classic didactic method present in primary and secondary education, which is characterized by a predominantly unidirectional information flow, e.g. lecturer to learner/s. Traditional teaching hardware, e.g. white boards, flip charts, commonly support the method.
Individualized learning space	Individueller Lernplatz	Learning centers provided with physical and virtual information sources enable knowledge transfer to the learner in an auto-didactic way, facilitating a self-determined progress speed.
Interactive man-environment learning system	Lernkabinett	The method refers to the education in a specific field conducted through especially conditioned premises such as laboratories. Laboratories provide a practical approach to substantiate theoretical knowledge acquired in classroom.
Internship	Famulatur	Young apprentices under particular guidance of an area expert acquire practical experience in a specific field.
Lecture	Vorlesung	Similar to the frontal teaching method, this model is based in a center figure conveying knowledge to an audience by means of support didactic infrastructure. Opposed to frontal teaching, bilateral interaction is expected

		in a lecture and is therefore commonly observed in higher education programs.
Peer tutoring	Tutorium	The method is based on a hierarchically-flat knowledge transfer from learner to learner.
Project / Problem learning	Lernprojekt / Arbeitsunterricht	Problem and project-based teaching are commonly interchanged, yet pedagogical literature has defined concrete differences between the methods, which nonetheless are based on the implementation of theoretic knowledge to solve tasks assigned by an academic. Due to its relevance for several learning theories, both models will be shortly addressed in a further part of this section.
Simulation	Simulation	Flechsig defined simulation as the learners' interpretation of a role within a fictive scenario in which an output is expected. The simulation method is better known today as gamification, or learning games.
Small-group learning	Kleingruppen-Lerngespräch	As its name implies, the method consists in the information-exchange between members of a micro-study group with different levels of expertise in a field.

Despite the fact that in the last decades, new concepts, terminologies and approaches have emerged, largely based on newly developed ICT solutions, most of the didactic models identified by Flechsig twenty years ago are still broadly utilized in formal education systems around the world. Some concepts have recently become a particular object of study facilitating thus their development, scoping and implementation in specific knowledge areas.

An example of these methods are the *problem* and *project-based teaching* (PBT) techniques. Both models have been defined by researchers as constructivist pedagogical techniques per excellence, which regardless certain similarities, most notably the acronym, pursue different objectives and feature different characteristics. Project-based learning has been defined by Rojter as "*the application of existing knowledge to new situations, which leads to the acquisition of practical skills*" while problem-based learning "*requires the acquisition of knowledge to address a particular problem"* [ROJ-09]. Both approaches have gained relevance in the last years in the field of engineering education, due to their emphasis in develop students' competences in solving open-ended, very often ill-structured or ill-defined tasks commonly encountered in the industrial real-life. Both methods promote independent work and thorough inquiry on behalf of the learners. An additional commonality is the role of the educator as a mere guide and moderator throughout the process [LAR-14].

Another didactic method rapidly being integrated into the curricula of engineering programs and embraced by many constructivist and experiential learning researchers is *gamification*. Gamification, defined as *"the utilization of game design elements in non-game contexts*", appears often in the literature as a superordinate concept to several related concepts such as serious games, serious gaming, playful interaction, and game-based technologies and learning [DET-11]. Detering and Dixon realized a survey of available literature in the field and determined that game design elements for teaching purposes can be allocated in one of the following five levels of abstraction [DET-11]:

- Interface design patterns such as badges or leaderboards;
- Game design patterns or game mechanics;
- Design principles or heuristics;
- Conceptual models of game design units;
- Game design methods.

The introduction of game mechanics in a learning environment pursues not the amusement of the learner as a primary objective but rather as a means to an end; namely the achievement of an educational target through ludic activities [KAR-11]. Much to the delight of connectivists, who see the model as a result of the influence of computer games and virtual worlds in current young researchers, gamification has been gaining popularity in engineering programs since the inception of the term in 2008. In [MAR-15], Markopolous and Davim compiled a series of application cases in engineering programs ranging from CAD-type environments to simulate assembly processes [BRH-07]; AutoCAD tutorials with missions, scores, and rewards [LI-12]; software to train designers to move from 2D to 3D environments [KOS-13], CAD/CAM/CAE applications to perform ergonomic analyses [PTC-15]; factory design and plant simulation [NIE-13]; as well as factory management simulation designed by the company Siemens mimicking popular Facebook browser games [SIE-11]. In [REG-09], the authors thoroughly describe an experiential learning approach to improve market and product analysis competences for engineers by means of gamification methods.

3.3 Instructional design

Instructional design is defined as a systematic process that is employed to develop education and training programs in a consistent and reliable fashion [RES-07]. It is the entire process of analysis of learning needs and goals and the development of a delivery system to meet those needs. It includes development of instructional materials and activities, as well as tryout and evaluation of all instruction and learner activities [ARL-96].

Instructional design has to do with translating pedagogical research and practice into instructional curriculum specifically crafted to produce desired learning objectives [CHP-15]. These learning objectives are to be achieved through the conception and conduction of formal instructional events[25] designed under consideration of learning theories, didactic models, educational technologies and evaluation criteria [REI-13].

Instructional Design Models (IDMs) are systematic methodological approaches to accomplish learning objectives by means of structured instructional events. IDMs' common objective is to help the designer to visualize a didactic strategy and break it down into discrete and manageable units [RYD-03]. Throughout the last century, various models with diverse instructional purposes and based on different learning theories have been proposed by educators aiming at designing and developing training programs while significatively reducing costs of education [NIX-01]. Some of the best known instructional design models will be shortly described below:

- **The ADDIE Model:** Acronym for Analyze, Design, Development, Implementation, Evaluation, the model is a generic IDM tool, which is adaptable to any design approach and serves as flexible guideline to elaborate complex models regardless of the subject of instruction. ADDIE has been particularly useful as a framework to initiate and compare well developed instructional design models [BRN-15], such as the ones presented below.

- **Gagné's 9 events of instruction:** One of the most prolific contributors to the development of systematic instructional design methods was Robert Gagné. Gagné, a behaviorist, proposed nine sequential events related to specific mental conditions of learning, each one with expected outcomes or behaviors. These were based on the

[25] Formal and non-formal educational activities such as courses, seminars, and workshops.

information processing model of the mental events that occur when adults are presented with various stimuli [CIT-16]. Gangé's 9 events of instruction are:

- First event: Gain attention;
- Second event: Inform learners of objectives;
- Third event: Simulate recall of prior learning;
- Fourth event: Present content;
- Fifth event: Provide learning guidance;
- Sixth event: Elicit performance;
- Seventh event: Provide feedback;
- Eighth event: Assess performance;
- Ninth event: Enhance retention and transfer to the job.

- **The Dick and Carey Model:** Walter Dick, Lou Carey and James Carey proposed what has been considered by many researchers and practitioners as one of the most popular IDM in primary, secondary and higher education. The model consists of an iterative sequence of ten steps to follow while designing education programs. These steps, shown in figure 23, range from the definition of instructional goals to the development of evaluation procedures to assess both, the learners' performance, and the course itself. Probably the biggest contribution of the model was to consider instruction as a closed system subject to continuous review and improvement [IDC-12]. According to the model authors, "*Components such as the instructor, learners, materials, instructional activities, delivery system, and learning and performance environments interact with each other and work together to bring about the desired student learning outcomes*" [DIC-90].

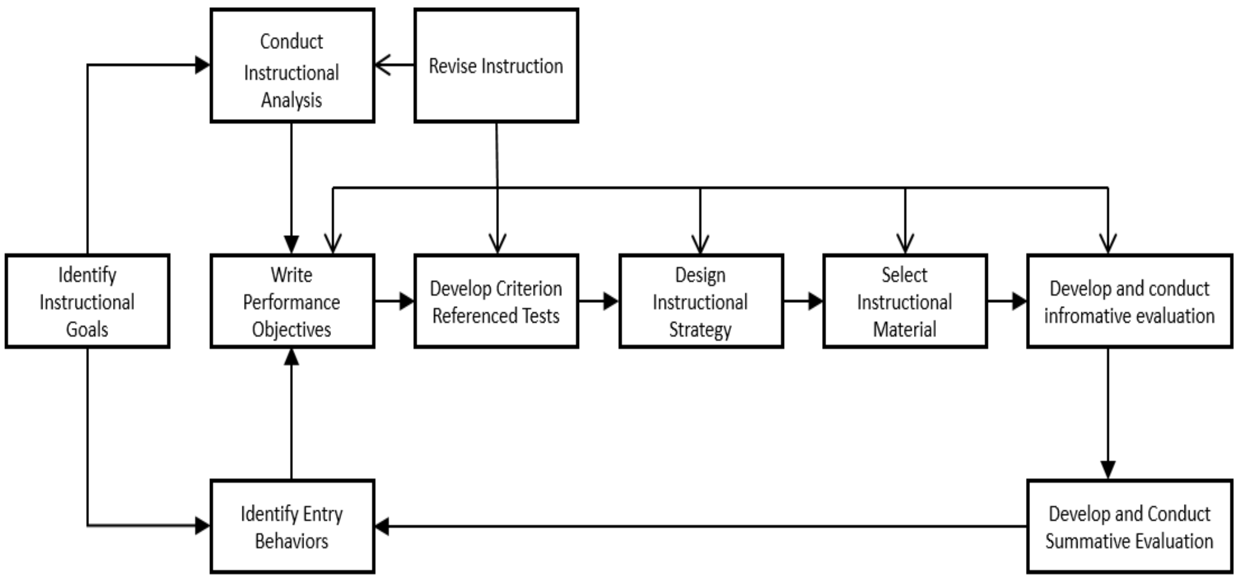


Figure 23: The Dick and Carey Instructional Design Model [DIC-90]

- **The BSCS 5E Model:** The non-profit organization Biological Sciences Curriculum Study (BSCS) developed in 1987 a constructivist, cycle-based Instructional Design Model widely utilized to develop biology and integrated science curricula in primary and secondary education programs. The model consists of five phases [BYB-06]:

- Engagement: The instructor accesses learner's previous knowledge in the field through activities that stimulate curiosity for the topic.
- Exploration: Learning tasks are given to learners in order to help them to generate ideas, concepts and questions related to the study topic.
- Explanation: Bidirectional communication between instructor and learners is engaged. Students explain their doubts; teachers explain the concepts.
- Elaboration: Instructors challenge students' conceptual understanding through the conduction of activities with the recently acquired knowledge.
- Evaluation: Students' understanding and progress is evaluated.

Other IDMs include the Merrill's First Principles of Instruction Model, which proposes a methodology to elaborate problem-based instructional courses following a constructivist approach consistent of integration, application, activation and demonstration elements [MER-04]. The Interpretation Construction (ICON) Design Model is also a constructivist framework proposed by John Black and Robert McClintock in [BLA-96], centered in the learners' interpretation of a specific event or artifact and their ability to draw, or construct, conclusions out of it. According to the authors, the model is especially suitable to design instructional events aimed at improving argumentation skills of the learners. The ICON model consists of seven elements, namely observation, interpretation construction, contextualization, cognitive apprenticeship, collaboration, multiple interpretations, and multiple manifestations.

3.4 Educational technologies

The effectiveness by which knowledge is transferred to a target audience is, along the learning theories and didactic models, largely dependent on the technologic means, e.g. hardware and software, used to convey it. Computational programs and physical devices are not only valuable as pedagogic instruments during the training phases of the learners, but are determinant in the future employability of graduates in a labor market, which is highly oriented towards high tech competences [MAL-15].

3.4.1 Definition

The interpretation of the term "educational technologies" is broad and keeps evolving over time. Breakthrough and disruptive technological innovation with substantial knowledge transfer potential, usually finds at some point its way into the classrooms of primary, secondary and higher education institutions. The Association for Educational Communication and Technology (AECT) defines educational technologies however as "*the study and ethical practice of facilitating learning and improving performance by creating, using, and managing appropriate technological processes and resources*" [JAN-13]. Appropriateness is described by AECT as the tool that is the simplest and most benign solution to a problem under technical, ethical, social and environmental consideration, while resources refer to hardware and software technologies and technological innovations that support learning [JAN-13].

Education technology is not restricted to the use of high technology [KOB-08]. Recognizing nonetheless the relevance that learners' interaction with digital, physical, and cyber-physical systems has on the development of modern engineering curricula, a special focus on these elements will be given throughout this dissertation.

3.4.2 Digital resources

With the introduction and popularization of the Internet in the last decades, accessibility of information has increased, exponentially leading to the enhancing of existent didactic models such as distance learning through the creation of brand new education domains englobed in what is popularly known as e-learning.

Finding a consensus-approved definition of e-learning is challenging due to the fast pace with which technology evolves [STE-11]. Arguably one of the most serious attempts to reach an agreement with regards to a unified definition was reported in [SAG-12]. According to the authors, e-learning can be defined as *"an approach to teaching and learning, representing all or part of the educational model applied, that is based on the use of electronic media and devices as tools for improving access to training, communication and interaction and that facilitates the adoption of new ways of understanding and developing learning"*.

The definition, obtained through a Delphi survey with global experts, attempts to emphasize four main characteristics of e-learning [SAG-12]:

- The quickly-changing nature of the uses of technology for teaching and learning purposes
- Its suitability not only for collaborative learning, but also for autonomous, individual learning
- Its potential to support formal and non-formal learning goals
- Its newness as a learning option

More recently, development in communication technologies have facilitated e-learning to be carried out through personal mobile devices in what has been defined mobile learning or "m-learning [GEO-04]. Techno-centric definitions of m-learning abound despite the arguments of some research circles in the sense that the term leads to misinterpretation and downplays traditional learning devices with intrinsic mobile characteristics such as books and Walkmans [RHE-02]; [SHA-06];[GUY-09]; [KNE-12].Some of the most cited m-learning definitions include:

> *"eLearning through mobile computational devices: Palms, Windows CE Machines, even your digital cell phone"* [QUI-00].
>
> *"Any sort of learning that happens when the learner is not at a fixed, predetermined location or learning that happens when the learner takes advantage of learning opportunities offered by mobile technologies"* [OMA-03].
>
> *"Any education provision where the sole or dominant technologies are handheld or palmtop devices"* [TRA-05].
>
> *"An ubiquitous learning activity occurring through person -to person communication using a mobile device which is supported by an appropriate mobile technology, user interface and a pedagogical approach*" [PET-07].

3.4.3 Physical resources

Physical educational technologies comprise analog tools, and mechatronic systems and components that contribute to the conveyance of knowledge in formal, non-formal, and informal education. Analog resources include traditional education devices, which preceded today's digital information resources such as VCRs, audio tapes, filmstrip projector, and radios, [JAN-13]. Meanwhile mechatronic systems are commonly used as educational technologies in technical fields of study such as engineering and sciences. Examples of these systems include robots, CNC machine tools, vehicle control systems, and simple process control systems. Most mechatronic single components have also own educational value. Components such as gears, motors, sensors, and circuits are usually presented as demonstrators in electrical and mechanical engineering courses.

Cyber-Physical Systems (CPS) are co-engineered interacting networks combining mechatronic systems with ICT such as Internet to enable improvement of capabilities, adaptability, scalability and usability of simple embedded technological systems [NSF-15]. CPS are gaining relevance in sectors including transportation, urban planning, product design, manufacturing, and electrical power generation and distribution. CPS are smart, networked systems, which include embedded components such as sensors and actuators that interact with the physical world, including people, and perform monitoring control and operational tasks [NRC-15]. CPS rapid pervasivity in primary consumption sectors is creating a high workforce demand, which cannot be covered through conventional education programs, due to missing links between study programs focusing on system thinking and those specializing in system interaction and control [NRC-15].

CPS are also gaining relevance in engineering educational arenas with so-called Cyber-Physical Laboratories (CPL) being developed as a means to enrich engineering students' instruction regardless of their physical location or faculty staff availability [GRU-11]. Classical examples of CPL are remote and virtual laboratories, which will be thoroughly described in section 3.5.4. In this regard, ontologies and design guidelines on remote experimentation have been issued by consortiums of leading education institutions such as the Global Online Lab Consortium (GOLC). GOLC's main objective is to achieve interoperability between platforms to allow exchange of content between physically disconnected laboratories [GRU-11].

3.4.4 Trends

With the consolidation of e-learning and m-learning methods in higher education applications, and the constant development of faster and smaller hardware and software processing units, researchers constantly debate about upcoming educational technologies benefits and their implementation potentials for formal and non-formal learning. Recent education paradigms such as "Smart education" and "Open education" have been paid a special attention by educational academic circles, who consider them paragon roadmaps towards global education [ZHU-16].

- **Smart education**: Smart education is defined as context-aware ubiquitous learning, which is centered in the learner but strongly dependent on smart technologies and environments [HWA-14]; [MID-15]. Zhu states that "*the essence of smart education is to create intelligent environments by using smart technologies*". Technologically speaking, education is supported by a so-called ambient intelligence (AmI). AmI encompasses hardware and software technologies that support people in executing their daily life activities by using intelligence and information from the network. These devices base their functionality in the interaction and communication independently without coordination with people and making decisions based on variable factors, including users' preferences and learning habits [ZHU-16].

- **Open Education**: Open education is a term used to describe institutional practices to communalize knowledge commonly offered in education institutions. Most often, albeit not exclusively, open education is associated to the context of postsecondary or higher education [BON-14]. The principle of open education is based on the use of Internet as a deposit of didactic material such as courses, designs and experiments accessible to anyone regardless of her or his geographical location, personal or financial status, or ability to access conventional education institutions [BRE-14].

When it comes to educational technologies, the Horizon Report of the New Media Consortium (NMC) is an annual briefing presenting breakthrough emerging technologies likely to have an impact in modern didactics. The yearly international publication identifies since 2004, six important developments in education technology covering three adoption time horizons - one year or less, two to three years, and four to five years -. Since 2014, the publication also presents an analysis of the key trends accelerating the adoption of the aforementioned technologies in higher education institutions, and challenges faced by them during the incorporation phases.

The NMC divides education technologies in seven categories depicted in table 6 [NMC-16]. Not all of them are digital or device-centered as some resort to strategic approaches, however the classification is valuable as a comprehensive review of methodical and technological trends expected to support formal education in the upcoming years.

Table 6: Classification of education technologies according to NMC [NMC-16]

3D Video	Bibliometrics and citation technologies	Crowdsourcing	Affective computing
Drones	Cloud computing	Online identity	Electrovibration
Electronic publishing	Networked objects	Social networks	Flexible displays
Qualified self	Semantic applications		Machinelearning
Robotics	Syndication tools		Mesh networks
Telepresence			Mobile broadband
Wearable technology			Natural user interfaces
Digital strategies	**Learning technologies**	**Visualization technologies**	Near field communications
Bring-your-own-device (BYOD)	Digital badges	3D printing / rapid prototyping	Next generation batteries
Flipped classrooms	Learning analytics and adaptive learning	Augmented and virtual reality	Open hardware
Locationintelligence	Mobile learning	Visual data analysis	Spreech-to-speech translation
Makerspaces	Online learning	Volumetric displays	Virtual assistants
Preservation / conservation technologies	Virtual and remote laboratories		Wireless power
	Open licensing		

Whether because of their practical nature, their potential to support concrete learning theories, or their capability to simulate or convey real-life problematics, some of these technologies display relevant potentials for engineering education and are worth a short description:

- **Makerspaces**: Technological communities gathering artists, engineers, and technology enthusiasts in order to share ideas and give them physical form is often referred to as "makerspace" or "hackerspace" [LMC-14]. Most of the times, members' unleashed creativity is materialized through 3D printers, robotics, 3D applications, and miniaturized machine tools installed in centralized physical spaces. The objective of makerspaces is to encourage and facilitate higher order thinking and improve problem-solving competences of users and learners through design thinking methodologies [360-15]. Makerspaces have been credited with not only stimulating creativity and problem-solving mentalities in students of higher education institutions, but also with supporting the development of local communities' economies [TIE-15]. This has been facilitated through an increasing quality and productivity of the technological enablers and by the diversification in their application fields often supported by engineering education programs [BAE-15].

- **Massive Open Online Courses (MOOCs):** A MOOC is a course of study made available over the Internet without charge to a very large number of people [TRC-13]. Since 2008, MOOCs are being supported and developed by ivy-league universities in the U.S. including Stanford, Columbia, Brown, and Duke Universities, leading Higher Education Institutions (HEI) in Europe, and global conglomerates such as Google, which introduced its own MOOC building online tool in 2012 [PAP-12]. MOOCs' biggest asset is the global democratization of knowledge. Contrary to conventional education, MOOCs are not associated with tuition fees, degree credits or limitation of participants. On the other hand, the approach has its drawbacks, commonly pointed out by traditionalist academic circles stressing the challenges faced by instructors by validating the identity of learners during the grading phase, cheating during examinations, and the limited validity of accreditations [FID-14]. Most importantly, MOOCs are appropriate to convey theoretical knowledge but fairly limited when supporting the acquisition of technical competences and skills [SUL-15]. Moreover, the idea that MOOCs enable "free" education has been considered by some authors as a euphemism. Sultan and Al-Lail argue that "*this idea is based on a big assumption that anywhere and everywhere people are carrying computers with open access to unlimited Internet connectivity",* adding that the philanthropic approach ends up benefiting almost exclusively the "*aristocratic urban class*" [SUL-15].

- **Virtual and augmented reality**: Virtual reality describes *"computer-generated environments that simulate the physical presence of people and objects to generate realistic sensory experiences"* [NMC-16]. Augmented reality in turn is defined as a "*technology that merges information or images with video-streaming from a web cam with a result similar to virtual reality but using real-world images in real time"* [DU-08]; [CAS-10]. Both technologies allow the user to be immersed in a blended or full-virtual reality exposing him to controlled environments with a specific purpose. In terms of educational purposes, pilot implementation projects in leading universities have borne positive initial results in engineering and medicine programs [EDN-15]; [BET-15]. One of the biggest potentials of the technology is the creation of a global collaborative-network, in which two or more users share an environment to solve a common problem [JAO-16].

3.5 Engineering Education

Since its establishment as field of studies in the late 19th century, the engineering profession has continuously evolved in order to adapt to global framework conditions. The last major shift in engineering education occurs currently with large sectors of academic circles stressing the urgency of educate new generation of engineers to address sustainable living challenges from an interdisciplinary perspective and on a global basis. These authors emphasize the need to develop new programs to build students' technical, socio-cultural and managerial competences to tackle issues of modern societies such as environmental pollution, resource depletion, climate change, protection of biodiversity and fair socio-economic development of the global village [ASH-04]; [DES-07]; [JOE-10]; [SEL-11]; [BLE-13]; [JAW-13]; .

However, the challenge of modifying current engineering education paradigms goes beyond a simple modification of the curricula. Embedded in a globalization context, competences of higher education institutions have been lately contested through what has been called the "democratization" or "communalization" of knowledge [GLA-03]; [BAJ-06]. With virtually every piece of knowledge traditionally conveyed in classrooms being freely available in Internet, Tyggvason and Apelian argue that in the near future, higher education paradigms will focus less in the knowledge to be transmitted and more in the technological and methodological means through which it is conveyed [TRY-12].

> *"While teaching engineering students how the physical world works will remain at the core of engineering education for the foreseeable future, re-examining how we teach the fundamentals of engineering science to students is needed. (...) The engineer of the future is likely to learn Thermodynamics interacting with a computer program that adjusts to his / her learning styles and speed, provides constant feedback and assures mastery of every step, rather from a faculty member droning on (and on) in front of the class"* [TRY-12].

The same authors stress the fact that the profile of the engineers of the new century will have to combine technical skills ("knows everything" and "can do anything") with interpersonal and social competences ("collaborates" and "innovates"). Moreover, globalization will demand from them a broader perspective when it comes to the implementation of their skills on a global basis. This will require her or him to understand and manage intercultural differences, for instance [TRY-12].

This same globalization context will inherently press on the long run towards a homogenization of education paradigms on a global level. Developing and developed countries share a common responsibility to prevent Earth's environmental collapse and the complete depletion of its resources. Instruments to share and transfer knowledge under consideration of existing socio-politic and infrastructure preconditions are to be implemented in the short and medium term.

3.5.1 Curricula

The field of engineering has been defined and re-defined in many ways throughout the last century. Each change of focus or re-interpretation over time has had strong influences while setting global approaches and directions regarding engineering education, or in other words, over what is to be taught in engineering programs. In his century-long recount of engineering education, Cheville presents in [CHV-14] an overview of the evolution of the U.S. engineering education definition, which despite bearing the limitation of territorial scope, grants the reader a detailed synopsis on the expectations, competences and qualifications academic circles placed in the engineering profession over time. In this analysis, the evolution of engineering studies throughout time is made noticeable, from the Mann report (1918) establishing clear priorities in the fields of science and mechanic arts, to the “Engineer of 2020” report prioritizing global challenges and interdisciplinary work [MAN-18]; [NAE-04].

On an internationally broader perspective, national governments, international organizations, NGO’s, industry, academic circles and researchers, as well as engineering practitioners have published innumerable reports and literature endorsing the necessity of engineering to take a leading role in the development of technical and non-technical solutions that contribute to achieve global sustainability. In its report, “Science, Education for Responsible Citizenship” the European Commission (EC) addresses the societal changes required so that communities worldwide are better integrated in research and innovation processes resulting in a sustainable development. The report includes a series of objectives and recommendations for policymakers and educators to improve science and engineering education programs. Among the most relevant ones for sustainability purposes are [EC-15]:

- Science education should be an essential component of a learning continuum for all, from pre-school to active engaged citizenship.
- The quality of teaching, from induction through pre-service preparation and in-service professional development, should be enhanced to improve the depth and quality outcomes.
- Collaboration between formal, non-formal and informal education providers should be enhanced to ensure relevant engagement of all societal actors and increase uptake of science studies and science-based careers to improve employability and competitiveness.
- Emphasis should be placed on connecting innovation and science education strategies, at local, regional, national, and international levels, taking into account societal needs and global development.

UNESCO’s report “Engineering: Issues, Challenges, and Opportunities for Development” addresses the urgent need to incorporate technical, managerial and social content into the curricula of worldwide engineering programs targeting to, among other, reduce poverty, facilitate a sustainable development and hamper climate change.

> *“An incipient broadening of the traditional frontiers of engineering that encompass interactions with sociology, economics, political science and other social sciences and processes, with healthcare, and with the agricultural sciences, is beginning to enable engineers to play a more effective and integrated role in addressing these issues”* [UNE-10].

In 2016, UNESCO signed an agreement with the International Association for the Evaluation of Educational Achievement (IEA) to assess the degree of available education possibilities in the areas of Global Citizenship Education (GCED) and Education for Sustainable Development (ESD). The agreement intends to measure target 4.7 of the 2030 Sustainable Development Goals [UNE-16b], which concretely establishes:

> *“By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture’s contribution to sustainable development”* [NIN-16].

With respect to the field of manufacturing and energy generation, researchers have, since over a decade, acknowledged the need to modify education structures in higher education to address sustainability. Ashford introduced an interesting comparison between what he called "current strategy agendas" and "sustainable development agendas". According to him, the former focus on conventional engineering educational programs, stressing processes and systems improvement, as well as cost efficiency. On the other hand, sustainable development agendas stress the need to pursue disrupting innovation in order to reduce resource consumption and achieve full fossil energy independence [ASH-04]. Since then, available research and literature seem to center in the need of modify and adapt the academic content of engineering programs of higher education institutions to embrace a clear focus on sustainable development.

Independently of technological breakthroughs, approaches suggested by some authors center in the need to change the mindsets of engineers as a necessary mean to implement sustainability. Mankind needs to learn how to substitute non-renewable resources through renewable ones but only to the extent that permits their regeneration. In case non-renewable resources need to be utilized, their disposal in landfills after their end-of-life cycle needs to be avoided through the shift from an open loop, single-life cycle paradigm to a multiple-life cycle one [SEL-12]; [JAW-13]. Strategies such as implementation of 6R approaches - Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture -, as well as the material usage minimization through an approach of selling functionality instead of tangible materials, are just some examples of how the manufacturing industry can contribute towards a sustainable improvement of quality of life on a global basis and need to constitute the backbone of education programs in manufacturing [SEL-12]; [JAW-13].

Finally, the improvement of engineering education in developing countries as a means to achieve global sustainability has also been addressed by academics and international development agencies. In [SEL-11], the authors discuss the advantages of transnational knowledge transfer mechanisms to improve competences of international students in the area of sustainable engineering. The authors suggest a curriculum model emphasizing three competence domains in order to disseminate modern paradigms on sustainable manufacturing on a global scale namely technologic potentials, entrepreneurship, and production. Borri and Maffiioli consider "ethics and social responsibilities" and the incorporation of non-formal learning as key topics of engineering education in developing countries [BOR-07]. UNESCO's report "Shaping the Future we want: UN Decade of Education for Sustainable Development" stresses the need "*for further alignment of education and sustainable development sectors"* referring to the need incorporate sustainability content in early childhood education, as well as in technical and vocational education programs [BOK-14]. The development of curricula or curriculum-elements to introduce sustainability in higher education study programs, especially in developing countries, is also addressed by publications such as [SHE-05], [CHY-09] and [BLE-13].

3.5.2 Learning styles

Engineering education has been characterized in the last decades by steep enrollment decreases and higher attrition rates [BEC-10]; [DIM-11]; [CHU-12]; [CHE-13]. Felder claims that many engineering faculty members often consider this attrition positively as a means to hinder the "unqualified" to become engineers [FEL-05]. The authors refer however to a comprehensive study conducted by Seymour and Hewitt pointing out that the grade distribution of engineering students who finished their studies, did not substantially differ from those deciding to leave. In other words, those who left where as good students as those who stayed [SEY-97]. Felder also claims that improving learners' thinking and problem-solving skills depends to a great extent on the understanding of the student's native ability and prior knowledge of the topic, as well as the compatibility between her or his learning attributes and the teaching attributes of the instructor [FEL-05].

Concerning students' attributes, Felder and Silverman defined in [FEL-87] what is to date arguably the most published model to identify psychological student traits in engineering. In this publication, Silverman, an expert in educational psychology, and Felder, a chemical engineering professor at North Carolina State University, thoroughly describe psychological profiles commonly observed in engineering students as well as specific teaching approaches to reach them individually. According to the authors, a conceptual framework consisting of 32 different learning styles conforms a learning model that "*classifies students according to where they fit on a number of scales pertaining to the ways they receive and process information*". These learning styles are a result of the combination of learning / teaching "dimensions", shown in table 7, which in some cases are derivations of concepts adapted from previous education models, for instance the "psychological types" described by Jung in [JUN-21] and the experiential learning from Kolb [KOL-84].

Table 7: Dimensions of learning styles [FEl-87].

Phase	Prefered learning style	Characteristics
Perception	Sensory vs. intuitive	Hands-on approach Understanding of principles and innovation
Input	Visual vs. auditory	Perception through sight Understanding by hearing or saying
Organization	Inductive vs. deductive	Inference of principles Deduction of consequences
Processing	Active vs. reflective	Physical experimentation Analysis of theories
Understanding	Sequential vs. global	Structured approach Chaotic approach

The learning dimensions proposed by Felder and Silverman in 1987 consisted of five sets of opposite learning preferences and their corresponding suitable teaching styles. These dimensions are summarized below:

- Sensing vs. intuitive learners: Based in Jung's classification of sensing and intuition, learners are differentiated in "sensors" or "intuitors". Sensors are those who prefer data and a hands-on approach, they like to resolve problems in a standardized way and are comfortable with repetitive tasks. Intuitors on the other hand, opt for the understanding of principles and theories. They are mostly keen towards innovation and unresolved tasks.

- Visual vs. auditory learners: Visual learners are those who are capable of perceive and retain information through the sight. Movies, charts, and demonstrations are preferred information conveying means for this group. On contrary, auditory learners remember more of what they hear and say. For them, a conversation is more profitable in terms of the amount of information they can retain, as they are able to receive and process data from the counterpart but also contribute with own ideas, generating thus more complete and long-lasting memories.

- Inductive vs. deductive learners: Induction is a reasoning process in which an event is observed and the principles originating or otherwise unleashing it are studied to understand their principles. In turn, deduction refers to the mental process undergone while understanding or learning a principle in order to be able to predict its effects. Citing Felder (1987), "*in induction one infers principles, in deduction one deducts consequences*". An inductive student follows human's natural instinct to observe a phenomenon or an event and reason it towards its generalities. An example of inductive learner would be an observer noticing a charging cellphone connected exclusively to a photovoltaic panel. The observer would probably be able to infer the charging function of the module and would be keen to find out its working principles through experimentation. Deductive learning happens the opposite manner, meaning, phenomena is only understood if the set of laws and principles ruling it have been established and explained. In the previous example, a deductive learner would thus prefer to firstly learn and understand the theory of semiconductors and electricity in order to proceed with experimentation. The majority of conventional frontal teaching in higher education levels can be defined thus as suitable for deductive learners [FEL-87].

- Active vs. reflective learners: An active learner can be defined as the one feeling attracted towards physical experimentation in order to trigger the transformation of information into knowledge. Active learners are clearly less capable to profit from frontal lectures than from laboratory activities. Reflective learners on the other hand process the information in an introspective manner. They prefer to listen first and analyze later on their own, potentially leading therefore to a deficit in their teamwork competences.

- Sequential vs. global learners: Sequential learners follow a linear and structured approach to understand phenomena. They start with the basics and increase their knowledge in a field progressively. Global learners follow though, a more chaotic approach learning bits and pieces from a field often coming to solutions that they are not fully able to understand themselves.

In order to identify preferred learning styles in students, Felder and Soloman developed in 1997 an online 44-item questionnaire known as Index of Learning Styles (ILS) [FEL-97]. The ILS has been commonly utilized since then as a design tool for education technologies by deriving the learning styles of target audiences. Case studies have been documented in [GRA-07] and [KAS-12].

Inclusion of learning theories and styles in the planning of instruction has gained an extraordinary relevance in engineering education research cycles since the last decade. In 2006, the final report of the National Science Foundation-funded project "Conducting Rigorous Research in Engineering Education" (RREE) proposed a categorization of "rigor" when addressing engineering education research. According to this taxonomy, thoroughly described in [STV-07], the maximum rigor level:

- Begins with a research question, and not an assessment question. The latest deals with the “what” or “how much”, while research questions focus on the “why” or “how” is learning conducted.
- Links the research question to learning, pedagogical, or social theories. It interprets the results of the research in light of theory.
- Pays special attention to the design of the study and learning methods used.

This taxonomy has since then ignited a bitter debate between antagonistic groups of engineering education researchers divided in “theoreticians” or those prioritizing the introduction of theory approaches as a bedrock of educational development, and “practitioners” pursuing the improvement of methods and structures. Felder and Hadgraft present an interesting comparative review of both stances in [FEL-13].

3.5.3 Instructional Design Models in engineering

Technologic globalization featuring an advancing democratization of knowledge by means of economic and novel educational technologies increasingly require changes in traditional paradigms concerning engineering education design and delivery [FEL-11]. In recent years, a handful Instructional Design Models have been proposed to achieve these changes. In some cases, these proposals have been adaptions of conventional IDMs to address specific engineering needs.

- **IEEE Reference Guide for Instructional Design:** based on the Dick and Carey model this linear methodology adapted by the Institute of Electrical and Electronics Engineers (IEEE) proposes a step-by-step approach to design objectives-based instruction [IEE-16]. Design stages according to this method comprise:

    - Assessment of instructional needs: Instructional goals to be conveyed and their relation to the intended audience are analyzed in order to determine the scope of instruction.

    - Analysis of learners: The method stresses the importance of gathering information concerning cognitive, psychosocial and physiological characteristics of the target audience. Cultural differences are to be acknowledged during the planning phases to support posterior development of adequate instruction material.

    - Writing of learning objectives: Deemed as “one of the most critical tasks” in the planning phase, the development of “clear, honest, complete and correct” learning objectives play a relevant role in the method. Learning objectives in this case are classified in skills, knowledge and tasks.

    - Selection of instructional strategies: The method refers to the need of testing “learners’ knowledge” through instructional strategies that depend on the instructional goal and content. The term “instructional strategy”, kept rather ambiguous in this case, hints no direct ties to pedagogic methods or theories.

    - Development of materials: Instructional material considered within the framework of this method include student and instructor manuals, instructional materials, as well as pre- and post-tests. Educational technologies are also considered as enablers of instruction, yet no selection criteria to fulfill their intended objectives is established.

- Evaluation of instruction: Audience data is collected in order to evaluate students' and course performance. Information gathering is conducted through traditional methods such as questionnaires and tables.

Due to its consideration of highly variable attributes of instruction such as diverse learners' audiences, as well as instructional strategies and materials, the IEEE's method is arguably one of the most holistic IDMs available in engineering education. The method is however also characterized by its superficial approach. Instructional strategies obey rather technical than pedagogical criteria, while no reference to criteria and methodologies to select or develop instructional materials are presented.

- **6E Learning Model:** An adaptation of BSCS' 5E Model (see section 3.3) was proposed in 2013 by Burke as a means to provide a "*student centered framework for instruction that leverages the T and E of STEM*" [BUK-14]. In his model, Burke adds an "engineer" phase as a means to describe design, modeling and development activities that an engineering student will conduct to materialize her or his ideas. Constraints concerning material and human resources are to be integrated as a means to capitalize on the hands-on interdisciplinary nature of engineering [KAT-09]. Burke also modifies the focus of each phase to adopt an engineering perspective describing each phase as follows [BUK-14]:

    - Engage: The objective of this phase is to stimulate the interest of a student in a given topic by getting her or him involved in the topic.

    - Explore: Students are given the opportunity to construct their understanding on a topic.

    - Explain: Students are provided the opportunity to explain what they learned so far.

    - Engineer: Students acquire a bigger insight in the topic by applying science and technological concepts to their own hypotheses and materializing results

    - Enrich: The purpose of this phase is to provide students with means to explore more in depth what they have learned so far.

    - Evaluate: Students and instructors are evaluated to determine how much learning has taken place.

- **Blended Project-Based Learning Creative Instructional Design Model (BPBLCID):** The BPBLCID is a Delphi method-based proposal that seeks to organize and structure creative instructional design indicators for blended project-based learning (PBL) in four dimensions: (I) creative character traits; (II) ability in the creative process; (III) innovative product design; and (IV) an instructional environment for creativity with a total of 23 design indicators [LOU-12]. Lou et al., creators of the BPBLCID model claim that blended learning environments integrated in PBL activities have a positive impact in learners' creativity development and performance [LOU-12]. This conclusion was drawn out of expert opinions, however, no validation of the model exists.

- **ASCE EXCEED Model:** As part of its Excellence in Civil Engineering Education initiative (EXCEED), the American Society of Civil Engineering (ASCE) derived an instructional strategy comprising eight sequential steps to support constructivist learning in engineering workshops. These steps thoroughly described in [EST-05] are:

    - Provide orientation: Before initiating instruction, the instructor communicates why the topic is of particular importance. This stimulates students as they perceive the value of what they are going to learn.
    - Provide learning objectives: The goals of the course will be communicated to the students. Higher layers of cognitive areas are to be targeted as a means to stimulate true synthesis-level thinking.
    - Provide information: Facts, information, methods, theories and terminology are conveyed to the learners as a bedrock to develop their further knowledge.
    - Stimulate critical thinking: By asking conceptually challenging questions, students are stimulated to critically review the information provided so far.
    - Provide models: Models are physical or conceptual examples of theoretical knowledge conveyed in the classroom.
    - Provide opportunities to apply knowledge: Students may think they understand a concept because they hear about it, however they don't truly know the concept until they apply it by themselves.
    - Assess performance and provide feedback: Learners are evaluated according to the degree in which learning objectives were reached. Formative assessment is provided to promote continuous improvement.
    - Provide opportunities for self-assessment: Peer evaluation among students is incentivized as a means develop objective critique skills.

- **Instructional Design Model for Blended Learning in Engineering Education:** The objective of this IDM is the design of strategies for the reproduction of "authentic contexts" for professionals following a six-dimensional methodology comprising: (I) The selection of authentic tasks that the experts can solve; (II) analysis of the context of solving the authentic task; (III) modelling of experts' cognitive and behavioral processes; (IV) development of assessment tools for the authentic task; (V) application of instructional strategies to provide authentic contexts by using technologies; and (VI) development of instructional resources and environments [PAR-15].

3.5.4 Laboratories

Educational technologies in engineering education can be roughly divided in two big segments. The first segment consists in computational multimedia to support understanding of abstract concepts in mostly a cognitive manner. Software such as Macromedia Flash, Director, Authorware, click2Learn Toolbox, MatLab, and Solidworks are a few examples of general and purpose specific IT tools common in most HEI. The knowledge in mathematical and conceptual models is however not enough to fulfill engineering's mission and contribution to achieve sustainable development [SIN-09]. The second segment answers therefore to the need of an engineer to manipulate materials, energy and information as a means to create societal benefit. To achieve this, engineers require physical contact to physical, chemical, mechanical, electrical electronic and IT laboratories [FEI-05]. However, despite the fact that most educators agree in recognizing these components as indispensable for the formation of technically competent specialists, a well-documented ill-integration of coherent learning objectives has limited their efficiency and hampered meaningful research in the area [FEI-05].

According to Feisel and Rosa, although laboratories have been a fundamental education component since the introduction of engineering as part of universities' curricula, there is still little consensus as for how to convey academic contents through them [FEI-05]. In other words, during the design of an instruction event, there is often little correspondence between content and didactic models' elements and the physical means to convey them. Feisel credits this to the fact that laboratory and hardware design represent a minuscule area in the engineering education research field, especially when compared to the development of curriculum and learning theories [FEI-05]. In this sense, the Accreditation Board for Engineering and Technology (ABET) convened in San Diego in 2002 has made one of the very few attempts to homogenize fundamental objectives of educational engineering laboratories. This set included thirteen points: instrumentation, generation of models, experimentation, data analysis, ability to design, ability to learn from failure, creativity, psychomotor development, safety awareness, communication, teamwork, ethics in the laboratory and sensory awareness [FEI-02]. A literature review conducted by Elawady and Tolba concluded that the ABET objectives can also be grouped in four educational goals depicted in table 8 [ELA-09].

Table 8: Educational goals for laboratory learning [ELA-09]

Lab Goals	Description	ABET goals
Conceptual Understanding	Laboratory support understanding and solution of problems related to topics covered in the classroom.	Illustrate science / engineering concepts and principles.
Design Skills	Laboratory supports students to solve open-ended problems through the design and construction of new artifacts or processes.	Ability to design and investigate. Also understand the nature of science.
Social skills	Laboratory supports to increase students productivity by working in teams.	Enhance social skills and other team behaviors, e.g. communication, problem solving, leadership.
Professional skills	Laboratory supports acquisition of technical skills that engineers are expected to have when practicing a profession.	Development of technical and procedural skills. Also the application of knowledge to practice.

Yet, globalization of knowledge has recently led researchers to integrate an accessibility dimension to laboratories' objectives as a means to enable collaborative environments among students and academics around the world [MAC-09]. In addition to conventional laboratories, Internet and other ICT educational technologies have embedded these facilities with ubiquity-similar features, which intend to increase the reach of laboratories' knowledge transfer potentials by enabling physically distanciated institutions to partake in the conduction and analysis of experiments in a remote or a simulated manner. Currently, there are two approaches to conduct online laboratories, namely virtual laboratories, aka simulation laboratories, and remote laboratories [BAL-09].

Remote labs are defined as internet platforms that allow users to carry out experiments online, which normally would only be conducted at physical laboratories [SEI-13]. These experiments use real components or instrumentation at a different location from where they are being controlled or conducted [CHE-10]. To be able to control and command an artifact at distance, the integration of additional software and hardware elements in the system such as drivers, video and databases servers, web servers and computer terminals is necessary [SAN-11]. Remote laboratories are characterized by a high flexibility in terms of time and space, which allow multiple users to sequentially conduct experiments regardless where they are located. A higher utilization is therefore achieved, which can lead to a shared investment, and thus reduce costs, in case of multi-entity participation [SEI-13]; [BAL-09]. The downside of the approach is the limited collaborative potential it offers, effectively limiting the number of users who can participate in the conduction of the experiment at the same time. Also, the interaction with the equipment is narrowly circumscribed to what can be seen and done through multimedia or computer interfaces. Finally, every educational organization develops its own solution so it is very difficult to reuse programming code [SAN-11].

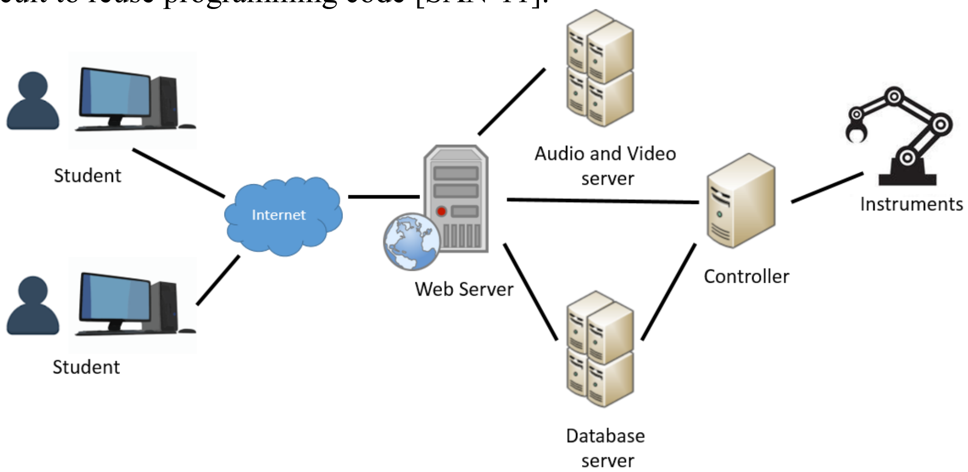


Figure 24: Architecture of standard remote labs [SAN-11].

On the other hand, virtual laboratories, aka simulation labs, are not linked to any physical hardware but virtualize real-life experiments by software means that intend to create a close-as-possible environment as the real scenario [SEI-13]. In this case, all results are idealized and there is no interaction at all with any laboratory equipment. Alternatively, simulation is a good mean to obtain similar data to real laboratories and therefore ideal if the costs of the infrastructure are too high. Virtual laboratories are also adequate to introduce visualization of concepts which are hard to explain. Finally, virtual laboratories share the time and place flexibility of remote labs but contrary to them, offline utilization is sometimes possible [NED-15]; [SEI-13].

Virtual and remote laboratories have been developed in the last years for a variety of disciplines mostly focusing on robotics, as well as mechanical and electronic engineering [NED-15]; [DAV-15]; [LEW-15]. The biggest challenge towards the further development and expansion of these approaches are issues concerning the incompatibility and the lack of standards when it comes to the implementation of software, followed by a lack of specialists in the area and the problems while digitalizing hardware components [SEI-13]. In this sense, the Global Online Lab Consortium (GOLC), a worldwide conglomerate of HEI including the Massachusetts Institute of Technology (MIT), the University of Stuttgart, and the Universidad Nacional de Educación a Distancia (UNED) among others, have lately striven to develop interoperable interfaces to improve communication protocols between remote laboratories [GOLC-16]. Some of these proposals and implementation examples have been reported in [TAW-12], [ORD-14] and [VOD-15].

Remote and virtual laboratories have advantages and disadvantages when compared to real laboratories (see table 9). Clearly, their biggest asset is their accessibility to higher education learners regardless their physical location. However, apart from the technical standardization challenges described above, these facilities are very limited when it comes to support instructional events following constructivist approaches, responsible to stimulate learners' higher cognitive processes. This is due to their narrow interaction possibilities between users, little flexibility and lack of contact with tangible devices [ORD-15]. More importantly due to their costs and technical prerequisites, remote and virtual laboratories are of very little benefit to learners without access to infrastructurally sound higher education possibilities [AZA-11]. Learners from underdeveloped world regions, are therefore excluded from potential instructional benefits of the approach.

Table 9: Comparison between laboratories types [NED-15].

Laboratory kind	Advantages	Disadvantages
Real - on-site (conventional)	• Hand-on approach allowing the user direct contact with real equipment • Realistic data • Collaborative work • Interaction with supervisor • Immediate feedback • Less dependent on software	• Time and place restrictions • Supervision required • Limited reach • High costs • Not accessible for non-higher education learners
Virtual	• No time or place restrictions enabling mobile learning • Capacity to manage large amounts of users at the same time • Allows information management through databases • High utilization potential • Lower costs in case of very expensive artifacts • Good to understand abstract concepts	• No interaction with real equipment • Idealized data • No collaboration between users • Limited amount of software available • Limited feedback • Hardware and software requirements make them inaccessible for learners un rural and urban informal communities
Remote	• No time or place restrictions enabling mobile learning • Capacity to manage large amounts of users • Realistic data • Allows information management through databases • High utilization potential	• No direct interaction with real equipment • Very high costs. However, these can be divided between several institutions. • No collaboration between users • Limited feedback • Highly dependent on quality of Internet connection • Conduction of experiments have to be queued and conducted sequentially • Complicated integration due to standardization issues • Not accessible for non-higher education learners

3.6 Socio economic factors in developing countries' education

Deficits concerning human and infrastructural education resources in developing countries have been described throughout this dissertation (see sections 2.1.5, 2.2.3 and 2.3). However, in order to understand better the root causes of these conditions, a deeper analysis with regard to the socioeconomic conditions framing education in developing countries is required.

There are several economic indicators to monitor the relevance of education in national policies. Arguably, some of the most representative consider national public expenditure on education expressed as percentage of a nation's GDP, or expressed in terms of public expenditure per student in U.S. Dollars (USD). However, while expenditure based in GDP percentage is a good rough indicator of the priority education occupies within the strategic development of a country, it is misleading when it comes to assess the real benefit experienced by the end beneficiary, or in this case the learner, because GDP represents an absolute value of a relative variable, which is dependent of the country's surrounding economic system. Indicators resorting to expenditures in terms of invested USD per student on the other hand, provide a stronger comparison base among nations in terms of average educational budget invested in education institutions. A comparative example: According to the UNESCO, in 2010 Cuba and the U.S. respectively spent 12.84 % and 5.42 % of their GPDs in education, figures that nonetheless ended up representing an expenditure of 2.971 USD and 11.450 USD per secondary student respectively [UNE-15a].

Another important indicator to assess education in developing countries is the determination of who is accessing education and for how long. The German ministry for Education Cooperation and Development reports that worldwide in 2014, some 57 million children of primary school age do not attend school. More than half of these children live in sub-Saharan Africa, and more than 20 per cent in South and West Asia. Fifty-four per cent of the children who do not attend school are girls [BMZ-14]. Achievement of tertiary education per country is also a relevant indicator of value creation and innovation potentials of a country. In this ranking, a study conducted by the OECD revealed that an average of 45 % of the population of developed countries are expected to graduate from tertiary education. Developing countries members of the organization reported however a mere 18 % in average [OECD-15].

These indicators are clear. In order to achieve a significant impact in developing economies, non-formal and informal education targeting non-academic audiences play a decisive role while aiming to encourage the introduction of sustainable practices in these economies. Non-formal education in form of on-the-field workshops for members of underdevelopment rural and informal urban settlements has been reported as efficient to generate sustainable value in these communities [UNE-10]. Out of the analysis conducted in sections 3.4.4 and 3.5.4, it can be concluded that current distance education approaches based in e-learning methods, e.g. MOOCs and remote or virtual laboratories represent undoubtedly a step forward towards the global democratization of knowledge. However, these approaches exhibit serious shortcomings especially when it comes to facilitate the appropriation of technical competences required by community members in underdeveloped world's regions to generate socio-economic wealth within environmental limits. Improved methods and technologies are therefore required to achieve this objective.

4 Research gap

Global sustainability roadmaps such as UN's Sustainable Development Goals recognize the importance of improving education as a means to accomplish strategic goals aimed to enable a more equalitarian socio-economic development among nations. Engineering education in particular plays a fundamental role given the impact of engineering activities in the development and implementation of technological and methodological solutions aimed to improve global societies' quality of life with minimum environmental repercussions.

The review of the state-of-the-art of methods concerning the design and delivery of engineering education presented throughout chapter 3 however, concluded that current educational frameworks are very limited in their contribution to the achievement of global sustainability. The reasons are manifold.

For starters, current paradigms in engineering education center their learning objectives in the technological and cost-efficiency improvement of processes and systems. Their approach is mostly techno-centric minimizing external socio-cultural and environmental aspects. Section 3.5.1 reported how sustainability concerns have lately originated a review on these paradigms claiming for the need to pursue the development and implementation of disruptive technologies that generate value while taking into account environmental frameworks and societal needs. However, the dissemination of these paradigms, especially in developing countries is challenging. Despite some advances, UNESCO reports that introducing sustainability content in engineering education on a global level requires a closer alignment and coherence across education and relevant sustainability actors on a national level, and the development of better knowledge, research and educational technologies [BOK-14]. The report stresses the need to improve and implement technological means to facilitate the access of high-quality engineering education to large sectors of developing countries' populations living in impoverished rural and non-formal urban communities. These sectors are characterized by unstable economies based mainly in primary economic activities, the lack of local competitive markets and poor public investment in educational infrastructure.

And yet, in order to adapt education to the local, regional and national needs, engineering education needs to develop a better understanding on how engineering is learned. Previous attempts to structure engineering education have often followed an ad-hoc path without a systematic understanding how learners' cognitive processes work and without the development of a body of knowledge to build upon [JOH-11]. Learning research conducted by psychologists, sociologists, and engineers has been in the past systematically shunned by a significant number of engineering educators, who in most occasions are accomplished disciplinary experts, but lack pedagogic fundamentals required to understand human's cognitive processes [JOH-14]. In the last decade, some attempts have been done to conceptualize engineering education under pedagogic frameworks. So-called engineering education Instructional Design Models (IDMs) have been proposed as higher abstraction methodologies in which specific pedagogic approaches are used to convey engineering contents (see section 3.5.3). Most of these IDMs however, are either too abstract and lack a systematic approach, or address very specific type of audiences consisting almost exclusively of higher education learners. Approaches towards the integration of appropriate educational technologies according to selected didactic models were not found in the IDM literature, which represents a significant gap for engineering education instructional designers requiring the implementation of technologies to support the accomplishment of specific learning objectives.

The gap is relevant as the integration of educational technologies are to be considered as fundamental in the achievement of sustainability goals. Engineering's contribution to sustainability is based in the correct implementation of technologies and methods to create value without exceeding environmental limitations. Building of engineering competences are mostly supported by laboratories. The advantages of laboratories as a means to enhance the competences of engineering students while manipulating materials, energy and information have been presented in sections 3.4 and 3.5.4 of this dissertation. However, as reported in 3.5.4, despite the acknowledged relevance of laboratories in engineering education, little consensus exists regarding the homogenization of laboratory design methods. Furthermore, up to date no validated framework exists that integrates relevant learning theories and styles as laboratories' design parameters. The result is a disassociation between cognitive processes intended to convey a given knowledge and the educational devices chosen as transfer enablers. In extreme cases technology is merely grafted onto existing teaching practices, so that the result is an instructional event that is technologically sophisticated but fundamentally conventional [RAP-03]; [JAR-13].

Finally, new educational trends are characterized by an almost frenetic mission to implement ICTs to accomplish global communalization of knowledge. Recent educational methods and technologies such as MOOCs, virtual and remote laboratories, presented in sections 3.4.4 and 3.5.4 respectively, have been gaining significant relevance in academic and public sectors due to their potential to materialize remote, ubiquitous and in some cases, free education. The same sections however, acknowledge the shortcomings of these approaches while providing high-quality education, characterized among others by laboratories' access, in underdeveloped regions of developing countries. Alternative forms of instruction are therefore necessary to convey engineering education to learners in these regions. An option could be the development of portable laboratories based on latest developments in educational technologies as a means to facilitate the integration of local communities as links in local or regional value creation chains.

In this sense, one of the biggest challenges for developing countries is the leverage of the social costs of education through the generation of local value chains able to rapidly transform knowledge into socio-economic profit. Therefore, the inclusion of non-formal and informal approaches in IDMs is of primordial importance when targeting underdeveloped rural and informal urban regions in developing countries.

Based on the previous analysis, it can be concluded that technological and methodological approaches to design formal and non-formal instructional events are required to enhance the contribution of engineering education as sustainability enabler. Instructional Design Models that support engineering educators to plan and deliver high quality instruction are necessary. Some of these IDMs exist and were analyzed in section 3.5.3. However, none of them offer a coherent and systematic method to align learning objectives with appropriate learning methods, and supporting educational technologies, or laboratories. IDMs such as the 6E learning and the ASCE EXCEED models constitute rather abstract formulations of walkthroughs to design a course based on sequential steps subject to subjective interpretation. On the other hand, IDMs such as BPBLCID or the IDM for Blended Learning in Engineering Education suggest a more structured methodology, which however exhibits exclusively constructivist characteristics per nature making their implementation in lower educational stages unsuitable. Moreover, none of IDMs found during the conduction of research offer insights concerning the integration of educational technologies in their methodologies.

This dissertation aims to fill this gap by proposing an instructional design model for engineering education which:

- Establishes learning objectives relevant to the field of knowledge and in accordance to the learners' socio-academic background. This is to be achieved by placing a special consideration on educational attributes of global target audiences, which are neither heterogeneous nor absolute per nature. Social, economic, cultural, and infrastructural frameworks of implementation will be considered as fundamental design parameters during the planning phases of instruction. The model will be adaptable to the needs of audiences comprising students of most layers in formal education, i.e. primary, secondary and tertiary levels of education, and non-formal education groups, e.g. instruction for rural community members.

- Involves a comprehensive understanding of pedagogic learning theories, styles and methods, which offer a profound insight of how humans' cognitive processes take place. Following Rigorous Research in Engineering Education (RREE) standards addressed in section 3.5.2, the proposed model will stress the need to integrate theoretic pedagogical frameworks into the instructional design process as a means to establish objectives and interpret results pertaining the instructional event conducted.

- Introduces a methodological approach to design educational technologies and laboratories according to particular learning objectives of instructional events with a sustainability focus. Dimensions such as instruction's content, target audience, and pedagogic approaches will be fundamental in the design methodology of educational technologies and laboratories aimed to improve the quality of engineering education and to support value generation in infrastructurally underdeveloped areas.

A special focus will be put in proposing approaches to improve engineering education in developing countries. The fields of manufacturing and renewable energy generation have been chosen as validation areas of the model due to their sustainability potentials thoroughly described in sections 2.1 and 2.2 of this study. An alternative approach to facilitate on-site high-quality engineering instruction in impoverished rural and urban informal communities in developing countries will also be introduced. The approach consists in the miniaturization and modularization of mobile, high-end laboratories to enable high-quality engineering instruction even in infrastructurally underdeveloped regions. The presented approach is based in the design of affordable mobile laboratories consistent of globally available educational technologies facilitating thus local reproducibility and further development. The proposed alternative seeks to overcome the shortcomings of ICT-based distance education methods and traditional partnership models presented in sections 3.4.4, 3.4.5 and 2.3 respectively, which concluded that existent approaches are often either too cost intensive or have a marginal impact targeting almost exclusively elite minorities at a higher education level.

5 Concept

The focus of the present dissertation lies in the development of an Instructional Design Model for Engineering Education (henceforth IDMEE). The proposed model aims to contribute to accomplish global sustainability by providing engineering educators with a guideline to design and deliver high-quality, audience-specific instruction. For this purpose and based on engineering's technical focus, following design aspects were considered essential:

- IDMEE is based on the premise that quality education in the field of engineering relies primarily in the capacity of instruction planners to align didactic principles and educational technologies to achieve the instructional event's learning objectives, determined in turn by the content of instruction and the target audience to be addressed. IMDEE's design focus relied therefore in elaborating a systematic method to determine how to elaborate and categorize learning objectives, how to determine the suitable didactic approaches to achieve them, and finally how to select or develop education technologies to support the instruction process.
- Four dimensions were therefore established as elements of design to take into account while planning and developing an instructional event, namely its "what". "who", "how" and "by which means", corresponding to content, target audience, didactic principles to be followed and required educational technologies respectively. A hierarchical sequence in which "what" and "who" determine the basic learning objectives of the course was chosen. "How" and "by "which means" are dependent elements to be aligned to the objectives by the designer. Tools and methods to secure this alignment were to be provided by IDMEE.

The present chapter will describe in detail IDMEE structure and its constituent elements.

5.1 Instructional Design Model for Engineering Education (IDMEE)

As previously states, IDMEE suggests a sequential methodology for the design of instructional events comprising four educational dimensions:

- **What:** Refers to the content of instruction. It determines general and specific topics to be addressed during the instructional event.
- **Who:** Determines the target audience including its social, economic, infrastructural, and cultural context.
- **How:** Encompasses appropriate learning theories, and didactic models in which instruction is based to convey knowledge.
- **By which means:** Comprises educational technologies constituted by physical artifacts and systems, as well as virtual applications suitable to support the selected didactic models and learning theories of instruction.

Grouped in design layers these dimensions will determine the intended learning objectives of an instructional event and establish appropriate didactic means and technologies to influence its learning outcomes.

Figure 25 introduces a graphical representation of the proposed IDMEE. Three main areas are depicted representing the dimensional configuration of elements determining the learning objectives, those with a direct influence on the learning outcomes, and a graphic representation of the ideal alignment between both, represented by the shadowed area "A". Partial alignment between objectives and outcomes, represented by the shadowed areas "B", will most likely affect the instructional event in different manners. An instructional event designed with disregard to the target audience will result in a "one-size-fits-all" event, alienating large population sectors with an important role in the achievement of global sustainability. On the other hand, an ill-definition of the event's content will lead to the conveyance of irrelevant or wrong knowledge to target audiences. Finally, a careless planning of didactic means and technologies will affect the quality results in terms of learning outcomes achieved by the learners. In this sense, the proposed IDMEE put a special emphasis in the compatibility of educational technologies (by which means) with respect to pedagogic methods and learning theories established during the determination of the "how". A systematic method to support decision-making processes concerning the selection of existing technologies or design of own solutions is included in the method.

Finally, as a way to contribute towards the accomplishment of global sustainability, the presented IDMEE has been proposed as an element to be integrated within national policies and priorities for the achievement of local sustainable development. By default, these policies have been considered to be framed by international sustainability targets established in global agreements such as UN's SDGs.

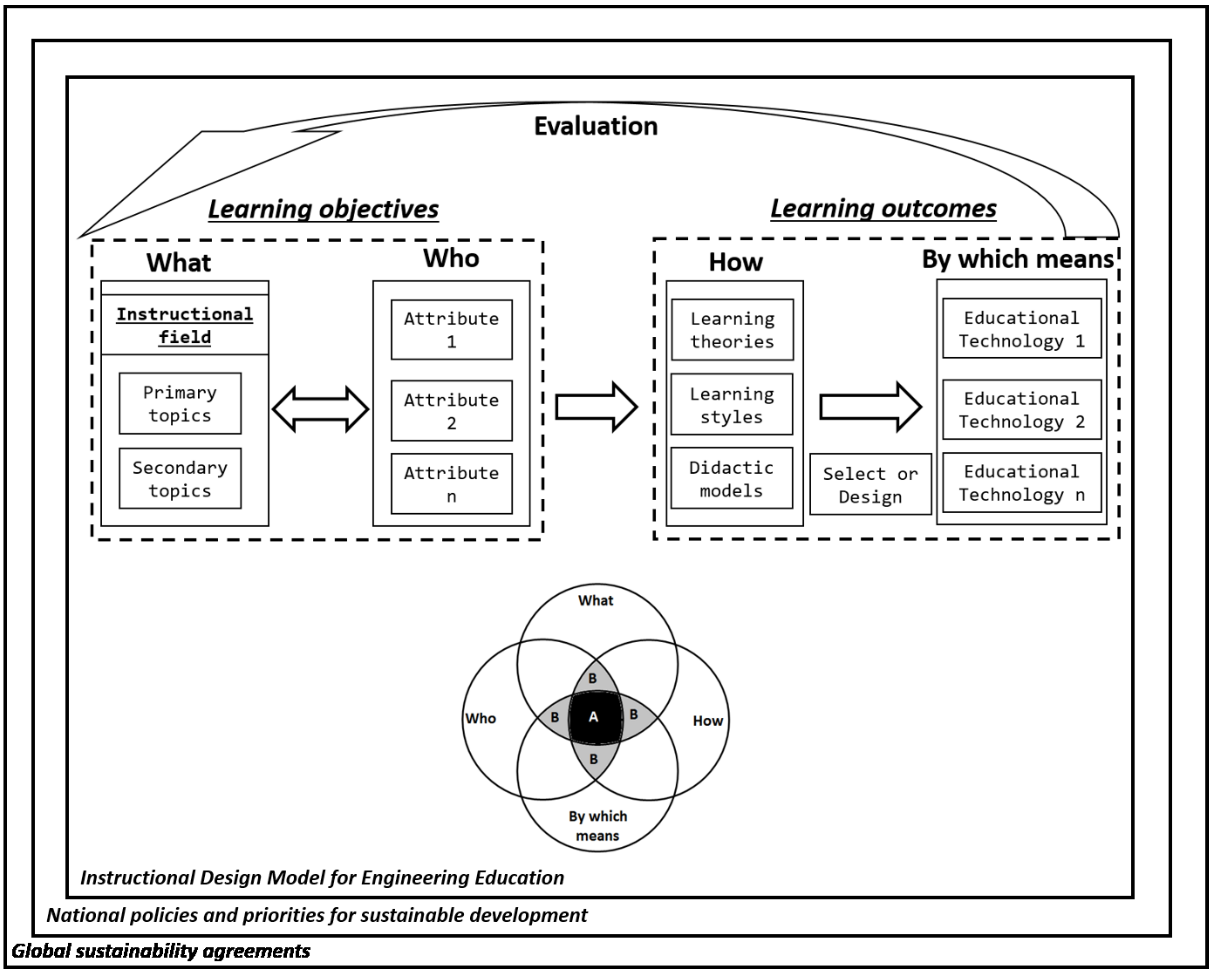


Figure 25: Instructional Design Model for Engineering Education (IDMEE)

5.1.1 Learning objectives.

One of IDMEE's pedagogical cornerstones is the determination of learning objectives. Given its importance, a comprehensive understanding of what exactly is a learning objective and how is it used in IDMEE is in order.

5.1.1.1 General definition

A learning objective is a statement of what learners are expected to be able to know or do when they have completed instruction. Learning objectives have three major components: (I) A description of what the learner will be able to know or do, (II) the conditions under which the learner will conduct a specific task, and (III) the criteria for evaluate student performance [ARR.98]. Learning objectives should be SMART - Specific, Measurable, Attainable for the target audience, Relevant for the study, and Time-bound - [ASM-15].

Roughly speaking, learning objectives can be reduced to the set of knowledge, skills, competences learners should be able to exhibit following instruction [TED-05]. Knowledge, skills and competences have been defined by the European Commission and its European Centre for the Development of Vocational Training (Cedefop) as follows:

- Knowledge: is the result of an interaction between intelligence, or the capacity to learn, and a situation, or opportunity to learn. Knowledge includes theory and concepts, as well as tacit knowledge gained as a result of the experience of performing certain tasks [CED-06].

- Skill: is usually used to refer to a level of performance, in the sense of accuracy and speed in performing particular tasks. Skilled performance has long been a subject of psychological studies, which consider both physical psychomotor abilities and mental cognitive abilities [CED-06].

- Competence: The proven ability to use knowledge, skills and personal, social and / or methodological abilities, in work or study situations and in professional and personal development [EC-08].

Most typologies consider knowledge as the basic element of cognitive structures of learning arguing that skills and competences require a certain degree of knowledge, however not every knowledge implies the acquisition of a specific skill or competence. Skills and competences are commonly related to a "capability to do something" and usually interchanged in the common language. The difference between both is that competences require a specific set of behaviors in order to carry out a skill under a specific context. A worker's skill can be determined by her or his mechanical ability of assemble a given work piece, yet she or he will be considered competent in the task only by demonstrating ability to consider and interact with the surrounding context, which could imply for instance, to check the existence of inventory, reviewing maintenance state of required tools, enforce and adapt safety regulations.

However, there is an entire industry devoted to classify learning objectives according to their degree of students' cognitive involvement and / or development [ASM-15]. Blooms taxonomy is regarded as the most common method to determine objectives in the curricula of primary, secondary and higher education institutions [KRA-02]. In his taxonomy, Bloom identified three domains of learning characterized by different levels of specification, namely cognitive, affective and psychomotor. The cognitive domain has been thoroughly studied and implemented throughout the last half century and is considered one of the most common models to understand the hierarchy of cognitive processes involved in an instructional event, or enhanced after it. Bloom's cognitive taxonomy is frequently represented by a six-element pyramid, depicted in figure 26, with categories ordered from simple to complex and concrete to abstract.

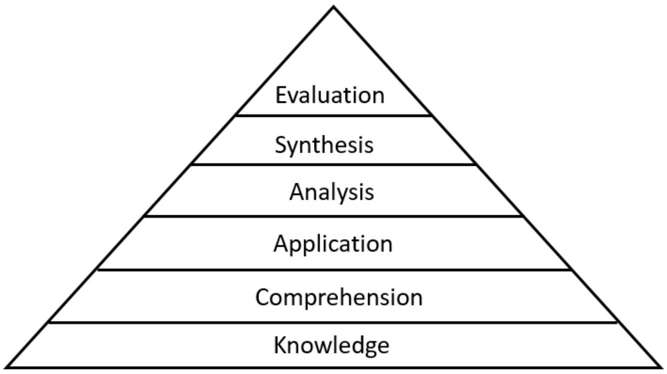


Figure 26: Original Bloom's cognitive taxonomy [BLO-56]

In his original hierarchy, Bloom considered knowledge of ways and means of dealing with specifics as the lowest element of a cognitive process [BLO-56]. Bloom reported in the sixties that up to 95 % of the test questions and tasks received by students of primary, secondary and higher education levels required them to think at the knowledge level, implying simple tasks such as the recall of information [IDC-12]. Knowledge was divided by Bloom in factual, conceptual and procedural. The second stage of Blooms taxonomy comprises the comprehension of what has been learned including the objectives, behaviors or responses, which represent an understanding of the literal message contained in a communication [BLO-56]. The application phase implies mental ability to decide which situation of life is intended to serve as application platform to whatever has been learned. The fourth level of the hierarchy refers to the analysis of information, which emphasizes the breakdown of material into its constituent parts and detection of their relationships [BLO-56]. The fifth stage, synthesis of knowledge, would allow a learner to combine knowledge and experiences from previous cognitive processes with the new acquired knowledge to form new cognitive schemes. Finally, the evaluation stage describes the ability of the learner to form own criteria regarding a specific topic allowing him to issue objective subjects and create new knowledge [BLO-56].

In 1990, a revision of Bloom's model conducted by his former students concluded with a series of modifications in the pyramid structure. In this revised version, presented in figure 27, three categories were renamed, the order of two was interchanged, and those category names retained were changed to verb form to fit the way they are used in objectives [KRA-02]. Arguably, the major modification was the inclusion of "*Creating*" as a cognitive level substituting the "*Synthesis*" layer. Create represents the ability of the learner to materialize knowledge in form of a specific product or service.

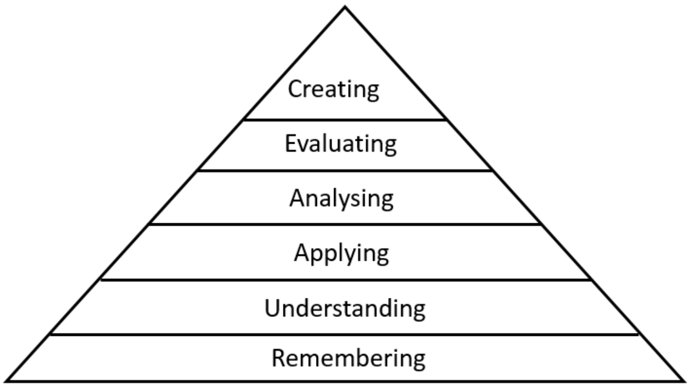


Figure 27: Revised Bloom's cognitive taxonomy [AND-00]

A series of verbs, best representing each one of the stages were also proposed and are introduced in table 10 [AND-00].

Table 10: Action verbs and objectives based on Bloom's taxonomy [FSU-16].

Level	Definition	Sample verbs	Sample objectives
Knowledge	Student recalls or recognize information, and principles in the form they are learned.	Arrange, define, describe, duplicate, identify, label, list, match, memorize, name, order, outline, recognize, relate, recall, repeat, reproduce, select, state.	By the end of the seminar, the student will be able to define the six levels of Blooms taxonomy of the cognitive domain.
Comprehension	Student translates, comprehends, or interprets information based on prior learning.	Explain, paraphrase, describe, illustrate, classify, convert, examples, identify, indicate, infer, locate, paraphrase, recognize, rewrite, review, select, summarize, translate.	By the end of the seminar, the student will be able to explain the purpose of Bloom's taxonomy of the cognitive domain.
Application	Student selects, transfers and uses data and principles to complete a problem or task with minimum direction.	Use, compute, solve, demonstrate, construct, apply, change, chose, discover, dramatize, employ, illustrate, manipulate, modify, operate, practice, prepare, produce, schedule, show, sketch, write.	By the end of the seminar, the student will be able to write an instructional objective for each level of Blooms taxonomy.
Analysis	Student distinguishes, classifies, and relates the assumptions, hypotheses, evidence, or structure of a statement or equation.	Analyze, categorize, compare, contrast, separate, apply, change, discover, choose, compute, , illustrate, interpret, predict, prepare, produce, relate, schedule.	By the end of the seminar, the student will be able to compare and contrast Bloom's taxonomy levels to other taxonomies.
Synthesis	Student originates, integrates, and combines ideas into a product, plan or proposal new to her or him.	Create, design, hypothesize, invent, develop, arrange, assemble, categorize, collect, combine, comply, compose, formulate, revise, rewrite, set up, summarize, synthesize.	By the end of the seminar, the student will be able to design a classification scheme for writing learning objectives that combines Bloom's to other taxonomies.
Evaluation	Student appraises, assesses, or critiques on a basis of specific standards and criteria.	Judge, recommend, critique, justify, appraise, argue, assess, attach, choose, compare, , describe, discriminate, estimate, evaluate, explain, relate, predict, rate, select, summarize, support, value.	By the end of the seminar, the student will be able to judge the effectiveness of writing objectives using Blooms taxonomy.

5.1.1.2 Integration in IDMEE

In the proposed model, learning objectives are determined by the content of instruction under consideration of the target audience, in other words, who should learn what. Both dimensions combined act as a vector with its direction determined by the topics to be taught and the magnitude represented by the depth of instruction, which in turn depends on the audience to be addressed. The sum of individual learning objectives' vectors establishes the orientation of the instructional event within a sustainability coordinate system and determines its focus, e.g. is it oriented towards technological solutions, or towards the teaching of local trainers (see figure 28).

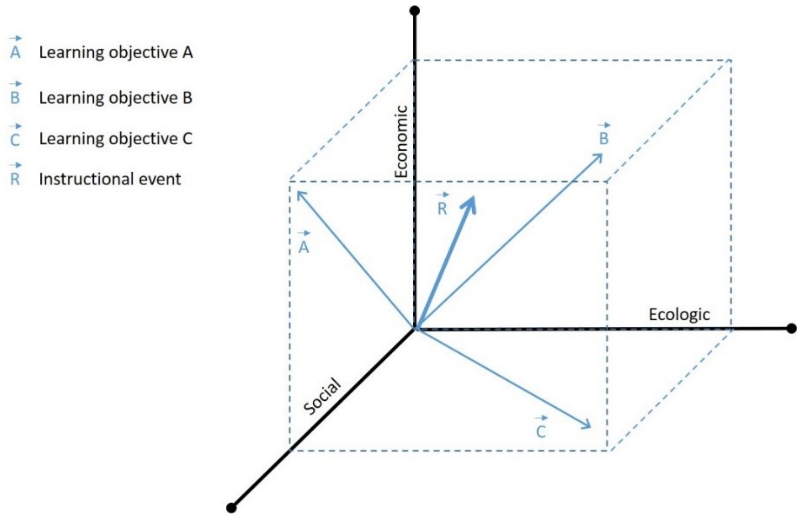


Figure 28: Learning objectives' vector field for sustainability

In IDMEE, learning objectives are categorized according to Bloom's cognitive taxonomy as a mean to correlate them in later stages to learning theories, learning styles, didactic methods and educational technologies best suit to support their achievement. The procedure on how to establish and categorize learning objectives in IDME will be introduced in section 5.1.2 "the what". However, it is important to establish that learning objectives in IDMEE are also important for another reason. In order to evaluate and continuously improve an instructional event, IDMEE proposes an iterative improvement cycle in which learning outcomes are evaluated according to the degree to which learning objectives were achieved.

5.1.1.3 Learning Outcomes

Learning objectives and outcomes are often mistakenly interchanged in the literature. Learning outcomes are however defined as measurable results attained by a learner and attributable to her / his participation in an instructional event [COL-03]. Contrary to learning objectives, which describe an intended state, learning outcomes expresses a present or observed state assessed under fairly objective conditions [DEP-16]. The assessment of these outputs at a program level has been a topic of international interest as a method for quality assessment and ongoing instructional enhancement [GOF-15]. The UNESCO, the Bologna Tuning Process, the Tuning Latin America Projects and Tuning USA have significatively contributed to initiate global discussions of how to interpret evaluation results as a means to improve education quality, transparency, as well as students employability [HAR-09]; [TRE-12]; [GOF-15]).

Multiple evaluation methods to assess the achievement of learning objectives exist. Some of the best known according to [ASU-10] are:

- Portfolio of work completed during program;
- Comprehensive examinations mostly conducted written or orally;
- Final and groups presentations;
- Exit interviews with students completing degrees;
- Success on national accreditation exams;
- Placement records of graduates;
- Survey of employers of students;
- Success of students continuing on in graduate programs;
- Continued scholarly success of graduates;
- Awards / grants received during and after the program;
- Independent research leading to work being published or presented at professional meetings;
- Theses, dissertations, and creative projects.

Evaluation of learning outcomes serves not only to assess students' success but also the success of instructional events and even programs. Evaluations conducted through survey or direct feedback is utilized as feedstock to better the course by means of iterative improvement cycles. [GOF-15] has proposed a four stage improvement cycle presented in figure 29.

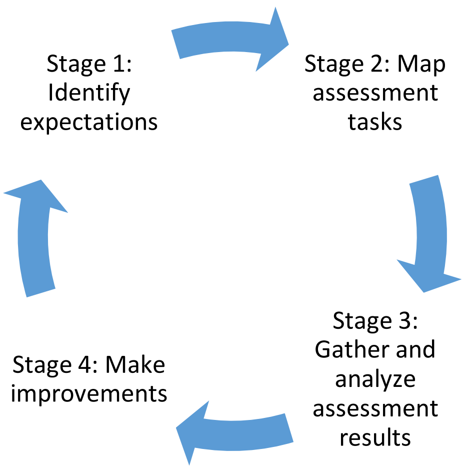


Figure 29: Goff's Four Stage Improvement Cycle [GOF-15]

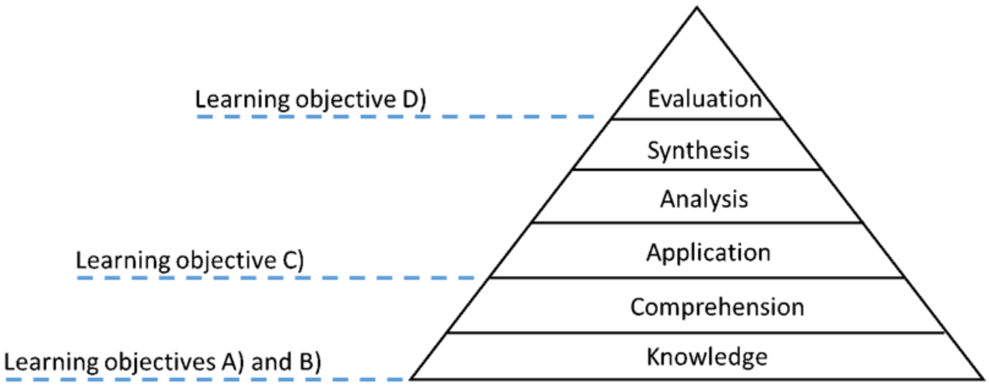
In Goff's improvement cycle, expectations in form of learning objectives are formulated clearly as a base for later evaluation stages. The mapping of assessment tasks describes in a visual manner the progressive evolution of knowledge, in other words when should what be learnt. Gathering and analyzing evaluation results consists in the methodological process to determine the extent to which students are meeting the learning objectives of the course, prioritize improvement areas, showcase the quality of education to relevant stakeholders, and document evidence for eventual accreditation purposes. Finally, gathered data is utilized to modify learning content, pedagogical means or technological enablers as a means to improve the results towards a better alignment to the learning objectives [GOF-15].

5.1.2 The "what"

As described in 5.1.1, in IDMEE, learning objectives are understood as educational vectors with its direction component determined by the dimension "what". "What" refers to the general and specific content to be addressed by the educator within an instructional event. Typically, instructional events hint automatically the general instructional field subject to be conveyed. This instructional field is specific enough to point the overall area of knowledge to be addressed and yet provides a minimum degree of specification regarding explicit topics to be delivered. This way, the general instruction field can be expected to be as ambiguous as “mathematics”, “electronic engineering”, or “physics”. In order to specify concrete learning objectives however, the instruction field is then broken down into specialization fields through iterations of the question “what exactly should be conveyed”. The depth of a “mathematics course” for instance, can this way be brought down to a “linear optimization” course derived from a broader “statistics” field.

Once the depth of instruction is determined, learning objectives are formulated in outlines and summaries of the topics to be covered during the instructional event commonly known as syllabi. As mentioned in section 5.1.1, learning objectives need to be SMART and be written in a way that they can be assessed. They also need to be independent from the learners’ initial knowledge stage, as not every participant has the same previous knowledge or abilities [ASH-04]. Learning objectives normally commence with an introductory sentence such as “By the end of the session / course / seminar / workshop, the learner will be able to…” followed by a verb determined by the type of cognitive domain influencing the type of knowledge, skill, competence or behavior expected to be acquired by the learner. Classification of these verbs based on Bloom’s taxonomy, as well as learning objectives examples were presented in table 10.

Categorization of learning objectives according to Blooms cognitive taxonomy is important as it will serve in later stages to determine which learning theories, learning styles or didactic models are better suited for their accomplishment. An example is provided in figure 30.



Learning objective	
A)	By the end of the course the student will be able to recall the three laws of thermodynamics
B)	By the end of the course the student will be able to recall the components of the most common concentrating solar power (CSP) technologies
C)	By the end of the course the student will be able to build low power CSP device.
D)	By the end of the course the student will be able to evaluate and audit solar thermal power plants

Figure 30: Example of IDMEE's categorization of learning objectives.

5.1.3 The “who”

The “who” responds to the need to analyze the instructional event’s target audience as well as its environmental context as a means to determine the magnitude of the event’s intended learning objectives. A target audience can be characterized according to the following attributes:

- **Demographics:** Demographic statistical data of the target audience plays a fundamental role in the design of instruction due to a number of reasons:

    - Age distribution of the audience has an impact on the didactic technological means and educational methods to be utilized during instruction. Younger audiences tend to be more visual and active than older ones, but have less experience to build new knowledge upon [NET-04]; [MCD-13].

    - Gender equality in education and employability has been prioritized in international agendas towards the achievement of global sustainability [UN-16]. Instructors perceptions of male- femaleness are crucial for their relations with pupils and can be an important factor in generating gender equity in schools [EC-09]. Additionally, female students have been found to place a higher value on corporate social responsibility exhibiting a higher value on ethical responsibilities [HAS-15].

    - Family’s income and socioeconomic status are good predictors of achievement due to the role of nutrition over attention paid in class, for instance [OKP-02].

    - Cultural dimensions of a society determine learning preferences on a national level. These dimensions include the observation of power distances to instructors; the learning individualism shown by students; masculinity of a society in terms of deeds’ recognition and material reward’s need; tendencies to avoid uncertainty; long term orientation for results; and indulgence to enjoy life as opposed to live by strict rules [HOF-11].

    - Nationality and ethnicity of the learners has implications on the language of instruction, their cultural background, political beliefs, and adaption to host education institutions in case the training event takes place outside the learner’s home country [RIE-11].

- **Academic background:** Apart from its obvious connotation in terms of latest academic degree obtained, educational background comprises also an understanding on common local instructional methods and models throughout entire educational systems, which differ from country to country. It has been suggested for instance, that East Asian education in Mathematics is oriented towards algorithm and application understanding, whereas traditional Western education in the field tends towards a deductive reasoning approach where application is less relevant [LEU-06].

- **Professional experience:** When it comes to adult extended vocational training, a further attribute considers also previous professional experience and hierarchy level of the event participants. Operative staff is commonly familiar with technical training and methods of instruction, while instruction for managers and decision-makers typically involves development of methodological and strategies-development competences.

- **Prior knowledge / experience in the instruction field:** Mostly consistent of knowledge relevant to the field of instruction, which has been previously gained by the learners through either non-formal or informal education. Previous knowledge in the field of instruction offers enhanced interactivity potentials as audience members with an advanced previous knowledge in the topic could act as assistant subject-matter experts [BRN-15]; [LAN-16].

- **Group characteristics:** The size of the group is determinant to establish a training method, as smaller groups facilitate a closer and more personalized contact with the instructor. From a socio-economic viewpoint however, larger groups save resources, most notably time and costs of instruction [EHR-01]. Another important factor is how homogeneous or heterogeneous is the group conforming the audience. Decades-long debates center in the advantages and disadvantages of each configuration. Heterogeneous groups characterized by an unequal academic performance or demographic traits, can serve as platforms in which team members benefit from the strengths of colleague students, whereas homogeneous groups provide the instructor to efficiently target needs of the group and focus on them [HEA-14]. In a globalized context, an educational challenge for the educator arises when the audience of an instructional event is composed of two or more distinguishable demographic groups, a situation which is commonly experienced in international study programs of developed countries.

- **Motivation:** Without engagement, learners are no more than observers. Motivation can be intrinsic when it comes from within the individual and extrinsic when incentives need to be provided to engage in an action that may not be inherently pleasing [STI-14]. Understanding the motivation of the learners in paramount while deciding on learning methods and means to be implemented because it helps to align course contents to the audience motivation, which produces higher quality outcomes and longer retention times. When rewards are to be used, these can also be aligned to motivation triggers of the audience, e.g. grades, economic incentives, and social recognition [ZIC-11].

Another important factor to be taken into account has to do with the learning environment in which the course will take place as it will help to determine the required physical and technical infrastructure to be available at the place of instruction. The latest aspect gains relevance while designing courses with high technical requirements common in engineering and science fields. It is also relevant for distance education approaches in which minimum technical requirements for software applications are commonly necessary [IEE-12]. Therefore, a thorough learner analysis should additionally consider following questions [BRN-15]; [LAN-16]:

- What is the approximate number of attendees and what is the exact location of the learning event? Are all learners concentrated in a classroom or are they geographically disperse?
- Will the cultural mix of learners have a specific effect in the training session?
- Are there participants with physical disabilities, who require special facilities?

5.1.4 The “how”

“How” is to be understood as the learning theories, styles, and didactic models to be implemented during the conduction of the instructional event in order to achieve the learning objectives established in the previous design stages. The proposed “how” deliberately decouples the pedagogic approach from virtual or physical educational technologies used during the instruction event, since the assumption that specific technologies are particularly linked to given learning currents or theories is utterly wrong. Instead, in this case “how” refers to documented conclusions of pedagogues, social psychologists, instructional designers, and engineering educators, who have reported that particular learning theories and styles are suited to achieve better results according to the course’s content to be taught and the previous stage of knowledge an audience has over it [DUF-92].

Behaviorism approaches for instance have been reported to suit learning in early or introductory stages and support accomplishment of learning objectives in the lower hierarchies of Blooms taxonomy (see figure 31). Behaviorism has been deemed therefore appropriate for the elaboration of courses in primary and secondary education levels and for training events for laymen or uneducated audiences [LEO-02]. A dissection of the traditional teaching approaches used for years would reveal the powerful influence that Behaviorists have had on learning. The concept of directed instruction, whereby a teacher is providing the knowledge to the students either directly or through the setup of "contingencies", is an excellent example of the Behaviorist model of learning. The use of exams to measure observable behavior of learning, and the use of rewards and punishments in national education systems are all further examples of the Behaviorist influence [FOR-98].

Cognitivism instruction strategies are needed when learning cannot be achieved through a series of sequential steps but rather through a recollection of memories, formulas, principles and rules mostly stored in the learner’s memory. Cognitivism supports the understanding and solution of mathematic algorithms depending on a set of variables for instance. Cognitive strategies enable learners to perform tasks that are complex but can be solved using information previously conveyed to him or her. Examples of didactic methods supporting this theory are conduction of reading comprehension, paraphrasing, simulation, calculation, and presentations [TUK-16]. In cognitivist events, the instructor fulfills a pivotal role, bridging the gap between the student and the content to be learned. This way, the educator provides base information on the topic to be learned and accompanies the learner throughout the learning process [TUK-16].

On the other hand, constructivist approaches have proven especially effective in intermediate and advanced education stages as a means to develop knowledge construction through context-driven evaluation [DUF-13]. Constructivism is appropriate when designing instruction events for adult audiences with existing skills relevant for the successful conclusion of the event, e.g. previous knowledge of energy concepts, CNC machine programming. Experiential learning events in turn are based upon previous learners’ experiences in the field of instruction and are therefore suitable for specialization programs. However, courses in higher education have been reported to apply experiential learning through an iterative constructivist approach in which knowledge constructed in an early course stage is utilized as experience feedstock in its advanced phases [REG-09]. Experiential learning has additionally been reported as an appropriate platform to link formal and non-formal education learners with communities and their needs [MA-16]; [CAN-97]. Paragon didactic models associated to constructivist and experiential learning approaches are the Project and Problem-Based Learning approaches, in which close-to-real life situations are portrayed and presented to the learners who will generate either a real or fictive solution to it.

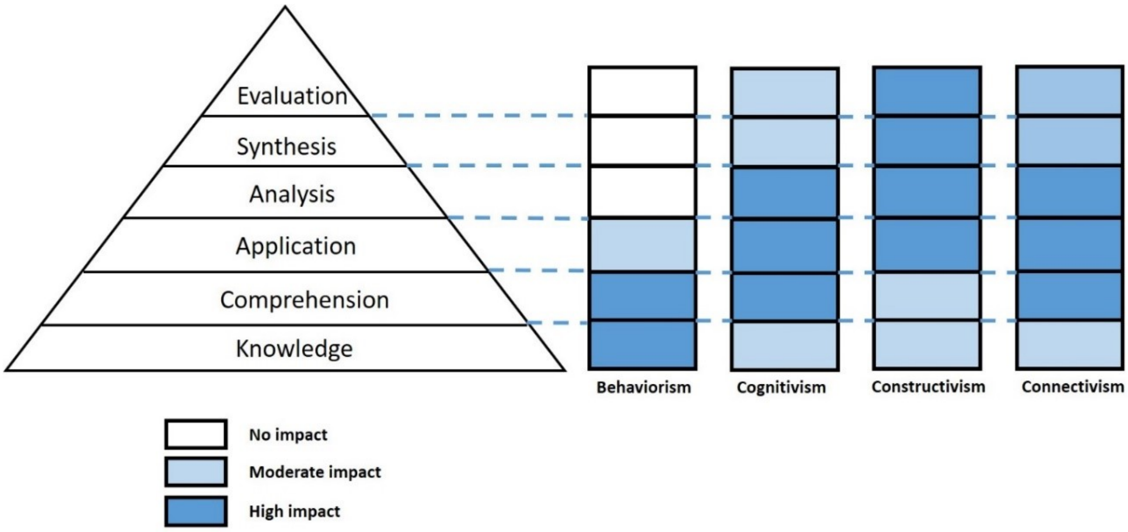


Figure 31: Learning theories according to learning objectives

Understanding the principles, advantages and limitations of each learning theory, considerably supports their implementation as a means to achieve specific learning objectives. A comparative list of theories' properties extracted from [ERT-93]; [JON-91]; [ALV-09]; [KEE-11]; [SCU-12]; [BEL-11] is summarized and presented in table 11 below.

Table 11: Properties' comparison between learning theories

Property	Behaviorism	Cognitivism	Constructivism	Experiential learning	Connectivism
How learning occurs	Through conditioning. A stimulus is provided to generate a response.	Knowledge is the interaction between individual and environment. Learners learn through receiving, storing, and processing information	Learners construct new ideas or concepts based upon their current / past knowledge, social interactions, and motivations.	Experience enrich existing knowledge. This can happen deliberately or not.	Through the influence of technology.
Influencing factors	Stimulus, response, consequences, reinforcement.	New information, existing schemes and memory	New situation, interpretation of experience, link with previous experiences.	Experiences, existing knowledge, enriching and modification of existing schemes	Social networks, technology, recognition of patterns in virtual environments
Role of educator	Educator designs the learning environment, establishes knowledge to be transmitted and molds the individuals	Instructor manages problem solving and structured search activities. Instructor fosters students	Educators act as mentors not as lecturers. Provide feedback as external observer.	When existent, the role of educators is limited to mentoring and feedback providers	Suggestion of technological sources. Feedback provider

	mindset through reinforcement.	to connect new information with schemas			
Suitable didactic models	Punish / reward activities, instructional cues to elicit correct responses, multiple opportunities, association of concepts.	Explanations, demonstrations, illustrative examples, mnemonics, analogies, summaries, metaphor, synthesis.	Problem based learning, project based learning, coaching, experimentation, learning by doing.	Problem based learning, project based learning, coaching, experimentation, learning by doing.	Multimedia, videos, chat, wikis, social networks.
Strengths	Clearly stated objectives that allow a learner to pursue a goal, feedback is clear and objective, appropriate for basic and intermediate stages of knowledge.	Cognitive theories are usually considered more appropriate for explaining complex forms of learning, e.g. reasoning, problem -solving	Learners learn through real-life situations where context is as important as content. Suitable for intermediate and advanced stages of learning	Enrichment of existing knowledge. Improvement of decision-making processes. Leads to innovation	Ubiquitous and immediate access to learning, democratization of learning. Self-paced learning
Weaknesses	Inadequate to explain the acquisition of high-level knowledge such as language development, problem solving, and critical thinking	Cognitivism is based in knowledge transferred, stored and recalled. Little support is provided for innovation and creativity	Unsuitable for introductory learning. In a situation where conformity is essential divergent thinking and action may cause problems	Experiences are personal and learning therefore subjective and variable. Unsuitable for introductory learning	Knowledge is easily corrupted leading to misinformation.

When it comes to engineering education, authors such as Felder and Silverman, insist in the importance of taking individual learners' traits and learning preferences into account, while developing instructional design models. Dimensions portrayed in the Felder-Silverman learning style model, described in section 3.5.2 have served as base to develop education programs and technologies specifically designed to address engineering students' characteristic profiles [GRA-07]. Analysis of these features are especially useful for the planning and design of online courses where the behavior of students can be qualitatively and quantitatively assessed, e.g. through direct feedback or parameters such online connection time [CHA-06]. Felder and Silverman suggest in [FEL-87] to identify the audience traits and find a balance concerning the didactic methods implemented to reach it accordingly. The authors advice to:

- Provide a balance of concrete information such as facts, data, real or hypothetical experiments and results, as well as abstract contents like principles, theories, and mathematical models.
- Balance material that emphasizes practical problem-solving with material that emphasizes fundamental understanding.

- Provide explicit illustrations of intuitive patterns such as logical inference, pattern recognition, generalization; and sensing patterns such as observation of surroundings, empirical experimentation attention to details.
- Use pictures, schematics graphs, and simple sketches for visual learners. Provide hands-on demonstrations if possible.
- Provide active learners the option of cooperating on homework assignments.

5.1.5 The “by which means”

In the suggested IDMEE, “by which means” refers to the educational technologies used during the conduction of an instructional event to facilitate or improve learning. The success in determining which educational technologies to implement during an instructional event is determined by the degree in which they are able to support the learning theories, styles and models chosen to convey knowledge to a particular audience.

Historically, educational technologies have been closely related to learning theories, learning styles and didactic models, and can, under certain circumstances, be associated to them. Behaviorism for instance, has seen Pressey’s and Skinner’s learning machines introduced in the 1930’s evolve into modern 21st century Computer-Aided Instruction (CAI). CAI is a computerized instruction consisting of small units of information followed by questions and a student response. A correct answer is rewarded, e.g. in a grading scale, while an incorrect one branches the learner to remedial sequence or submit him / her to an easier question [JAN-13].

Cognitivist technologies are based in audiovisual and multimedia means such as slide presentations, educational videos, and recordings very much in line with visual learning styles [JAN-13]. Researchers have suggested diverse categorizations to present information from a cognitive perspective such as representational, pictures that resemble the thing or idea pictured; analogical, showing known objects and implying similarity to new knowledge; and arbitrary, charts or diagrams that attempt to depict a concept but do not physically resemble it [ALE-84]; [CAY-02]. Cognitivists have also found support in multimedia software capable to transform abstract information into a visible result such as models or graphics. Simulation software for instance, allows learners to explore own hypotheses obtaining immediate response [JAN-13].

Constructivism in turn is best supported by activities in- and outside the classroom that focus in enhancing learners’ performance while solving complex and partially unpredictable problems that allow knowledge to be constructed rather than learned [JON-03]. In this sense, there is a vast array of technologies that would qualify as constructivist, but their classification depends on the use it is given during an instructional event [EBR-UK]. Nonetheless, current trends in constructivist learning tend to concentrate in technologies capable to allow the learner complete creative liberty. Constructivism didactic models such as project-based and problem-based learning, gamification, and flipped classrooms are commonly supported by project specific software, prototyping technologies such as 3D printing, creative environments such as makerspaces flexible laboratories, and tangible materials to be altered in their structure and composition by mean of external energetic input.

Finally, connectivism educational technologies are centered in the utilization of online media as a means to achieve decentralized, network-based pedagogy. Knowledge to be acquired is commonly open, free, ubiquitous and to be found or conducted through modern ICT such as Internet. E-learning, m-learning and further derivations of distance learning are educational technologies per excellence from a connectivist perspective with Massive Open Online Courses

(MOOCs) gaining popularity since almost a decade. In connectivism, the principles of quality educational design are based on the properties of networks that effectively respond to, and recognize, phenomena in the environment [DOW-16]. Education is therefore as good as the sources "broadcasting" it, which is at the same time connectivism's weak spot.

An adequate selection of education technologies is therefore of the utmost importance to achieve the learning objectives established by the planer during the design of an instructional event and constitutes therefore one of IDMEE's pillars. Selection of educational technologies in IDMEE responds not to fashion reasons but to a sequential procedure consisting in determining technology features according to individual learning objectives and the pedagogic strategies to achieve it. In this sense, the selection of adequate educational technologies in IDMEE builds up on decisions taken during the determination of the previous three dimensions. Figure 31 depicted the relationship between learning objectives of an instructional event, categorized according to Bloom's cognitive taxonomy, and learning theories most appropriate to reach the intended cognitive level. The figure established for instance that behavioristic approaches are better suited to convey lower knowledge in the first layers of Blooms pyramid, e.g. information that requires to be remembered without further analysis. In principle, if the planned instructional event would pursue a single learning objective, the selection of a proper educational technology could probably be considered straightforward and a behaviorist approach could be supported by modern CAI devices.

However, selection of educational technologies can be seldom conducted forthright. Firstly, in the real world an instructional event is most of the times constituted by a set of learning objectives, which are divergent from each other, either due to inherent nature, or simply because learning objectives in later stages of the event build upon previous ones. As a result, during the planning and conduction of an instructional event, it might happen that the achievement of different learning objectives requires implementation of different pedagogic approaches, i.e. different learning theories, or didactic models as depicted in figure 32.

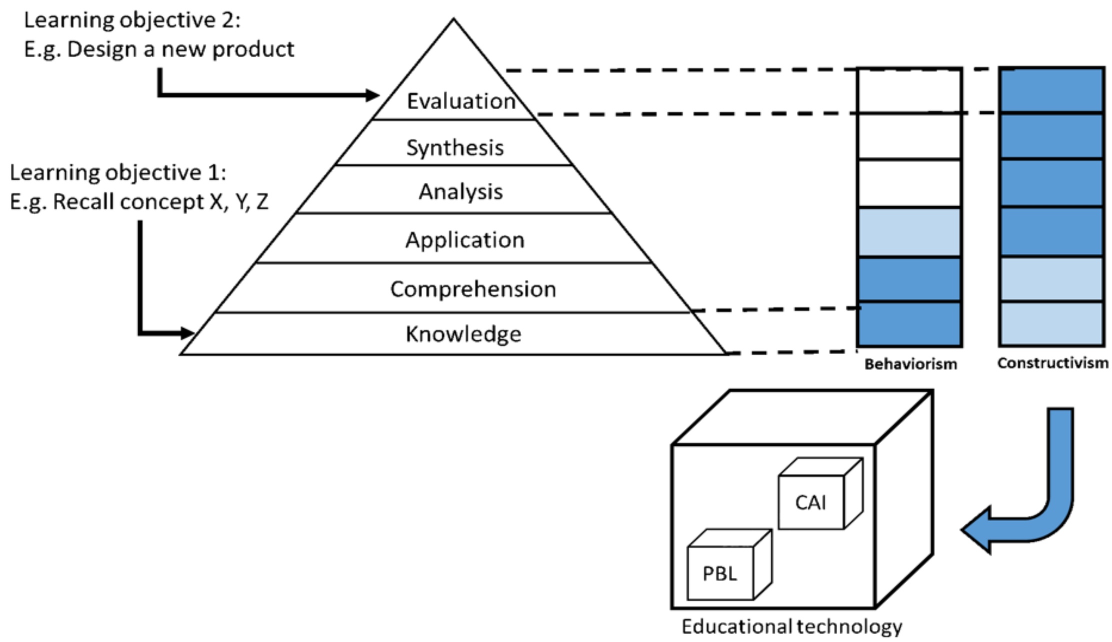


Figure 32: Determination of educational technology according to learning objectives and didactic principles

Also, as previously mentioned, in some cases the association of certain educational technologies to learning theories and didactic models is not pre-determined and depend on their implementation during the instructional event. In this sense, the same carpentry tools used in an instruction event with a constructivist connotation, e.g. design and build a house, are the same tools used during earlier stages of the same event to learn the principles of drilling in a behavioristic fashion. Moreover, ICT tools normally associated to cognitive approaches can be also used in a behavioristic manner. In this regard, researchers have documented the utilization of ICT based learning artifacts named “Learnstruments” to train factory workers during remanufacturing processes of alternators [POS-11]; [MCF-13]. The working principle of this “Learnstrument” consist in an assembly cell equipped with a 3D camera and image recognition- and processing software that provides instant feedback to the learner in case the process’ manual steps divert from pre-recorded standards [POS-11]. Furthermore, ICT-based learning such as e-learning and m-learning, has served all sort of learning theories approaches implemented in a vast field of knowledge fields [KOO-09]; [BAT-14]; [KER-15].

In IDMEE, the process of determining an adequate educational technology initiates with a select or design decision-making process described in the following sections.

5.1.5.1 About selecting or designing an educational technology

With a vast range of physical and virtual educational technologies to support instruction in an equally extensive range of pedagogic methods and learning theories, the instructor designer’s task to determine the most proper technology to fulfill his / her instructional objectives is undoubtedly challenging. This is especially true for instructional events that go beyond the utilization of conventional frontal teaching / presentation based learning methods. For the purposes of this dissertation, a methodological approach to support this decision-making process was developed and is depicted in figure 33 below.

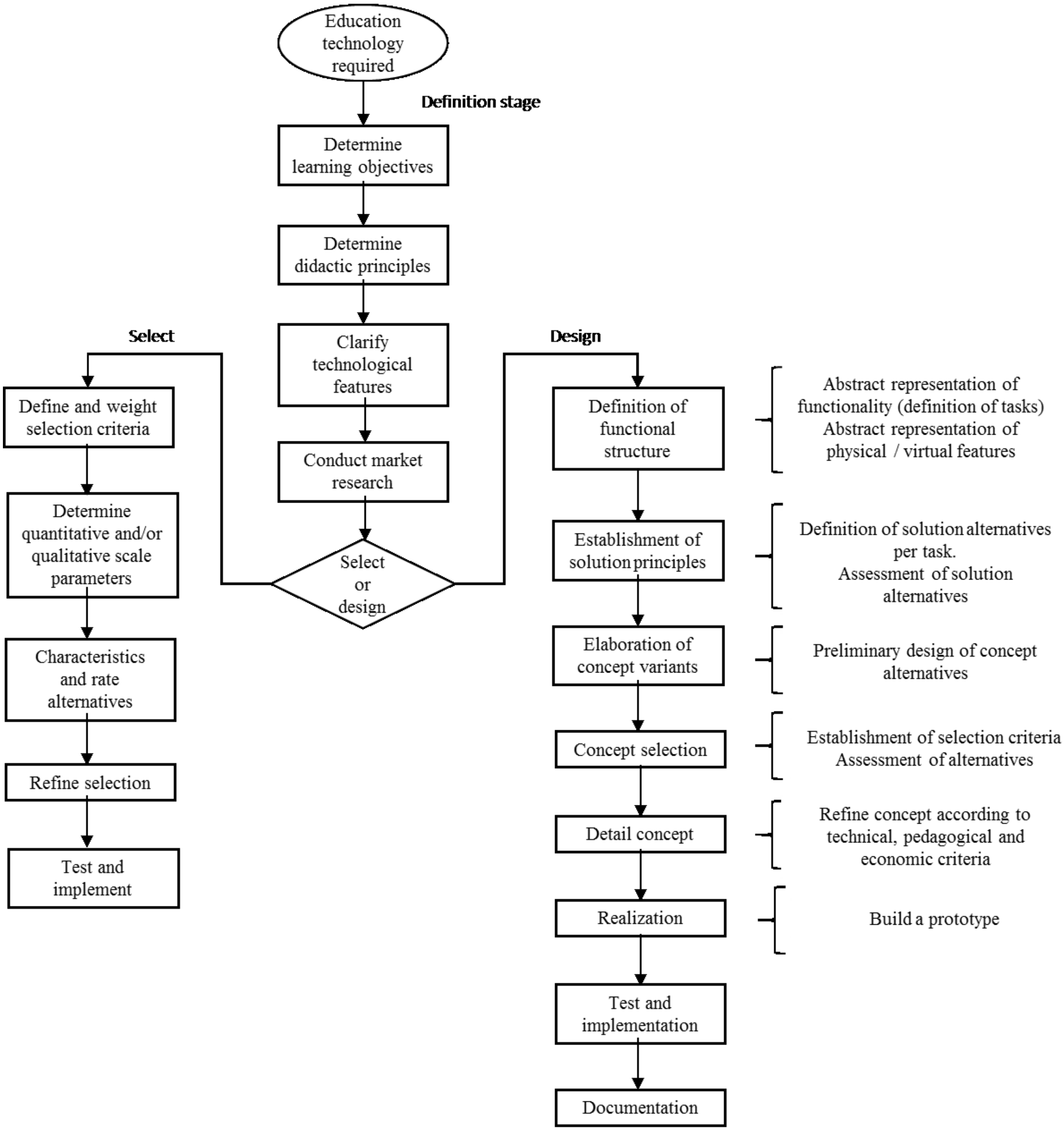


Figure 33: Select or Design decision-making process for educational technologies

In most of the cases, the first significant decision to be taken by the instructional planner concerns whether to select a commercially available technology and adapt it to the event's purposes, or design and develop own technological solutions. Advantages of selecting existing technologies are manifold [CAE-00]; [COH-14]; [GAL-13]. These include:

- Product variability and costs: Commercially available technologies, especially in a competitive market, are often offered in a wide range of product variants, which in most cases include economically affordable solutions.

- Saves time and effort: Selecting existing technologies can be lengthy process, especially when the product offer is large, which however is not comparable to the time and effort put by designing and developing new technological solutions.

- Does not rely in the planner's technical design competences: Despite the advantages of having a profound understanding of the technologies to be implemented, technical design and development competences on behalf the instruction planner are not mandatory.

- Proven technology: Commercially available technologies are in most of the cases subject to quality monitoring and certification from national and / or international consumer agencies that scrutinize their functionality.

- Offer technical support: In most of the cases, technology owners and retailers offer an array of services associated to the technological solution. Mandatory or extended guarantee, technical support, renting / leasing of equipment, regular maintenance and updates, are just but a few of examples.

- Standardized technologies: In many cases spare parts, components, protocols, and technology carriers themselves are standardized either by the industry branch of by national or international regulations. This facilitates maintenance and repair activities.

- Transferable technology: The technology is not bound to the planner and can therefore be easily transferred to further users or parties.

However, in some cases existing technologies do not fulfill the instruction requirements set by the planner, or their offer is extremely limited and consequently extremely costly. The alternative is then the design and development of own technological solutions, which might exhibit following advantages:

- Instructional planner as technology owner: Technological solutions can be improved, maintained, updated and repaired by the instructional planer. The instructional planner is also fully able to support the user during its operation or usage.
- Customized to the instructional event needs: In most of the cases, the developed solution is tailor-made to fulfill the pedagogic needs of an instructional event, facilitating thus a more effective knowledge transfer.
- Technological innovation. Development of technological solutions often involve innovation whether in the field of instruction or in the field of educational technologies. Spillover effects of technological innovation might benefit knowledge areas with similar needs.

The presented Select or Design method argues that decision regarding the selection of commercially existing devices or the development of own technological solutions is preceded by a definition stage comprising four common steps:

1) **Determination of learning objectives:** In most of the cases, the technology functionality is delimited by frameworks set by the content of instruction and the target audience. A math software can be programmed to fulfill instructional needs of specialized personnel being trained to solve complex algorithms in linear optimization, or to teach basic algebra and calculus for secondary education students.

2) **Determination of pedagogic methods and learning theories:** As previously established, education technologies are mostly neutral elements until their functionality is aligned to a specific learning theory or pedagogic model. Self-contained programs or software-pieces commonly known as Apps, could be used for instance to facilitate the knowledge transfer in higher education courses. The App's functionality would then depend on the pedagogic approach chosen by the instructional designer. A behaviorist approach would imply for instance a series of multiple-choice questions issued through the App launched during a classroom course. These questions would be relevant to the topic being discussed and the student would be encouraged to answer them through the App during the lecture. Correct answers could turn into extra credits for the final examination.

   A cognitivist approach in turn could use the App as carrier of a task that needs to be performed outside of the classroom. The approach would involve the application of knowledge and not its memorization. The App could be in this case turned into a sort of simulation tool through which the student is expected to solve a problem applying a specific method and considering starting parameters.

   Finally, an alternative constructivist approach could involve be the programming of an App itself without the need of attending a lecture. In this case the students could be asked to program a code to teach content of the specific field of study to younger students, e.g. secondary education students, being therefore forced to learn the content in order to effectively teach it. App developers would receive periodic feedback from lecturer to monitor their progress.

3) **Clarification of technological features:** Once the learning objectives and didactic approach is set, functional and / or physical characteristics, as well as implementation frameworks are to be determined. Functional characteristics are mostly inherent to the technology. In the previous example, Apps are software tools normally limited to simple functions, which however are economically accessible for students and allow ubiquitous learning. An alternative to these apps could be highly specialized, license-bound software usually found in on-campus laboratories, which in turn offer in most of the cases larger functionality in terms of analysis, presentation and processing features. Physical devises in turn are, among others, characterized by variables such as dimensions, weight, range of experiments or activities they are able to support, and modularity.

4) **Conduction of market research:** The final step before the select or design decision-making process involves a thorough analysis of the educational technologies market. The market analysis aims in the first instance to collect and analyze data concerning available devices that might fulfill the requirements specification conducted above. Information concerning economic characteristics, e.g. price tag, maintenance & operation costs, as well as service features, e.g. periodic updates, and technical support of the devices, are also of the utmost relevance.

   Once the decision regarding "select or design" has been made, the proposed method bifurcates into a select or design paths described below.

5.1.5.2 Select

When considering industrial settings, several methodologies for the selection of technological solutions exist. Houseman et al. presented in [HOU-04] a holistic technology selection method for the aviation industry based on the assessment of alternatives within a fuzzy environment. Shehabuddeen, Probert and Phaal described in [SHH-06] a technological selection framework for industrial managers based on the consideration of technical, financial and external (environmental, regulatory and standards) pressures. More recently, Hung and Lee suggested in [HUN-15] a technology selection model for new technologies, e.g. nanotechnologies, biotechnologies, green energy and photonics, by means of an importance / performance matrix. Other popular methodologies for technology selection can be found in [CHN-00], [TAV-03], [CHE-09] and [KIM-10].

In the specific case of methods to select educational technologies, the literature is less extensive and often less holistic stressing rather a review of relevant product attributes than the selection process per se. However, in [ZAI-07], the author conducts a review of selection methodologies for educational technologies existing at the time. The study concluded with the identification of 19 independent and relevant criteria for the selection of appropriate technologies for teaching. Ozkan and McKenzie published in [OZK-06] a similar criteria set obtained through the conduction of a Delphi study realized on a Higher Education Institution level. More recently, in [ANT-16] the author emphasizes the importance of align needs, abilities and so-called affordances of the student in the selection criteria.

The presented selection approach takes some elements from these methods while incorporating the need to take into account pedagogic approaches described in the previous section into the process. It consists of five sequential steps described below:

1) **Define and weight selection criteria:** The first step into the selection of adequate educational technologies is the determination and prioritization of the selection criteria used to evaluate the alternatives identified during the market research phase. Each selection process is different in terms of objective and priorities, however the literature review and the experiences gained during the realization of the study permits to hint attributes most commonly deemed as relevant by instructional planners.

    - Compatibility with chosen didactic principles: It was argued that education technologies can in certain occasions be associated to specific learning theories or didactic models, e.g. CAI supporting behaviorist approaches, or remote laboratories supporting distance learning.
    - Ease of access and use: User-friendly, hazard-free technologies are to be preferred to facilitate learner's contact with the technology. This is especially relevant in primary and secondary education stages.
    - Costs: Including price tag, operation, maintenance and service costs. This criterion is of special relevance while planning instruction in poor, underdeveloped regions.
    - Physical dimensions and weight: These features help to determine physical location requirements and are highly relevant when considering laboratory mobility options.
    - Operation principles: Referring to specific technology features such as virtual vs. real and mechanic vs. electronic.
    - Upgradability or capacity to adapt to changes in learning objectives: Referring to the capabilities of a given educational technology to integrate add-ons and new modules as a means to enhance its teaching features. In case of software, are regular

online updates and upgrades available? Can the functionality of the program be modified through a programming interface by the user?

- Technology life cycle: Referring to the expected technology lifespan, afterlife options, e.g. disposal, recycle, refurbishment, in case of physical devices
- Compatibility with other technologies: Especially relevant in the case of IT systems such as virtual and remote laboratories. Refers to operative systems and communication protocols, in which the technology is based.
- Ease of Maintainability: Required competences and skills for technology maintenance. Alternative refers to the accessibility of maintenance services provided by the manufacturer or program owner.
- Technical skills needed for operation: Required competences and skills for the operation of the technology. Especially relevant while addressing primary and secondary education stages.
- Extent of technology use: Referring to the common utilization of the technology for similar instructional purposes. Extended use of the technology in specific implementation settings commonly means the technology has been proven and might even count with organized users-communities for knowledge exchange purposes.
- Reliability and reproducibility of results: Determined by the technology components' quality and number of variability factors.
- Potentials to motivation self-learning in students: Availability of online operation and implementation tutorials, interactive interfaces. Application possibilities in real life.
- Technical support: Technical services availability in case of technologies disruption or malfunction. Technologies offering 24-hours online or telephonic support are better suited to conduct learning activities off-classroom.
- Student support: availability of student licenses.

Once the selection criteria are determined, a process of weighting each criterion is conducted according to the priorities set by the instructional planner. These priorities are commonly influenced by variable economic, institutional and environmental frameworks. In many cases, prioritization is represented either by a point or percentage system in which more important criteria are given higher numeric value, or by means of comparative tables against a standard product.

2) **Determine quantitative and or qualitative scale parameters:** Criteria are to be rated according to quantitative values, e.g. ideal weight of the machine = 20 kg., or qualitative characteristics, e.g. the app needs to be user-friendly. There is no standard to formulate parameters, however these need to be comprehensible for the decision-making responsible/s and eventual auditing entities. A common tool used by product developers to assign objective weights to parameters in a linguistic or numerical scale is the pairwise comparison [HOU-04].

3) **Characterize and rate alternatives:** Once criteria and weights are set, comparison processes among alternatives are to be conducted as a means to select the best technological alternative to support knowledge conveyance according to the priorities established by the instructional planner. Well-known decision-making tools such as Pugh matrixes or cause / effect matrixes (C&E matrixes) can be implemented to facilitate an objective selection of the best option. A Pugh matrix is especially helpful while conducting comparisons of alternatives using a large number of decision criteria,

while the C&E Matrix put a stronger emphasis in the consideration of weighted scales. Regardless of the method, the ultimate objective of the step is to facilitate an unbiased selection of the best technological solution available in the market. Additional information can be obtained from the analysis such as potential requirements, not included by the best option, which would need to be externally covered.

4) **Refine selection:** Commercially available products are seldom tailor-made to suit every pedagogic requirement of a given instructional event. In many cases, features will be missing or are included in the technology but not needed for the specific courses of the course. Inclusion of add-ons or further technologies to cover instructional elements not considered by the selected technology might need to be acquired or developed apart.

5) **Test and implement:** Testing of the technology conducted by the instructional planner and / or a control group is highly encouraged prior to its purchase and implementation in an official instructional event. Instruction planners will have then the opportunity to discover and handle unpredictable technology shortcomings by either adapting the technology specifications or shifting products. Once technical details have been cleared and the technology has demonstrated its suitability to cope with the pedagogic requirements of the course, on-site implementation can commence.

5.1.5.3 Design

The design approach presented in the proposed methodology adopts elements of traditional product-development methods such as Pahl & Beitz' Systematic Approach to Engineering Design (SAED) and Pugh's Total Design. The structure of the presented method, is however adapted to incorporate pedagogic requirements to the educational technology specification lists. These pedagogic requirements might include criteria to support specific learning theories, e.g. incorporating social network interfaces to support a connectivism approach, or the programming of software to conduct simulation analyses.

The SAED method is a well-known method, which has influenced national product design standards such as the German VDI guidelines 2222 and 2221 [PAH-96]. Contrary to design approaches followed in the U.S.A. and UK, in which the design process centers in considering the inherent characteristics of the product, the SAED methodology focuses in in the systematic generation of solutions to a problem-oriented task [ZEI-09]; [EDE-12]. This characteristic is favorable to the needs of instructional designers as it facilitates the integration into the design process of vaguely-defined pedagogic requirements. By encouraging the designer to prioritize his efforts in developing solutions to his particular pedagogic necessities instead of designing product features driven by market needs, the developed educational technology will have better chances to accomplish his instructional event's particular learning objectives.

The proposed method consists of eight sequential steps described below:

1) **Definition of functional structure:** The functional structure of an educational technology refers to the physical or virtual characteristics it should feature in order to support the learner to acquire specific knowledge in a specific manner determined during the definition stage. The definition process takes into account preconditions such as knowledge to be conveyed, target audience to be addressed, physical implementation environment and didactic principles to be supported. At this point, most of these characteristics will most probably have been addressed by the design team as described

in "clarification of technological features". Nonetheless, the decision to design an own solution, is in many cases symptomatic of the lack of standardized solutions or architectures to fulfill the instructional designer needs, which need to be overcome. During this stage, concrete tasks to be fulfilled by the technology are defined and interrelated, e.g. "convey knowledge on CNC machines programming to war refugees with limited English language competences". These tasks are always oriented to support the accomplishment of concrete learning objectives through determined didactic principles, e.g. "use a behavioristic approach that can be implemented within a short-duration workshop or seminar".

Tasks and their interrelations are left purposely ambiguous at this stage and should address both, structural and operative characteristics. Examples of tasks to be accomplished by a photovoltaic laboratory to be utilized as practical component of a theoretical-experimental workshop in impoverished regions could be:

- Autarkic functionality in terms of independence from unstable power sourcing.
- Mobile, as a means to increase the geographical reach of instruction.
- Should support appropriation of basic photovoltaics installation skills.
- Should support theoretical knowledge transfer on photovoltaics.

2) **Establishment of solution principles:** There are many technological and methodological ways to tackle a single problem. During this stage, the designer will identify, articulate and analyze potential solution principles for each task. During this stage, the instructional planner will elaborate a set of criteria by which each principle will be weighted upon. These criteria will consider economic, technological, pedagogic, social, and environmental factors. Considering the photovoltaic workshop example presented in 1), potential solutions for the third task, "Should support appropriation of basic photovoltaics installation skills", could include:

- The development of an instructional video of installation practices, which in the end presents the user with a questionnaire to evaluate his acquired knowledge, or
- A set of real PV components to be installed in a dummy rooftop per hand by the user using a written / video manual for reference, or
- A simulation software in which virtual components will be used in a real-world representation to plan and simulate PV systems and their output.

Advantages of the first solution are relatively low production costs and virtually no resources consumption, the second option in turn could improve the chances of appropriation of technical skills through a hands-on approach, while the third alternative would present the advantages and disadvantages of virtual learning systems introduced in section 3.5.4.

In order to assess the best alternative, options are weighted against each other based on the selection criteria and priorities established during the conduction of the first three steps of the definition stage, namely the determination of learning objectives, determination of didactic principles and clarification of technological features. Once more, Pugh or C & E Matrixes, such as the one depicted in table 12, can be used as analysis and decision-making tools as depicted in table.

Table 12: C & E decision-making matrix example

	Constructivist approach	Light weight	Low cost	Minimum supervision required	
	Weight = 10	**Weight = 6**	**Weight = 5**	**Weight = 4**	**Total**
Instructional video	1	5	5	5	80
Real components	5	2	2	3	**82**
Simulation tools	3	3	3	3	72

3) **Elaboration of concept variants:** Once solution principles have been established for each task, the planner can proceed to integrate them into rough concept drafts portraying different alternatives concerning technology's appearance, functionality, dimensions and pedagogic features. These concept alternatives will present different ways to comply with the constraints determined during the definition stage seeking to achieve the best possible fulfilment of the learning objectives. Alternatives will be rough enough to easily identify their particularities, without the need to provide too specific details concerning its physical realization.

4) **Concept selection:** During this stage, selection criteria will be generated and weighted, and the alternatives will be evaluated through traditional selection tools such as Pugh or C&E matrixes. At the end, a preferred concept will be objectively selected out of the options and will undergo a refining process.

5) **Detailed concept:** The detailed concept is the first step towards the physical realization of the final result. It includes the parametric and economic specification of material and virtual components, as well as their arrangement in a final product with specific properties. The detailed concept contemplates the type of materials to be used during the fabrication of a physical device, or the type of software used to program a specific application. Technical drawings and / or programing algorithms will be delivered during this stage along with an educated estimation on the total costs. In ideal cases, the detail concept will include a project management-based development including development schedules, responsibilities, work breakdown structures and list of activities to be outsourced. Finally, during this stage a failure analysis is recommended to minimize realization rework in further stages.

6) **Realization:** The realization stage comprises the manufacturing of physical components and / or the code-programming of software elements of the educational technology, as well as their assembly into a final product. Most probably the realization involves different actors coordinated by the technology designer, and its end result is a fully-functional prototype of the final product.

7) **Test and implementation:** The test phase corresponds to the try-out period of time in which the technology will be evaluated either by the instructional planner or a learners' control group. During this phase, design mishaps, programming bugs, or concept improvements potentials can be identified and corrected. Once the technology has been tested, it can be implemented in a real instructional event.

8) **Documentation:** As in any other complex product-development project, the design, realization and implementation of new educational technologies requires the elaboration

of conscious documentation on behalf of the developers. Due to the uniqueness of the solution, modifications, improvements and replication of the technology is closely linked to a thorough, clear and understandable record of activities and processes that conducted to a successful project.

5.2 Laboratory mobility

Education of engineers in the fields of sustainable manufacturing and energy generation requires students to have contact with high-end laboratories and state-of-the-art educational technologies in order to competently develop solutions for real problems once education is concluded. Laboratories are commonly associated with bulky infrastructure mostly located and fixed within facilities of education institutions. Collaboration approaches between developed and developing countries and existing distance education technologies seeking to overcome infrastructural deficits in higher education institutions in developing countries have been described in sections 2.3 and 3.5.4 respectively. Yet, the gap identified in chapter four acknowledged that the present instructional approaches have a very limited impact while enabling education of members of underdeveloped and impoverished communities in developing countries. Development and rapid implementation of new education approaches to reach these population sectors are therefore of paramount importance if the UN's SDGs are to be accomplished by 2030.

The present dissertation intends to contribute towards this end by proposing the development of flexible, yet cost-accessible, mobile high-end laboratories to support long-range dissemination of high-quality education in the fields of sustainable manufacturing and energy generation, deemed as preeminent to achieve socio-economic and environmental global sustainable development targets. Physical mobility of small scale laboratories intends to introduce a viable alternative to overcome shortcomings of current distance education approaches previously reported in sections 3.4.4 and 3.5.4. Massive Open Online Courses (MOOCs) for instance, have been deemed a practical solution to transmit theoretical knowledge to audiences worldwide having as only precondition an Internet connection. The approach is however very limited when supporting the acquisition of technical competences and in most cases non-affordable for rural communities' dwellers in underdeveloped world regions. So-called remote and virtual laboratories on the other hand make a serious attempt to convey practical knowledge to engineering learners without access to own physical laboratories. A comparison between the advantages and disadvantages between real on-site / remote / virtual laboratories has been summarized in table 9 and comprehensively described in section 3.5.4. The comparison evidently applies when substituting real on-site vs. real mobile laboratories. Although well-designed virtual and remote laboratories can be useful to deepen student's conceptual understanding in engineering topics, they are in many cases considered poor replacement for practical real laboratories as their interaction with real components is limited or even inexistent, in the case of virtual laboratories [NED-03]. Moreover, lack of standardization of communication protocols difficult their implementation on a broad scale [SEI-13]. Finally, accessibility to these laboratories is usually reserved to students of HEI or individuals who can afford the acquisition of the required software platforms, which almost immediately excludes underfunded education institutions or poor individuals in rural and informal urban communities.

Arguably the biggest advantage of mobile laboratories is their capability to change traditional education paradigms regarding knowledge accessibility by enabling decentralization of formal and non-formal practical instruction. Advances in micro-technology have recently facilitated the development of miniaturized laboratory equipment and machine tools indispensable for instruction purposes in fields such as medicine and manufacturing [WAL-14]; [PIQ-15]. With the miniaturization of high-end equipment components, high-quality level instruction in technical fields such as engineering can indeed be brought into communities and to audiences who otherwise have no possibility to attend specialized instruction facilities commonly located in either big formal urban centers or foreign institutions. This way, mobile laboratories can in principle be deployed in rural and informal urban communities to support help for self-help, and generation of local value creation programs.

Other advantages of mobile laboratories include:

- Its portable feature enables site-independent, high-quality, practical education. Members of underdeveloped communities worldwide become direct beneficiaries of technical instruction approaches without the need to abandon their communities. Mobile laboratories can be combined with autarkic features to overcome local infrastructural deficiencies. Many education institutions in rural and informal-urban communities lack conduits for electrical devices; adequate electrical features, such as proper outlets; or even uninterrupted power, water or gas supply [GAO-00].
- Physical contact to affordable state-of-the-art educational technologies facilitates the contact of learners with training devices and systems common in the industry and higher education institutions. This increases the chances of the learners to deal with close-to-real-life wicked problems during their implementation and operation and improve their employability chances [MAL-15].
- The use of low-cost, globally-available technologies and the utilization of open design platforms facilitates local laboratories' reproducibility and customization considering local and educational needs. Technology appropriation on behalf of local communities, resulting out of the laboratory replication, might conduce to further technological developments that take into account design features particularly useful for local markets. Local reproduction of mobile laboratories might also generate positive economic side effects by opening of potential business opportunities such as the design, development, purchase and rent of similar laboratories on a regional scale.
- Mobile laboratories can be shared among education institutions in order to maximize their utilization while reducing investment, operation and maintenance costs. Contrary to on-site conventional laboratories with restricted access, mostly limited to learners and faculty members of the hosting institution, mobile laboratories are capable to serve several audiences on a schedule manner increasing thus the equipment's utilization and reducing lab costs per student. By engaging a laboratory-sharing scheme, consortiums of rural and informal urban education institutions, individually unable to finance laboratory infrastructure would be able to have permanent access to the facilities when needed.
- Facilitates on-site training as a means to generate socio-economic value in impoverished rural and informal urban communities. Given the capabilities of mobile laboratories to support non-formal instructional events for audiences outside formal national education systems, uneducated member of underdeveloped communities can be reached and trained to acquire relevant competences and skills to create value in their communities in a sustainable manner.

When compared to real on-site laboratories, table 13 presents a summary of advantages and shortcomings exhibited by mobile laboratories.

Table 13: On-site vs. mobile on-site real laboratories

Laboratory kind	Advantages	Disadvantages
Real on-site laboratories [NED-03]	• Hands-on approach allowing the user direct contact with real equipment. • Contrary to simulation or virtual approaches, results obtained through the interaction with physical equipment exhibit real, not simulated, data. The result is an improvement in learners' practical skills by allowing them to test theoretical knowledge, learn by trial and error and perform analysis on the obtained results. • Collaborative work is enabled, and might even be demanded, due to physical presence of participants in laboratory sessions, thus not only conveying technical knowledge but reinforcing team work and communication competences. • Interaction with supervisor. Faculty members or tutors are physically available to guide learners through experimentation, and help them to interpret results. They also assure the correct and safe equipment utilization. • Less dependent on software, especially when it comes to teach basic engineering and science concepts such as mechanics, electronics, and chemistry. • Access to full-size equipment similar to those used in real-life industrial settings.	• Time and place restrictions. Equipment can be used by a limited number of learners and only within the premises of the education institution. • Limited reach. Laboratories are reserved for students and academic staff of the particular education institutions housing them. Access is limited and most of the cases denied to external participants limiting their societal benefits. The possibility of taking the equipment to external communities is excluded, especially if the lack the required supporting infrastructure. • Supervision required. Faculty members and tutors need to be constantly present to safeguard equipment's and participants wellbeing. • Normally high costs are involved due to the cost of equipment, its maintenance and operation, cleaning and maintaining costs of housing halls and support infrastructure, e.g. vigilance. Cost are normally borne by the education institution alone.
Mobile laboratories	• Hands on approach, same as real on-site labs. • Same advantages over virtual and remote labs as real on-site labs. • Same collaborative possibilities as real on-site labs. • Same interaction with supervisors as real on-site labs. • Similar software dependence as real on-site labs. • Unlimited reach due to their intrinsic transportable nature. Uneducated audiences and students from diverse education institutions have access to infrastructure normally available to selected audiences. • Accessible to learners in underdeveloped rural and urban informal communities lacking required infrastructure to house large scale laboratories.	• Time restrictions subjected to equipment availability. Mobile laboratories cannot be assumed to be full-time available to a given institution throughout the semester or academic year as It might be in operation somewhere else. • Machine restrictions. Technology allows nowadays to miniaturize a large number of otherwise large-scale machinery and laboratory components. However, not every piece of equipment available in a traditional laboratory can be made transportable or keep its accuracy and capabilities while miniaturized, e.g. complex CNC machines, or chemical treatments. • Supervision required. Faculty members and tutors need to be constantly present to safeguard equipment's and participants wellbeing.

The presented mobility concept goes along with an intuitive dimension as a means to reach a broad range of audiences throughout education systems in developing countries, including low-educated audiences, major stakeholders of strategies targeting socio-economic development through local value creation. Laboratory mobility is based on the principle of miniaturization of high-class laboratories and components without functionality forfeiture allowing their transportation in conventional commercial transportation means such as commercial flights and small to medium-size land vehicles.

As part of this dissertation, prototype mobile laboratories were designed according to the IDMEE presented in this chapter, developed and tested with control student groups consisting of learners from mostly developing countries. These laboratories consist of:

- A mobile PV charging station for E-Bikes and Pedelecs: The laboratory, intends to convey basic and intermediate topics in the field of photovoltaics to an audience ranging from K-12 to graduate engineering students. Its design, similar to modern urban infrastructure for practical and commercial purposes intends to raise the awareness of the course participants concerning implementation fields of photovoltaic technologies apart from domestic energy generation through the installation of panels in rooftops.
- A portable Eiffel wind tunnel for the conduction of wind energy experiments: The so-called "WindLab" was designed to serve teaching purposes for a diversity of audiences, from K-12 Students to Wind Energy specialists. It consists of four main elements, namely the mechanical structure, a wind turbine, an electronic backend and an intuitive front-end interface.
- A Mobile Learning Factory for manufacturing (MLF), consisting of a freightable manufacturing facility: The MLF is a miniaturized version of multimillion-euro teaching facilities, which are getting more common in universities in developed countries. These functional factories provide students and participants the opportunity to interact with real production technologies and implement production strategies in a real environment shop floor. The MLF is equipped with last-generation desktop machine tools, demountable working stations and raw materials and consumables for the production of real products

6 Validation

The present dissertation has stressed the importance to improve developing countries' education in the fields of sustainable manufacturing and energy generation as a means to contribute to achieve the targets of UN's Sustainable Development Goals, especially those corresponding to the goals 4, 7, 9, 12, and 17 (see section 1.1). In order to validate the IDMEE presented in chapter 5, exemplary instructional events developed to train specialists in the above-mentioned fields will be presented. The chapter will initiate with a comprehensive socio-economic description of the target areas of implementation. Secondly, technological means and approaches to offset local educational infrastructure deficits, consistent in the development of mobile laboratories will be additionally introduced. The presented mobile laboratories are deliberately designed and developed foreseeing local multiplication as a means to enable a broader dissemination of knowledge in underdeveloped rural and informal urban regions. The chapter finalizes with the thorough description of the planning and realization of courses, along with their respective mobile laboratories on sustainable manufacturing, photovoltaics and wind energy aimed at training developing countries' specialists.

6.1 Seminar on photovoltaics

A one-day seminar covering practical application fields of photovoltaics was developed as a means to stimulate the interest of secondary education, and university freshman students in this area of study. The primary objective of the course is to facilitate learners' access to the most common elements and components of a fully-functional PV system as a means to, on the one hand demonstrate their individual and systemic functionality, while at the same time explaining the principles of photovoltaics. The seminar combines theory presentations with practical experiments in a mobile PV charging station to suit principally inductive, deductive, active and visual styles of learning. A description of the course planning following the proposed IDMEE will follow.

6.1.1 What

The design of the seminar on photovoltaics started with the formulation of the learning objectives expected to be acquired by the learner upon event's conclusion. For design purposes, a comprehensive description of these objectives, listed below, was conducted by the instruction planner in order to avoid ambiguous interpretations in later development phases.

- Familiarization of the learners with conventional PV components, systems and installations: This includes the introduction to photovoltaic module types, charge controllers, inverters, tracking devices, sensors, battery banks, utility meters and performance monitoring devices, as well as their interactions.
- Review of basic electricity concepts such as current, voltage, power and resistance, as well as their interrelations: An important aspect of this content's item is to ensure that learners are acquainted with relevant laws and theorems such as Ohm's law, as well as concepts such as electric short and open-circuits.
- Principles of photovoltaic energy conversion: Photovoltaic typical concepts such as characterization of solar modules, conversion efficiency, and maximum power point are introduced to the learners, who are expected to have minimum, if any, previous knowledge of the terms.

- Photovoltaic power generation variables: The influence of environmental parameters over the system's power output is to be thoroughly addressed. Energy conversion dependence on factors such as temperature, light intensity, shadowing, and modules' direction towards the sun need to be reviewed in detail. Relation between the intensity of these effects and the kind of photovoltaic technology is an important outcome of this item.
- Photovoltaic systems, implementation potentials and troubleshooting: Learners will be introduced to diverse real PV application fields. In this specific case, the potentials of PV systems as clean energy sources for electro mobility applications is to be stressed. Analyses of typical e-mobility devices energy demands, e.g. E-Bikes, against power output of PV systems will be carried out as an introductory step towards the design and characterization of own systems. Additionally, system's troubleshooting methods regarding the identification of defect components will be conducted.

Once the content of instruction was clarified, concrete statements addressing the course participant were formulated as learning objectives indicating Bloom's cognitive level intended to be reached. The classification is shown in table 14

Table 14: Learning objectives PV course

Cognitive level	Learning objectives - By the end of the seminar you will be able to:
Knowledge	Identify the most common components of a PV system
Comprehension	Explain the functionality of each element and its relation to other components.
Comprehension	Describe relevant electric power concepts such as current, voltage, resistance, power, and efficiency.
Comprehension	Explain relevant electric power laws and theorems such as Ohm's law.
Comprehension	Explain relevant physics principles of the photovoltaic effect
Knowledge / Comprehension	Identify, understand and be able to explain the environmental variables with a significant effect on the power output of photovoltaic systems, e.g. temperature variance.
Knowledge / Comprehension	Identify different PV technologies and their sensibility towards environmental variables.
Application	Modify environmental or system variables to achieve maximum power output.
Evaluation	Appraise and argue potential implementation fields of PV systems.

6.1.2 Who

The target audience of the developed PV seminar consists of learners of secondary education levels with a technical focus, as well as undergraduate students in first university semesters of engineering bachelor programs in developing countries. Energy or environmental engineering students are preferred due to assumed intrinsic motivation in the field of renewable energies. The seminar can additionally be offered as an introductory course on photovoltaics in graduate or specialization programs at higher education institutions also in developing countries. By focusing on developing countries, the suggested Photovoltaics course seeks to contribute to the achievement of UN's SDGs 4, 7, 11 and 13.

Accepting pedagogic theses arguing that education is highly specific to context [GUT-11], the environment in which the course is taking place has been considered of the utmost importance while defining design criteria for the elaboration of the laboratory and the teaching method. The characteristics of the learners are largely determined by the region in which they grew up.

Native language, quality of background education, cultural attributes, and attitudes towards the instructors are essential to determine the approach of the instructional event, especially if conducted locally. For designing purposes therefore, developing countries in Latin-America have been selected as implementation focus in this case. Centering in a region allows the planners to identify nations' common traits as a means to reduce context variability and achieve a higher dissemination potential.

The first aspect to consider is the market expansion that photovoltaics is having in this region despite a notable scarcity in available specialized human resources. According to some prognoses, the Latin-America PV market is set to install 2.2. GW of capacity by the end of 2016, which represents a growth of over 55 % with respect to the capacity installed just a year before [MUS-16a]. This market expansion is result of market dynamics such as plummeting oil prices, which have forced national economies to diversify their income sources, and regional political agendas set to comply with international environmental agreements. Specialists however agree that despite this remarkable growth, many PV projects have been hampered due to a lack of PV specialists in the market due to a relative recent technology's market incursion and a lack of public technology acceptance, especially in rural areas [FLA-14]. Moreover, as for now, 92 % of solar power in Latin-America is generated by utility-scale sources [MUS-16b], which means that small-scale PV power generation, such as household-size power plants and rural PV electrification projects are barely disseminated.

A second aspect relevant to take into account during the design of the photovoltaic seminar are the particular education traits in the region. Education in Latin-America is characterized by the existence of large disparities in terms of instruction offer and quality between high-class urban, low-class urban and rural levels, and by a continuous dependence on supranational financing organizations such as the world bank [NEU-06]. Urban centers offer in most cases high quality private and public education based on western education models and culture. Internationalization aspects in education are not uncommon, prioritizing in many cases the instruction of English language. International models of education are also common, with several higher education institutions collaborating with foreign institutions on a multi-layered basis [KNI-07]. Sentiments of nationalism are rare facilitating thus the introduction of oversees technologies and education methods. In many cases, technology or instruction is beforehand subjectively considered as "superior" simply because of being foreign. Low-class urban and rural populations however, are characterized by a contrasting, complex and often times contentious relationship between modernity and tradition [PEO-11]. The "own identity" of these regions is clearly more conservative and indigenous leading education institutions to advocate for alternative didactic methods that divert from traditional western education and integrate local needs and knowledge instead [REA-15].

Another important cultural trait of Latin American countries and regions in general is a high Power Distance Index[26] (PDI), which leads to higher collectivism rates in their populations [ELV-07]. In terms of education this means that Latin-American students are highly dependent on paternalistic instruction figures and prone to work in groups to achieve common results. Learning methods in Latin-America tend therefore to be behavioristic and cognitivist by nature

[26] Power Distance Index expresses the degree to which the less powerful members of a society accept and expect that power is distributed unequally. People in societies exhibiting a large degree of Power Distance accept a hierarchical order in which everybody has a place and which needs no further justification. In societies with low Power Distance, people strive to equalize the distribution of power and demand justification for inequalities of power [HOF.

which difficult a sudden introduction of constructivist approaches in these areas of implementation.

The net-enrolment ratio[27] for secondary education in Latin-America can be considered moderate to high depending on the country, e.g. El Salvador 55 % vs. Cuba 83 % [PRO-12]. National education expenditure in 2012 ranged from 2.6 % of GDP's share in Peru to a 12.8 % in Cuba with a regional average of 4.6 % [FRE-12]. A more meaningful figure however is the governmental expenditure per student in USD. The UNESCO Institute for Statistics reports a regional average of 1.267 USD, which represents barely more than 10 % of what countries such as Germany and the U.S. invest in secondary education students [UNE-15a]. Table 15 below, shows that governmental investment in education in the Latin America is highly heterogeneous, however clearly low when compared with investments incurred in developed countries.

Table 15: Government expenditure per secondary student (USD)[UNE-15a]

Indicator: Government expenditure per secondary student (USD)					
Country / Year	**2010**	**2011**	**2012**	**2013**	**2014**
Argentina	$2.289	$3.017	$2.883	$3.133	
Belize	$1.111		$1.041	$1.015	
Bolivia	$371	$453	$524		
Brazil	$2.368	$2.894	$2.753		
Chile	$1.949	$2.219	$2.756	$2.379	
Colombia	$950	$1.057	$1.180	$1.333	$1.370
Costa Rica					
Cuba	$2.972				
Dominican Republic	$346	$384	$485	$855	$887
Ecuador	$667	$888	$823	$1.087	$398
El Salvador	$389				
Germany	**$9.980**	**$10.691**	**$10.207**		
Guatemala	$159	$157	$171	$189	
Honduras				$428	
Mexico	$1.413	$1.561		$2.201	
Nicaragua	$112				
Panama		$860			
Paraguay	$487	$672	$638		
Peru	$541	$538	$687	$691	$853
United States of America	**$11.440**	**$11.581**	**$11.357**		
Uruguay					

In conclusion, PV markets in Latin-America have a great expansion potential due to favorable legislative policies and excellent climate conditions. Broad scale dissemination of the technology and further conduction of utility-scale projects are however conditioned to the availability of specialized local human resources and an increase of the public acceptance. To support the achievement of both, the targeted “who” in the proposed seminar on photovoltaics corresponds to a large sector of the Latin-American population, which can be roughly divided in two sectors. On the one hand, a reasonably well-instructed “western-like” high-class urban

[27] The Net Enrolment Ratio (NER) is defined as the enrolment of the official age-group for a given level of education expressed as a percentage of the corresponding population [UNE-16b].

population open to new technologies and a more conservative indigenous rural community who might still be reluctant to the introduction of new technologies.
Following the proposed Instructional Design Model for Engineering Education, didactic approaches and custom-made educational technologies were elaborated to convey the instructional content presented in 6.1.1 to both population sectors described above.

6.1.3 How

As established in chapter 5, "how" refers to the learning theories and styles as well as pedagogical methods to be used as a means to achieve the learning objectives specified during the definition of "what".

In this case, the method selected to achieve the learning objectives listed in section 6.1.1 consists of a seminar on photovoltaic systems based on a combined instruction model comprising theory and practical components. Given the preconditions determined in 6.1.2 concerning the relative late introduction of PV technologies and little public technology acceptance in Latin-America, a lack of previous knowledge in the field on behalf of the participants is assumed. In both cases, namely instruction for well-educated urban and indigenous rural audiences, a conventional frontal teaching method is required as introductory mean to familiarize the audience with potential new terms, definitions, components and technologies. A hands-on component consisting of experimental activities conducted in a physical laboratory, thoroughly described in the next section, is additionally required to harness the theoretical knowledge provided during the theory seminar and to put the audiences in contact, probably for the first time, with real PV components.

The suggested seminar favors cognitivist approaches of learning by allowing the student to apply knowledge acquired during the frontal seminar in practical laboratory activities and discuss the results with the instructor. The utilized approach, followed a traditional deductive orientation starting with fundamentals in order to proceed with the applications. A visual teaching style was also preferred due to the potentials of modern ICT technologies to stimulate the interest of young students in the area of photovoltaics.

The final structure of the instructional event consisted in a short seminar of seven hours of duration, three-hour theory seminar and four hours of laboratory interaction, in which following topics were addressed:

- Brief introduction to photovoltaics: The photovoltaic effect, potentials of photovoltaics, advantages of photovoltaic (PV) energy over fossil-fuels, basic concepts, e.g. efficiency, IV curves.
- Components of a PV system: What is a PV system, PV systems traditional components, e.g. modules, charge controllers, inverters, sensors, introduction to the PV modules technologies, e.g. monocrystalline, polycrystalline and thin film.
- Application fields of PV systems: household energy generation, large power plants, e-mobility appliances.
- Variables affecting a PV system performance: Light intensity, temperature, shadowing and light's angle of incidence.

6.1.4 By which means

Following IDMEE's methodology, a mobile solar charging station was developed by the author and a team of product developers to serve as a teaching unit to support the realization of the proposed seminar on photovoltaics. The mobile charging station is specifically designed to support the hands-on component of the seminar previously described in 6.1.3. The charging station has also been designed to serve particular needs of the target audiences described in 6.1.2. by integrating for instance, graphic control interfaces with minimum written information as a means to minimize potential language barriers with indigenous Latin-American audiences.

Opposed to conventional commercial laboratory systems, the mobile charging station seeks to include concrete application fields to its didactic repertoire. In this case, it was decided that the laboratory should take the form of a charging station for E-Bikes, deliberately distancing itself from mainstream application examples such as household electricity generation systems in order to familiarize students with non-traditional real-world PV systems with potentials of decentralized value creation. Following the Design or Select decision making process suggested in 5.1.5.1, a market research was conducted in order to determine if commercial systems were available that could fulfill the learning objectives proposed in 6.1.1 and serve learners' audiences detailed in 6.1.2. In this sense, an online and literature search was conducted to identify PV charging stations designed as pedagogic instruments to support the delivery of the intended course's instructional content detailed in table 14.

The search resulted in no charging station facility for teaching purposes being found. Conventional PV training systems are easily accessible in Europe due to a buoyant market of engineering laboratories designers and manufacturers. Companies such as Gunt, Edibon, PA Hilton, Lucas Nülle, Amatrol and IKS have developed a range of photovoltaic training stations to convey basic principles of photovoltaics such as characterization of solar cells and modules [GUN-16a]; [EDI-16a]; [PHI-16]; [LNU-16]; [AMA-16]. A widely-distributed system in Germany and Austria for instance is the IKS Solartraining Profi. The system, developed in cooperation with the Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES) is a modular training system developed to support education in the fields of design, construction, operation, connecting and installation of PV power plants [IKS-15]. These systems however do not fulfill the intended pedagogic target as there are limited to the analyses of components without a specific application purpose. On the other hand, PV charging stations exist in the market provided by companies such as Paugger, Envision Solar, Giulio Barbieri, however they can be barely considered mobile due to their large dimensions. Most importantly, no PV charging station for didactic purposes could be found. An analysis of the commercially available PV systems found during the conduction of this research is included in appendix 9.1.

As a result, an own PV charging station design was required. Following the design method described in 5.1.6.3, design specifications of a station's prototype were elaborated based on the learning objectives specified in 6.1.1 and 6.1.2. Design specifications comprising pedagogic and structural design criteria, shown in table 16, were formulated by the team to address each specific learning objectives.

Table 16: Design specifications - Mobile solar charging station

Type	Objective	Design Criteria
Learning	Identify the most common components of a PV system	Inclusion of three PV module technologies, charge controllers, inverter, PV cables, and environmental sensors, e.g. temperature, light intensity, GPS.
	Explain the functionality of each element and its relation to other components	Every component should be visible. Output display integrated, i.e. no need of electronic measuring devices such as multimeters.
	Describe relevant electric power concepts such as current, voltage, resistance, power, and efficiency.	Constant display of voltage, current, power and charging status.
	Explain relevant electric power laws and theorems such as Ohm’s law.	Design of explanatory visual aids. Generation of spreadsheets with system and output characterization
	Explain relevant the photovoltaic effect	Visualization of IV curves
	Identify, understand and be able to explain environmental variables with a significant effect on the system's power output	System design to allow changes in environmental variables. Generation of spreadsheets with system and output characterization.
	Identify different PV technologies and their sensibility towards environmental variables	System design to allow changes in environmental variables. Generation of spreadsheets with system and output characterization.
	Modify environmental or system variables to achieve maximum power output	System design to allow changes in environmental variables. Generation of spreadsheets with system and output characterization.
Structural (based on target audience)	Lightweight structure	System maximum weight = 90 kg
	Robust and autark	Power independent. Able to withstand harsh operation and transport handling
	Modular design	Easy plug and play of components
	Easily reproducible	Maximum total cost of the system = 15.000 €
	Mobile	System to be distributed in cases with a maximum weight of 32 kg each. System should be transported in regular-size SUV and comply with flight regulations
	Language independent	Station’ assembly and operation should be intuitive and as language-free as possible. Graphic interfaces to be integrated whenever possible.
	User friendly and safe	Considering the target audience comprising also secondary education students, interface should be user friendly. Safe access to electrical components to be guaranteed.

Structural design criteria presented above should ensure a smooth and safe implementation of the station despite adverse infrastructural conditions and consider cost and reproducibility aspects to foster local multiplication efforts. Specification of following items was required during the design phase:

- The mobile solar charging station needs to perform the same way as and resemble conventional docking station systems for E-Bikes. In this case, the maximum number of vehicles to be attached to the station was determined to be three. The amount was based in estimations concerning the optimal balance between productivity, number of bikes being able to be charged at the same time, and mobility, system’s weight and dimensions.

- The charging station should mainly serve teaching purposes: A knowledge transfer focus in developing countries should be expected. A continuous utilization and a constant vehicle flow need therefore not to be considered.
- Mobility: Transport into and within the target countries by means of conventional transportation means is to be assured. In this case, the dimensions and design of the station and its transportation cases were delineated by cargo specifications of commercial airlines and regular-size SUVs.
- Reproducibility has to be assured through the utilization of commercially available and cost-accessible components. Online suppliers with worldwide dispatch capabilities are to be preferred.
- Robustness and autarkic function: Given the uncertainty regarding the type of showroom and its infrastructural characteristics while presenting the mobile charging station abroad, the system had to fulfill following criteria in terms of mechanical design:
- Lightweight with a maximum weight limit of 90 Kg. to be distributed in a maximum amount of three transportable cases of 30 Kg. maximum weight each
- Resistant to corrosion
- High stability to withstand medium-strong wind currents as operation is intended to take place in open spaces.
- Safe access to electrical components with metallic connections covered, but otherwise granting access, contact and in some cases interaction with components such as charge controllers of monitoring devices.
- Fire proof
- The mobile charging station should serve as platform to conduct at least six basic experiments: Component tour; characterization of PV modules; temperature dependence; intensity dependence; shadowing effect; and identification of damaged cells.
- A didactic ICT platform to save, retrieve and assess data provided by the station is required. Potential language incompatibilities can arise due to the intended implementation areas. The platform's architecture therefore demands a user-friendly, language independent front-end interface to be considered as part of the system design.

According to the IDMEE's design methodology, several concept sketches were realized and assessed. A graphical description as well as a functional evaluation of the alternatives can be found in appendix 9.1. Upon conclusion of the concept evaluation process, the team opted for a single foot design with PV modules atop, serving as sun cover for charging E-bikes, and electronic components in the bottom part, close to the station foot. A desktop-computer monitor or a laptop would be positioned in the front at a height of approximately 1.30 m. from floor level to serve as front-end interface with the user. Iterative concept reviews supported by a market research of the individual components led to a series of improvements, mostly weight-related, and finally a definitive prototype shown in figure 34.

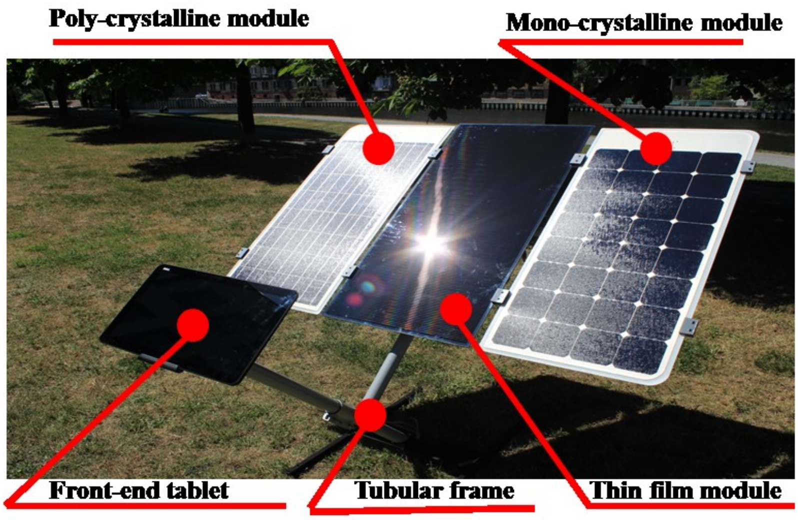


Figure 34: PV charging station

The final system consisted of a hollow tubular supporting frame attached to a flat extension for mounting up to three medium-sized PV modules. The flat extension allows a single degree of freedom about its centroid permitting a tilting angle from 0° (horizontal plane) to 90° (vertical plane to the ground). The entire structure is nonetheless light enough to be manually positioned toward sun's trajectory in the experimentation site. In the opposite end of the flat extension, the tubular frame extends to provide a support structure for the user's control panel.

The supporting frame and its base are able to hold a load of at least 25 kg, which is the estimated weight of three light-weight PV modules, and stand a wind Beaufort rate of 7, equivalent to a wind speed of 50 – 61.8 km/h. The base serves at the same time as cover for the PV system components including charge controllers, invertors, batteries and battery management systems, as well as for elements of the control electronics such as the information-processing microcontroller.

Finally, the interaction with the user is conducted through a front-end user interface installed in a light-weight tablet computer. The interface allows the conduction of a series of experiments intended to support the achievement of the seminar learning objectives. The interface has a single-way information flow. It allows the user to monitor environmental conditions and relevant information such as the station's power output and the state of charge of the system's battery bank, and save data for analysis purposes. A comprehensive description of the individual station components is in order.

6.1.4.1 System components

The selection of the components for the mobile PV station was conducted following PV systems design methods suggested in [LUQ-03]; [HAN-10]; [MCE-12]; [HAE-12]; [DGS-13]. The design of a PV system usually starts with the calculation of load energy requirements, which in this case amounted to 344 Wh/day, including system loses, to power up three E-Bikes as per specification demands. The individual components are briefly described below:

- PV modules: Due to the didactic focus of the mobile charging station, three different PV technologies were selected. The selection criteria favored factors such as weight, ease to handle and power output. Another critical factor was the customization degree while defining the module sizes since congenial dimensioning would facilitate the transport and handling of the modules in a single case, supporting the mobility of the device. Furthermore, same-size modules favors aesthetics as well as a balanced distribution of the structure loads once the station is fully assembled. After a thorough market review, following modules were selected:

- Custom-made super-light Semiflex polycrystalline PV module: 1190 x 560 x 3 mm; 3.3 kg; 82W
- Calyxo CdTe thin film PV Module: 1200 x 600 x 7 mm; 12 kg; 80 W
- Custom-made super-light Semiflex monocrystalline PV module: 1190 x 560 x 3 mm; 3.3 kg; 101 W
- Custom-made super-light Semiflex polycrystalline PV module: 1190 x 560 x 3 mm; 3.3 kg; 82 W – Defect

- Battery bank: A Lithium Iron Phosphate $LiFePO_4$ (LFP) battery bank was selected as storing element of the mobile charging station. In this case the bank is constituted by four LFP series-connected cells with an overall capacity of 12.8 V and 60 Ah and a 0.3 C rate. The units can also be considered as lightweight high density elements (60Ah / 2 kg), in alignment to the general specifications of the mobile charging station. The battery bank is protected from operating outside its safe operating voltage and current areas by means of a battery management system (BMS). The BMS also serves to balance state of charge (SOC) disparities in the individual batteries caused by normal manufacturing variation.

- Charge controllers: Charge controllers are electronic devices designed to prevent standalone battery banks from overcharging and excessive discharge [LUQ-03]. This is achieved through monitoring and managing of the PV array and batteries' power, current and voltage outputs. Charge controllers additionally serve as short-circuit and reverse-polarity protection. In some cases, they support the determination of accurate state of charge, battery maintenance procedures, tracking of Maximum Power Point (MPP), and data information processing [DGS-13]. In this case, a Western's WRM-15 charge controller was selected. The device includes an information monitoring display to track PV array's power output, battery status and load's power consumption. Each charge controller is able to comply with the nominal voltage requirements of the system (12 V) and with the maximum module's current output. Moreover, each charge controller of this type includes a charge algorithm for Li-Ion batteries.

- Inverter: Inverters are electronic devices that convert low DC voltages generated by a PV array into a high, typically 230V, AC voltage that can be either fed to the public electricity grid or directly to AC electrical appliances. Inverters efficiency is commonly high, over 90 %, and additionally to its power conversion functions, it also operates as an internal maximum power point tracking system. For the mobile charging station, a Volcraft SW-150W inverter has been included power output for AC battery charging docks.

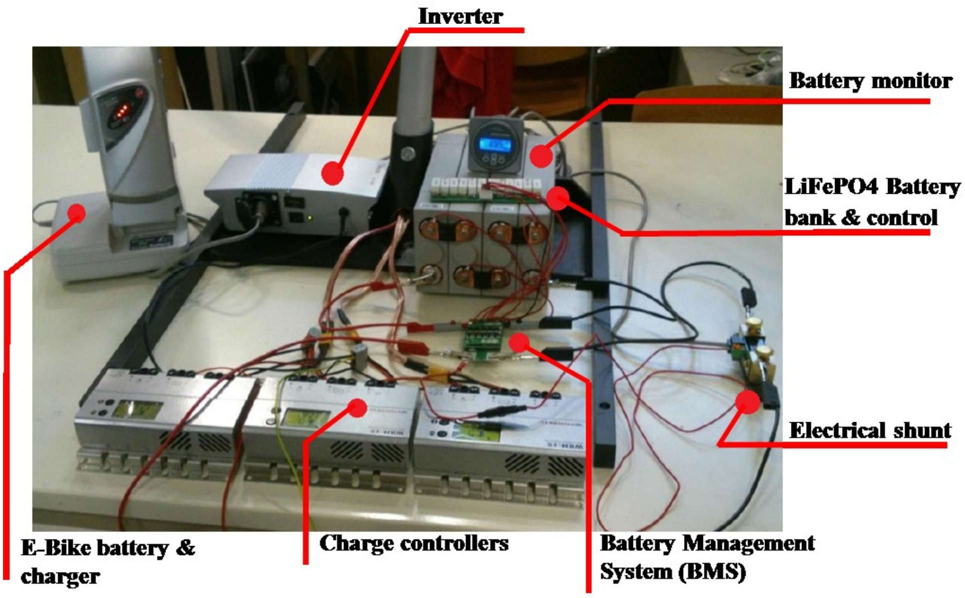


Figure 35: Charging station electrical system components

6.1.4.2 Back-end control system

The station's knowledge transfer principle is based on the acquisition and analysis of data generated from environmental sensors and their integration of these assessment results into new learners' cognitive schemes. The ensemble of these sensors along with an electronic central processing unit comprises the system's back-end Data Acquisition System (DAS). DAS is primarily responsible of the collection of environmental and component's output information and its transfer to further processing stages as an information data string.

The core of the station's DAS is an integrated circuit consistent of an Arduino MEGA ADK3 microcontroller board comprising a USB host interface, 54 input / output ports, 16 analog inputs, a USB connection, a power jack and an In-Circuit Serial Programming (ICSP) header. The Arduino obtains environmental information from digital and analog sensors attached to the station and electrical input / output values from the PV array and the battery bank. The core set of information collected by the system sensors consists of:

- Voltage sensing: The voltage signals of each PV module are transmitted from their respective charge controller output to the Arduino analog inputs. Due to the 5V input limit of the microcontroller though, the charge controllers' incoming V/I signals need to be damped below this limit by resistor voltage dividers before being read.
- Current sensing: Current values are indirectly provided by the charge controllers attached to each PV module. As charge controllers don't provide current values directly, an electronic array of shunt resistors is required to determine current out of voltage through Ohm's law. Through the inclusion of shunt resistors, the transformed voltage values of the current will remain between zero and the reference voltage level in the Arduino, yet the voltage width of steps are still dependent from the 10-bit resolution of the microprocessor ($2^{10} = 1024$).
- Battery bank monitoring: The battery bank data is transmitted directly to the Arduino by the battery management system through an embedded text-mode interface called VE.Direct. This interface transmits additional information to the Arduino such as state of charge and rate of charge / discharge.

- Environmental temperature sensing: Part of the environmental sensing function of the DAS include the monitoring of ambiance temperature. Three Maxim Integrated programmable resolution 1-wire digital thermometers register temperature in °C with a resolution of 9 to 12-bit. The thermometers include an Arduino compatible library, which facilitates the interface between the thermometer and the DAS. Each thermometer is attached to a respective PV module which allows the system to asses and monitor individual values.
- Environmental light intensity sensing: The incidence of luminosity over the PV modules is registered and transmitted by two photodiodes and a CMOS integrated circuit embedded into a TSL2561 ambient light sensor. The light intensity is converted to a 16-bit resolution output signal within the sensor and conveyed to the Arduino board by an I^2C interface. Output units provided by the sensor are W/m^2 yet the input light is registered in Lux.
- Inclination angle sensing: A tilt sensing system was developed and attached to the mobile charging station as a means to determine the angle of the PV modules towards the sun. The system comprises basically an accelerometer and a data bus wired to the Arduino board. An accelerometer is a device that can be used to determine pitch and roll orientation angles of a specific plane by calculating the difference between any linear acceleration in the accelerometer's reference frame and the earth's gravitation field vector [PED-13]. The selected accelerometer module was an ADXL345 3-axis MEMS. The breakout board for this module features an onboard 3.3V voltage regulation and level shifting which simplifies its interface with the Arduino board.

In order to centralize power and control signals' incoming into the mobile charging station, a printed circuit board (PCB) has been produced. A PCB allows data to be transmitted between electronic devices - in this case sensors and Arduino - replacing bulky breadboards as well as light detachable resistances and capacitors. The schematic diagram of the developed PCB is included in appendix 9.2.

The Arduino offers a software component called "Arduino IDE" that provides the user with a programming platform to manage and control the interaction between the Arduino board and the devices attached to it. A program to monitor the electric values from the PV array, stand of battery bank and sensors' data has been developed for the mobile charging station under this open platform to support and improve the knowledge transfer effect. The program, presented in appendix 9.3 generates data strings as input for a front-end interface presented next.

6.1.4.3 Front-end interface

The front-end interface, depicted in figure 36, is a user-friendly, language-independent interactive application developed to serve as link between the end user and the PV system elements.

In the interface, virtual representations of the real PV components introduced in the previous section are visually displayed as interactive elements with which the learner can familiarize easily. Data logs provided by the DAS are transmitted in real-time allowing the user to observe the effects of environmental variations over specific elements' outputs. By this mean, the user will receive immediate feedback when the system is altered, and will be able to observe for instance how the system's power output varies as temperature increases.

A major characteristic of the interface is its data-saving and analysis tool. Through this feature, information strings consistent of output information of every major component can be compared as environmental variables are modified. The information strings are saved in Excel spreadsheets facilitating their access and assessment in virtually any personal computer.

The interface is built on a Bootstrap framework, combining HTML and CSS languages to design the graphical interface and a JavaScript jQuery library for data processing, event handling and measurement presentation. The programming code and documentation is included in appendix 9.4.

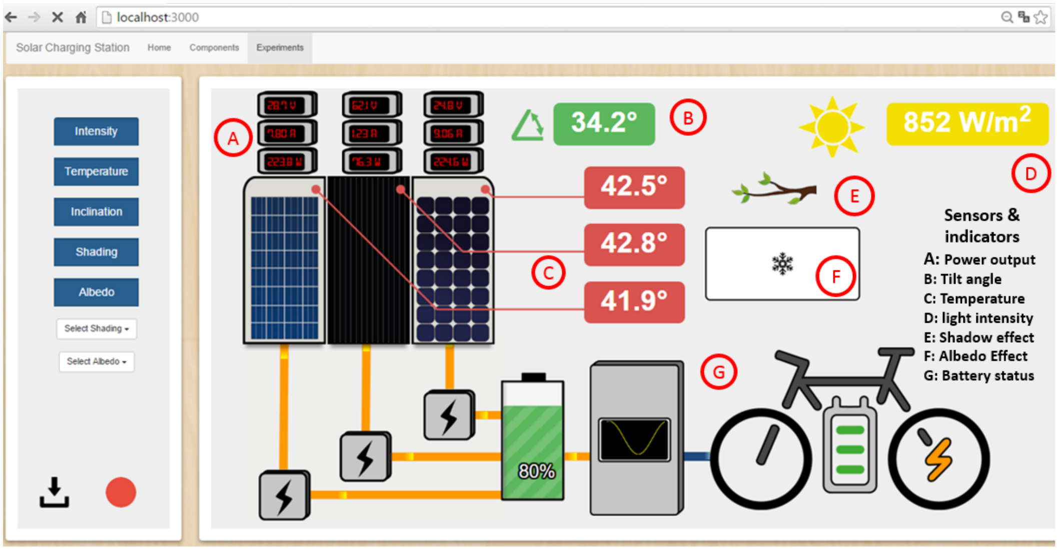


Figure 36: Front-end interface - Mobile solar charging station

The knowledge transfer approach pursued by the interface is centered in the conduction of a set of real-time experiments, described thoroughly in the upcoming sections, in which the user is allowed to modify environmental and systemic conditions bound to the mobile charging station and observe its immediate effects over the station's power output or the E-Bike's current loading status. These effects are then recorded in databases that serve further analysis purposes conducted by the user in order to correlate theoretical knowledge with practical observations.

6.1.4.4 Experiments

- Photovoltaic conversion: The first topic the user is expected to get familiarized with while getting in contact with the solar charging station is the characteristic parameters of PV modules. According to the previous user's knowledge in the field of electricity, concepts such as voltage, current, power and resistance are initially reviewed by means of general IV curves of the modules. Once these basic concepts have been understood, the user is introduced to the front-end interface of the mobile charging station, where graphical representations and a real-time output data display for each one of the three included PV technologies are permanently displayed. These data consist of voltage, current and power transmitted by the system's charge controllers. The intention of the permanent data gauges displayed for each PV module is to allow the interface user to visually track, and later on also record, variations in each PV module's power parameters caused by the modification of environmental variables. The user is also able, through save and analysis functions included in the interface, to perform comparative analyses between the modules and their responses to environmental changes.

- Temperature dependence: PV modules are semiconductor-based power generation elements that, as most electric components, are temperature-sensitive. Solar irradiance directly affects the module current in a proportional rate. This means that by an irradiance drop of 50 %, the generated power drops by half. In contrast, the voltage MPP remains almost unchanged. On the other hand, the module voltage is inversely affected by temperature variances due to the decreasing band gap of the semiconductor, which affects the intrinsic carrier concentration in the solar cells' open circuit current. In other words, an increase in the environmental and / or systemic temperature results in a decrease of the voltage output, while a decrease in the temperature would increase the power generation [DGS-13]. Most thin film modules are composed of semiconductors with a larger band gap, they are less sensible to variations in their power output due to temperature variations. Users of the charging station are able to observe and analyze this phenomenon by increasing the temperature and plotting the power output of the individual modules of the PV array. The heat induction process is realized through a customized conduction heating system shown in figure 37, which consists of an encapsulated heating foil capable to raise the system's temperature in up to 45°C. the system is placed beneath the PV array and reaches its maximum temperature after approximately 10 minutes. During this time, electric parameters of the PV modules are registered against time by the system. With this information, the user is able to empirically determine the temperature-power coefficient of each technology and compare it against the theoretical values presented previously.

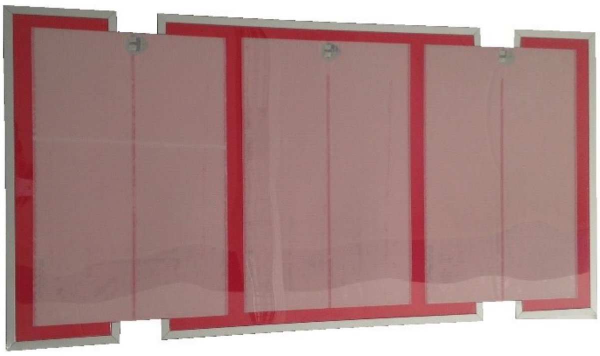


Figure 37: Customized PV modules heating system

- Intensity dependence: Due to the photovoltaic principle they are based on, PV modules' power output is also determined by the amount of light photons, striking onto their surface. During the intensity dependence experiment, the user is presented with technical specifications, in form of IV curves corresponding to each of the PV modules attached to the mobile charging station. Since the short circuit current of almost any PV module (j_{sc}), is equivalent to the number of electron-hole pairs generated by its absorbed photons, it is valid to assume that the system's power output is proportional to the light intensity to which it is subjected [WUE-05]. Similar as with the temperature dependence effect, the user of the mobile charging station is able to corroborate theory by artificially increasing light incidence over, either the complete PV array, or over the individual modules. The outcome in terms of power output variations in each module can be again assessed by means of the save and analysis function of the interface.

- Inclination angle dependence: The term “solar constant” describes the solar radiation incident on a perpendicular unit of a surface area outside Earth’s atmosphere. While this value is relatively stable (1376 $\frac{W}{m^2}$), the radiation incident on Earth’s surface varies widely according mostly to atmospheric conditions, the latitude of the geographical location, as well as the season and time of the day [DGS-13]. These variations have a significant impact on the light incidence over the system and therefore its power output. Concerning thus the angle between a PV module and the sun, the power output of the first will always be at its maximum when the module is perpendicular to the sun. However, since the angle between the sun and a fixed surface changes throughout the day, the power output of a fixed PV module will be timely dependent. Consequently, in order to utilize the optimal solar power throughout the year, the inclination angle of a PV module must be continually modified. In the mobile charging station, the flat arm supporting the PV array mechanically permits tilting angle variations from 0° in the horizontal plane to 90° in vertical plane to the ground. The user is then able to manually modify the angle of incidence and observe resulting power output. The tilt angle is obtained by the embedded sensor and displayed in the front-end interface. Angle variations and corresponding power outputs can be, as in previous cases, registered and plotted fur further analysis.

- Shadowing effect: Casting a shadow over a PV module active surface has grave consequences in terms of power output losses as individual cells power might enter their reverse zone, a phase in which they stop delivering power and start consuming it [DIA-10]. The density of those losses is initially complicated to estimate as they depend on the type of the module, the way in which cells are connected, e.g. with or without bypass diodes, and the type of the shadow and the surface percentage it covers. In order to demonstrate this effect, the user of the mobile charging station will be able to determine the power loss in each module under specific shadowing conditions. For this, he or she will select among several cardboard silhouettes representing shadows casted by physical objects over a pre-determined surface percentage and place it directly over the array modules. A virtual version of the same objects can be selected and dragged to the modules in the interface in order to mimic the real setup. By recording the power behavior of the modules, the user is able to determine the effect of similar shadowing conditions in the different modules.

- Recognition of defect modules: One final experiment on the solar charging station consists in the determination of the effects of a broken cell within a PV module. For this purpose, a PV polycrystalline module with a broken cell used is installed in the array. The defect cell can be identified at plain sight through careful observation, yet the task of the users is to register the performance of the defect module also under modification of environmental variables and compare it to the results obtained with the regular module.

6.1.4.5 Mobility

According to the “who” dimension specified in 6.2.2, the solar charging station is to be designed as a knowledge transfer enabler to support education in the field of photovoltaics in Latin America. Acknowledging the current deficits in terms of educational infrastructure existing in the region, as well as the need of high-class laboratory equipment to achieve high-quality education in the area of renewables, mobile physical laboratories provide an alternative to increase the dissemination range of education efforts in the fields of renewable energies. Advantages of creating mobile physical infrastructure are manifold. Decentralized laboratories allow on the one hand shared-ownership schemas among educational institutions and other stakeholders increasing utilization rates and decreasing initial investment and maintenance costs. Mobile laboratories open also the possibility to create local value with business models based on equipment renting or leasing. Most importantly, a broader geographical reach generates a biggest impact in the amount of total final beneficiaries.

Enabling mobility of a medium-sized training station such as the mobile charging station carries challenges ranging from obvious system design aspects such as component modularization and selection of lightweight elements to less evident attributes. Costs are a crucial variable, as an incentive to local infrastructure reproducibility generating thus a sense of ownership and fostering local further development. Further planning considerations include the design or selection of transportation elements, e.g. cases, as well as the review of international and regional shipping policies.

In the specific case of the mobile solar charging station, the system consists of de-attachable single modules that fit three lightweight custom-made shipment cases depicted in figure 38. The total weight of the system mounts up to 53 kg. The weight and size of the filled transport cases comply with IATA flight regulations and are therefore suitable to be documented as checked luggage in most conventional airlines. The total volume of the solar station in transport mode (0.33m^3), allows also land transportation by means of regular-size SUV. With total prototype material costs of less than 7.400 €, the station presents an affordable option for many higher education institutions or education consortia.

Figure 38: Solar charging station in transport mode

6.2 Wind energy course

A higher education course covering principles of aerodynamics, wind energy and design of wind turbine components has been developed as a means to train specialized wind energy professionals. Core audiences of the course are higher education undergraduate and graduate students. However, infrastructure and content flexibility allows shorter course versions for professionals or secondary education students. The primary objective of the course is to facilitate learners theoretical, practical and design knowledge in wind energy technologies, with a special focus in the design of wind mills' rotor blades. The two-semester course combines conventional lecture approaches with practical experiments in a mobile wind laboratory comprising an open-looped wind tunnel, sophisticated wind turbine mock-ups and an intuitive back-end / front-end controlling interface. The experimental component of the course intends to physically demonstrate the principles of wind energy conversion, as well as the challenges by the design of complex wind energy components through a cognitivist-constructivist approach. The course planning following the proposed IDMEE follows below.

6.2.1 What

The course "Utilization of Wind Energy" has been a core module of the renewable energies specialization of GPE since 2013. Lectured by experts with over 20 years of expertise in the field of wind energy, the module focuses in conveying basic, intermediate and advance knowledge in: (I) wind physics, (II) the components of wind turbines, (III) the flow of power from the wind to the rotor, as well as (IV) the aerodynamic and mechanical behavior of rotor blades, leading to the determination of wind turbines power curves [GPE-15]. Learning objectives of the course are formulated in table 17.

Table 17: Learning objectives "Utilization of Wind Energy". Adapted from [GPE-15]

Cognitive level	Learning objectives - By the end of the seminar you will be able to:
Comprehension	Understand wind energy physics
Knowledge	Recall wind turbine components
Comprehension	Understand Betz theory
Application / Analysis	Calculate optimal rotor configuration and design according to Betz theory
Knowledge / Comprehension	Recall and be able to explain rotor performance variables and load behaviors
Knowledge / Comprehension	Recall and be able to explain drive train components and concepts
Knowledge / Comprehension	Recall and be able to explain stall and pitch controller concepts
Knowledge / Comprehension	Recall and be able to explain working principles of wind turbines' electrical systems
Knowledge / Comprehension	Recall and be able to explain technical operation concepts of wind turbines
Knowledge / Comprehension	Recall and be able to explain manufacturing processes of wind turbines
Application	Employ specification sheets of wind turbines and rotor blades
Analisis / Evaluation	Analyze and evaluate wind turbine /rotor blade performances
Synthesis	Design and produce wind turbine rotor blades
Knowledge	Recall future technological developments

6.2.2 Who

Global Production Engineering (GPE) is a full-time international master's program offered at the (TUB). The curriculum is designed for outstanding international graduate students seeking to improve their personal competence portfolio in the fields of production, management, engineering, and intercultural communication [GPE-15]. The program hosts an average of 60 students per year, thoroughly selected out of a pool of over 1500 applicants, originating from over 40 developing countries.

GPE has a specialization in New Energy Technologies (GPE-NET), which is particularly oriented to the requirements of enterprises in the field of renewable energies. As part of GPE-NET's curriculum, the course "Utilization of Wind Energy" addresses international graduate engineering students commonly wielding an undergraduate degree in electronic or mechanical engineering. The majority of the program participants possess little to no previous experience in the field of wind energy but an obvious interest to acquire it. Individual participants' motivation to engage the module varies, mostly referring to perceived economic and environmental potentials offered by wind energy technologies in their countries of origin.

Besides the platform offered by GPE-NET, leaner and / or compact versions of the course are offered for a broad fan of audiences ranging from primary and secondary education students to professionals with a particular interest in the field of wind energy. Strategically, two implementation approaches have been defined according to the target final beneficiaries:

- "Open house presentations" aimed to stimulate interest in the field of wind power generation in younger generations by means of easy to follow instructions, visually appealing animations and an interactive interface. K-12 audiences are a representative example of these target audiences.

- Full modules addressing engineering students, technicians as well as professionals and researchers with prior knowledge in the field of power generation, who wish to get a profound insight in wind energy technologies including the development of rotor geometries for wind turbines.

6.2.3 How

The GPE-NET module "Utilization of Wind Energy" consists of a two-semester long blended course that integrates conventional frontal teaching with embedded hands-on laboratory experiments. The module aims to stimulate a cognitive and constructivist thinking in the learners by providing them with theoretical and practical design means and tools to develop their own wind turbines components, specifically rotor blades, as well as the physical infrastructure to test their performance.

During hundred-twenty hours, distributed along two semesters, learners experience theory lectures and experiments held and supervised by experts in the field of wind energy. Individual seminars on topics such as aerodynamics principles, aerodynamic of wind turbines, characterization and dynamics of wind turbines, electrical and mechanical components of wind turbines, rotor blade design, wind turbine design and control, and electric load simulation are intercalated with practical exercises in a customized wind laboratory where theory acquired within the classroom is immediately applied and validated. The module is concluded at the end of the second semester with the conduction of a group project, in which learners' teams are compelled to implement their knowledge and experiences gained throughout twelve months, by designing and constructing a set of rotor blades with specific performance specifications set by the lecturing team. The performances of rotor blades' sets presented by the student teams are determined and compared in the laboratory facilities and the outcome is discussed in the final session of the module.

The pedagogic concept of the module is based in five elements:

- Face-to-face conveyance of theory content relevant for the understanding of wind energy generation, including aerodynamic concepts and mathematical equations. Depending on the audience's background, basic concepts of power generation such as voltage, current, electric load can be integrated into the course and explained based on the turbines power output. Audiences with a higher understanding in the field of electric power generation are presented with concepts and equations corresponding to wind turbine power coefficients, power curves as well as mechanical and electrical losses.
- Conveyance of knowledge with regards aerodynamic components design. A strong emphasis will be put in design techniques of wind blades.
- Practical validation of theoretical concepts through presented in class, by means of the interaction with mechanical components of full-operational wind turbine mock-ups as well as real mechanical and electrical control systems. Users are expected to achieve a better understanding of core components of wind turbines and their power generation function. Sophisticated control mechanisms such as pitch angle steering, and electric load variation need to be physically demonstrated to familiarize the user with the parameters with the highest influence over the power generation.
- Computational infrastructure is required to support the audience as platform for the validation of aerodynamic equations provided by the course's lecturing staff. A bidirectional interface with data-analysis capabilities is necessary as it allows audiences to intuitively deduct and correlate cause-effect relations between relevant variables such as the influence of wind speed over the amount of power generated by a windmill. The intended effect is to enhance understanding and retention of aerodynamic and power generation concepts through self-interpretation of the results conducted during experimentation. This is to be achieved with minimum input on behalf the training staff during the conduction of the experiments and the assessment of results.
- Use of cognitivist and constructivist learning theories to enable learners to build their own knowledge based on the theoretical and practical basis provided by lectures and exercises. At the end of the instructional event, learners are not only supposed to understand concepts, but also apply them in real case scenarios. The final course's project will require them to design own windmill components partially based on the theoretical input provided by the teaching staff, but most importantly based on the experiences they won during the conduction of experiments throughout the year.

6.2.4 By which means

Once more, following the Design or Select decision making process suggested in 5.1.5.1, a market research was conducted in order to determine if commercial systems were available that could fulfill the learning objectives proposed in 6.2.1 and serve learners' audiences detailed in 6.2.2. In this sense, an online and literature search was conducted to identify mobile wind tunnels designed as pedagogic instruments to support the delivery of the course's instructional content detailed in table 17. A selection of the products encountered during this research phase is presented in appendix 9.5

Numerous wind energy laboratories for didactic purposes in various educational stages exist in the market. Companies such as Gunt, Edibon, Armfield, offer a selection of low-speed Eiffel wind tunnels, or similar devices, to conduct aerodynamic experiments for multiple purposes, including conveyance of wind energy concepts [GUN-16b]; [GUN-16c]; [GUN-16d]; [EDI-16b]; [EDI-16bc]; [ARM-16]. A few of them can even be considered mobile featuring weights ranging from 15 to 50 kg. However, none of the commercially available products found during the conduction of the market research fulfilled entirely the pedagogic and structural requirements of the course. Shortcomings manifested by the existing products were also to extensive to be overcome with customized solutions. For starters, only 30 % of commercially available products found, displayed transportability traits capable to serve the target audiences described in 6.2.2. These mobile wind laboratories, were either unsuitable to conduct wind energy experiments, being rather devices focused in the visualization of streamlines [GUN-16d], or lacked the computerized interface to conduct multi-variable bidirectional control and data analysis required by objectives of the course [EDI-16b]. All of the commercially available laboratories lacked particular features deemed by the instructional designers as indispensable for the conduction of the course. These features included pitch control mechanisms embedded in windmills and the possibility of integrate students' designed and manufactured components, needed for their final project.

Due to the inexistence of commercially available products, which satisfy pedagogic and mobility characteristics deemed by the instructional designer as essential, a portable wind laboratory (hereinafter WindLab), firstly reported in [PAL-15], was designed and developed at the institute of machine tools and factory management from the Technische Universität Berlin (TUB). The primary objective of the WindLab is to serve as hands-on component of the course "Utilization of Wind Energy", part of the curricula of the international master's program "Global Production Engineering" (GPE). However, the WindLab has been explicitly designed as a mobile laboratory to also assist instruction in education institutions in developing countries. The WindLab consists of a combination of physical and virtual elements interacting over a JavaScript application. The WindLab has been designed to facilitate experimentation and project-based learning in young audiences providing them with intermediate and advanced knowledge in aerodynamics and wind energy. The ultimate WindLab objective is to build local human capacities, responsible of disseminate and popularize the use of renewable energies in their countries, while at the same time serve as increasing the locally available professional talent pool required by the industry sector. By means of a bidirectional front-end interface for instance, users of the WindLab are progressively introduced to concepts such as power generation parameters, elements of wind turbines, turbine efficiencies, as well as components design. Design specifications elaborated following the design method proposed in 5.1.6.3 are shown in table 18.

Table 18: Design specifications WindLab

Type	Objective	Design Criteria
Learning	Understand wind energy physics	Integration of stroboscope to analyze wind dynamics in measure chamber
	Recall wind turbine components	Development of real wind turbine mock-ups including core electro-mechanical components
	Understand Betz Theory	Plotting function of C_P-λ curves
	Calculate optimal rotor configuration and design according to Betz theory	Plotting function of C_P-λ curves

	Recall and be able to explain rotor performance variables and load behaviors	Plotting of power curves
	Recall and be able to explain drive train components and concepts	
	Recall and be able to explain stall and pitch controller concepts	Integration of pitch control mechanism in wind turbine
	Recall and be able to explain working principles of wind turbines' electrical systems	Generator / motor analysis
	Recall and be able to explain technical operation concepts of wind turbines	
	Recall and be able to explain manufacturing processes of wind turbines	
	Employ specification sheets of wind turbines and rotor blades	Plotting of C_P-λ and power curves
	Analyze and evaluate wind turbine /rotor blade performances	Plotting of C_P-λ and power curves
	Design and produce wind turbine rotor blades	Utilization of additive manufacturing technologies to produce customized rotor blades; fixing mechanist to adapt constructed blades
	Recall future technological developments	
Structural	Mobile	Modular design involving detachable components, robust, constructed out of light materials, transportable by one person in commercial flights and SUVs, assembly to be conducted by one person, intuitive assembly
	Features of wind tunnel	Target wind speed: 12 m/s, transparent measurement chamber to house wind turbine mock-ups with a maximum height of 40 cm and 20 cm diameter.
	Features of wind turbine	Real turbine mock-up with integrated control electronics, pitch angle, and data acquisition system. Flexible rotor blade insert mechanism.
	ICT features	"Intuitive" bidirectional front-end interface to allow parameters control and display of data
	Dimensions	Maximum surface of tunnel in operation mode: 2.0 mt2; Maximum dimensions in transport mode 0.5 m3
	Weight	Total weight including transport case less than 60 kg
	Safety issues	Measurement chamber as safeguard against loose airfoils
	Costs	Maximum material costs: 10.000 €

The design specifications depicted above summarize both, the learning objectives specified in section 6.3.1 and the structural objectives required to reach the target audience described in 6.3.2. Structural design objectives should also ensure a smooth and safe implementation of the WindLab despite adverse infrastructural conditions and include cost and reproducibility dimensions to foster local multiplication efforts. Specification of following items was required during the design phase. The functional structure proposed by designers included:

- Purpose: A training station to support hands-on education in the field of wind energy should be designed as a mobile laboratory.
- Technical specifications: The mobile WindLab should consist in a subsonic wind tunnel with a maximal wind speed of 12 $\frac{m}{s}$ and a laminar wind flow.

- Mobility: The device is to be transported by means of medium-size land vehicles with a truck or back seat capacity of maximum $0.5m^3$ or as check-in luggage in commercial flights.
- Dimensions of built-state: The training station should not exceed 1.6 m^2 of working area once fully assembled.
- Training focus: The WindLab will serve entirely teaching purposes. Two main focus groups are to be considered as knowledge transfer beneficiaries. On the one hand, students of the international master program GPE-NET at the Technische Universität Berlin and on the other, primary, high school, undergraduate and graduate students in developing countries. The utilization frequency of the training station is estimated to be once a week with a mean running time of five continuous hours.
- Low cost: As a means to foster reproducibility in developing countries. Globally economically accessible components and materials are to be utilized during the manufacture of the training station.
- Robustness: Given the uncertainty regarding the type of showroom and its infrastructural characteristics while presenting the WindLab abroad, the system had to fulfill following criteria in terms of mechanical design:
    - Light structure - The overall weight of the device in transport modus should not exceed the 32 kg. This constraint is given by the hold luggage limits set by the IATA.
    - Resistant to corrosion - Corrosion of main components of the device such as turbines, rotor blades and tunnel body should be avoided regardless the environmental conditions of any given exhibition site.
    - Robust materials - Intended users of the training station include K-12 and undergraduate students. Direct interaction with the device is encouraged.
    - Safe electronics - The electronic backbone of the device is to remain locked away from the audience as a means to avoid potential misuse and harm to users and / or equipment
    - User safety - As revolution speed of the turbine rotor blades is expected to reach high velocities. The audience, which is allowed to take a closer look into the turbine while in operation, should be protected from a loose airfoil. A measurement chamber capable to uphold a high-speed rotor impact is thus mandatory.
- The wind tunnel should serve as platform to conduct at least five core experiments:
    - Introduction to wind energy turbines: In which basic components -including their functionalities- of conventional Horizontal-Axis Wind Turbines (HAWT) such as tower, rotor blades, generator, nacelle, and power electronics are presented to the users. Additionally, aerodynamic and electric concepts such as angle of attack, voltage, current, power coefficient and electric load should be introduced to the audience.
    - Speed-up test: Users should be able to understand the effects of controllable variables such as wind and rotor speed, as well as rotor blades' pitch angle over the mechanical and aerodynamic rotor power coefficient.
    - Calculation of power output: The audience is also to be introduced to the energy generation principle of wind turbines. The power output and losses of the wind turbine generator in relation to its power coefficient and controllable variables should be thoroughly explained

- Wind turbine control: the two control types present in most conventional wind turbines, namely the torque control and pitch control, and their purposes should be explained.
- Design of rotor blades: WindLab should serve as experimental platform for the trying of students' self-designed airfoils
- Moreover, fluid dynamics of fog and wind around the rotor should be demonstrated to the audience.

6.2.4.1 Wind tunnel

A wind tunnel is a device commonly utilized in aerodynamic research to assess effects of a wind stream over a specific object mounted in the center of a so-called test section. Objects of study are commonly aircrafts, or aircraft components, aerodynamic components from the automotive industry, as well as wind energy turbines and their corresponding rotor blades. The test section fulfills several purposes. On the one hand, it accommodates the test object and a series of support devices such as manometer, pressure sensor, anemometer, and fog generator. On the other hand, it keeps the test conditions in terms of wind speed, pressure and humidity controlled within the cross section of the system [ANS-14]. Wind tunnels are designed to serve a specific purpose and speed range [NASA-15]. Mostly due to dimension constraints and power performance, a subsonic wind tunnel serves the learning objectives established in 6.2.1 the best.

According to its layout and construction type, subsonic tunnels can be classified in two types: Open-loop tunnels (aka Eiffel tunnels) and closed-loop tunnels, aka Göttingen tunnels [ECK-97]; [BAR-99]. Advantages of Eiffel tunnels over their closed-loop counterparts include smaller dimensions, ease of design and lower costs [ECK-97]; [GON-13]. These characteristics are fundamental to achieve the intended mobile characteristic of the WindLab, reason why this tunnel type was selected to continue with the design.

Figure 39 portrays the basic architecture of an Eiffel wind tunnel consistent of:

- A settling chamber commonly comprising air filtering screens and a honeycomb mesh. The chamber will reduce fluctuations in the transverse air velocity straightening and stabilizing out the inflow. External air turbulences are just mildly countered [BRA-15b]
- A contraction cone also known as nozzle characterized by a continuously decreasing cross section in which air is accelerated by pushing -or pulling- a large volume of air through its narrowest end [SCI-12].
- A measuring chamber in which model-sized mock-up of study elements, in this case a wind turbine, are placed. As its name suggests, within the chamber, sensors monitor diverse parameters relevant to the conduction of experiments.
- The diffuser is the gradually-expanding passage that keeps the air flow moving towards the fan. Due to its cross-section's increase, the air speed in this point decreases and the pressure raises as it exits the tunnel [BRA-15a].
- The fan, located in one of the tunnel's ends, is responsible to generate the system's air flow. This can be achieved either by blowing air into the system or drawing it. Most of the commercially available models though opt for the second variant as this reduces turbulence potentials and enables a homogeneous distribution of the air [BRA-15a].

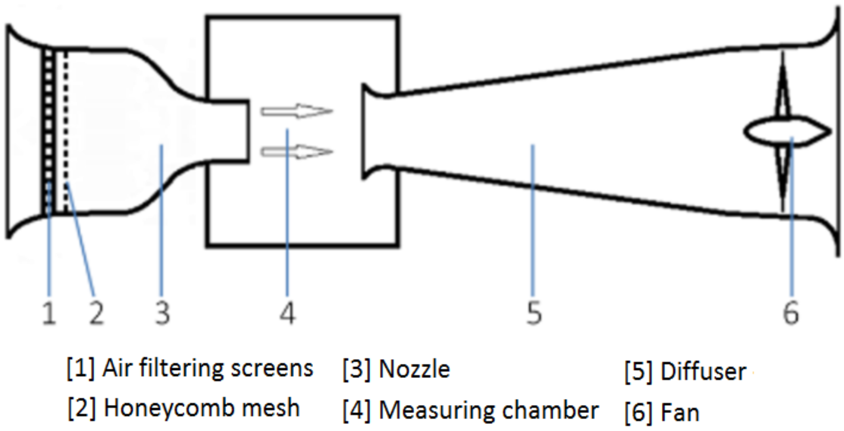


Figure 39: Eiffel tunnel basic components. Adapted from [ECK-97]

A state of the art analysis and a review of commercially available Eiffel tunnels, included in appendix 9.5, revealed that no currently available market options existed that complied with the performance and mobility specifications of the course's learning objectives. A customized Eiffel tunnel was therefore developed by the design team. A brief description of each components is included below.

Measuring Chamber: As opposed to most wind tunnels, the WindLab's main purpose is to test wind turbines with a much higher vertical than longitudinal axis. In order to be able to maintain the technical specifications listed in the design specifications cross section dimensions of nozzle's exit and diffuser's inlet needed to be determined from scratch. Following parameters were especially relevant:

- a maximum rotor trajectory diameter of 200 mm,
- a maximum wind speed of 12 $\frac{m}{s}$ at the contractor cone's exit.

The most relevant parameter to calculate the diameter of the cone and diffuser intersections with the chamber is the wind speed distribution in the different tunnel stages, which in turn directly depends from the withdrawn potential energy caught by the rotor. We can therefore consider three wind speed stages in a wind tunnel (figure 40): The wind speed in the exit of the nozzle (v_N), the wind speed impacting the rotor (v_R) and the wind speed at the diffusors entrance (v_D). Due to the conservation of mass theorem shown in equation 1, we can deduct that without a slowdown effect of the rotor blades turning, the nozzle wind speed would equal the wind speed in the diffuser entrance ($v_N = v_D$), this in turn would mean that the power output of the rotor is zero. The opposite extreme would assume a totally blocked airflow rendering thus v_D= 0 [GAS-05].

$\dot{m} = \rho \cdot v \cdot A = \text{constant}$……………………………………………………………………[1]

Where:
$\dot{m}$ = Mass flow rate
v = Velocity
A = Area
ρ = Air density

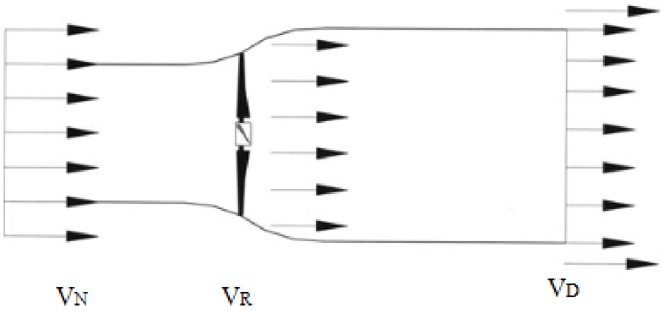


Figure 40: Wind speed distribution in a wind tunnel [GAS-05].

The Froude-Rankine theorem establishes that the optimal energy transformation can be determined according to the following equation.

v_R = ½ ($v_N + v_D$)…………………………………………………………………………[2]

The optimum relation between V_R and the other two stages can be derived from the Betz theorem expressed in equation 3.

$$P_W = \tfrac{1}{2} \cdot \rho \cdot F \cdot v_N \left[\tfrac{1}{2} \cdot \left(1 + \frac{v_D}{v_N}\right) \cdot \left(1 - \frac{v_D}{v_N}\right)\right]$$

……………………………………………………………………[3]

Wind Energy $\quad$ C_P Power coefficient

Where:
P_W = Extracted power
F = Circumference area from rotor blades
ρ = Air density

According to Betz theorem, the maximal extractable power output out the potential wind energy is limited by a maximum C_P power coefficient of 0.59, which appears when $v_D = \frac{1}{3}\, v_N$ and $v_R = \frac{2}{3}\, v_N$. By a given $v_N = 12\,\frac{m}{s}$, $v_D = 4\,\frac{m}{s}$, $v_R = 8\,\frac{m}{s}$.

Referring again to the conservation of mass theorem in equation 1, it was deducted that:

$\rho \cdot v_N \cdot A_N = \rho \cdot v_R \cdot A_R = \rho \cdot v_D \cdot A_D$ ………………………………………………………[4]

And thus:

$$A_N = \frac{A_R \cdot v_R}{v_N} = \frac{\left((200mm)^2 \cdot \pi \cdot \frac{1}{4} \cdot 8\frac{m}{s}\right)}{12\frac{m}{s}} = 20933 \text{ mm}^2$$

$$A_D = \frac{A_R \cdot v_R}{v_D} = \frac{\left((200mm)^2 \cdot \pi \cdot \frac{1}{4} \cdot 8\frac{m}{s}\right)}{4\frac{m}{s}} = 62832 \text{ mm}^2$$

A minimum diameter of 163.25 mm for the nozzle's exit and 282 mm for the diffuser's entrance was therefore required to secure the necessary mass flow rate to achieve the maximum power output in the rotor.

Concerning the chamber walls, according to the requirements catalogue, visibility of the conducted experiments should be guaranteed from every viewer's perspective, yet at the same time the audience's physical integrity needs to be secured from potential loose airfoils turning at high speeds. Therefore, transparent and impact-resistant walls are required to form the body of a test section. During the design phase was also determined that the measuring chamber should serve as a transport container for further elements of the tunnel such as nozzle, diffuser, settling chamber and electronic components.

In conclusion, the end dimensions of the chamber shown in figure 41 are therefore determined out of mainly three factors:

- Dimensions of the wind turbine model
- Required airflow and power output requirements
- Mobility purposes

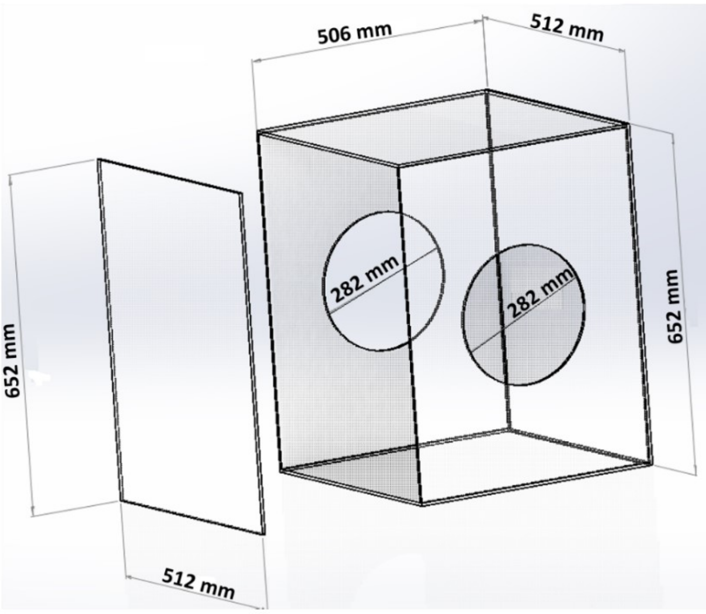


Figure 41: Test section design

Fan: Depending on the working principle and the position of its fan, a wind tunnel can be differentiated between a blower and a suction type. While in the first case the air flow is pushed into the diffuser by a fan located in the tunnels upstream, in a suction tunnel the air flow is extracted from the system by the fan located in the tunnels downstream facing outwards [PUR-10]. Regardless of its working principle though, the function of the fan in the tunnel is limited to the generation of a continuous air flow into the system.

There are several kinds of fans in the market divided mostly in two generic categories, namely centrifugal and axial fans, which in turn are further divided in subcategories according to its volume flow rate, induced pressure, space limitations and efficiency. Although axial fans are generally slightly less efficient than their centrifugal counterparts, they possess advantages such as smaller dimensions, less weight and a physical shape that suits better the mobile feature of the proposed wind tunnel. In this case, the VA08-BP70 Model of Spal Automotive proved to be the best suitable option due to its operation curve, which indicated better pressure drop compensation characteristics. Additionally, its physical characteristics (2.3 kg weight and a height of 382 mm) were proper for mobility purposes.

Nozzle: The nozzle or contraction cone is an extremely relevant component of each wind tunnel as it is direct responsible of the airflow quality throughout the system. Its aim is to accelerate exterior air into the measuring chamber in an ideally turbulence-free form. The degree of attenuation of air disturbances and speed increase depends on the contraction ratio between the contraction semi angles of the nozzle's inlet and those at its throat. In the case of tunnels for industrial applications, a contraction rate between 3.0 and 6.0, achieving up to 2 % turbulence, is sufficient [GON-13]. While designing the nozzle, two other criteria regarding the nozzle shape bear certain importance as well. The first one involves the minimization of the exit boundary layer thickness, the second recommends a minimum contraction length in the nozzle longitudinal axis [MEH-79].

In the case of the WindLab, mobility continues to be a fundamental design aspect. An inlet diameter of 450 mm with a contraction rate of less than 2 %, and a length of 525 mm was selected seeking a compromise between transportability and performance. Regarding the shape, mainly due to the round intersection with the test section, a cylindrical structure was deemed appropriate due to aesthetic and production purposes. [MEH-79] and [GON-13] recommend in this case to divide the nozzle in two segments of third degree polynomial curves (splines) in order to reduce pressure loss coefficients related to dynamic pressure in the narrow section.

Settling Chamber: The objective of the settling chamber is to improve speed uniformity of the airflow entering the contraction cone. Also misleadingly called "stilling section", as it is hardly long enough to have any significant effect in turbulence decay, the settling chamber is in most of the cases a preceding stage or even an extension component of the nozzle and is characterized by having the system's largest cross section. The settling chamber consists in most of the cases of honeycombs and / or screens that correct fluctuating transverse and streamwise velocity fluctuations [BRA-15b].

The design of the settling chamber in the WindLab, shown in figure 42, considered a mountable carrier including screen and honeycomb, which is fixed into the nozzle by an inlet. The extended inlet avoids unexpected border air inflow by sealing the elements juncture. Once mounted in the nozzle, the elements behave as a unit.

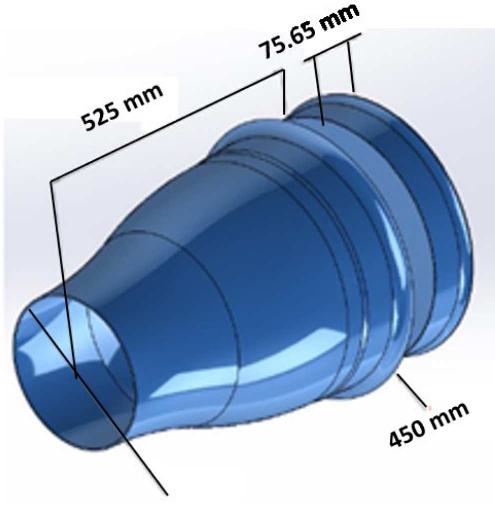


Figure 42: Nozzle and settling chamber

Diffuser: Diffusers in an Eiffel-type wind tunnels are mainly used as wind speed reducing and pressure recovery element [KRU-05]. As pressure in the measuring cross section is below atmospheric, the flow requires to recover pressure from kinetic energy in order to reduce the power to drive the tunnel. In the case of subsonic wind tunnels, diffusers are commonly cone shaped with a maximum semi-opening angle of less than 10°. Values of less than 5° are preferred though, in order to keep the turbulent boundary layer separated from the rest of the system [BAR-99]; [GON-13]; [BRA-15a].

In the case of the WindLab, the throat and outlet dimensions of the diffuser are constrains given by the measuring chamber intersection cross section (250mm) and the fan diameter (382mm) respectively. In order to comply with the open angle constraint, but also taking into account the measuring chamber-based transport concept, a total length of 915 mm has been determined as ideal functionality / mobility compromise. To adapt to the dimensions of the measuring chamber in transport modus, the diffuser has been divided in two detachable and nestable segments shown in figure 43 and figure 44. A semi-opening angle of 4% is obtained in this case.

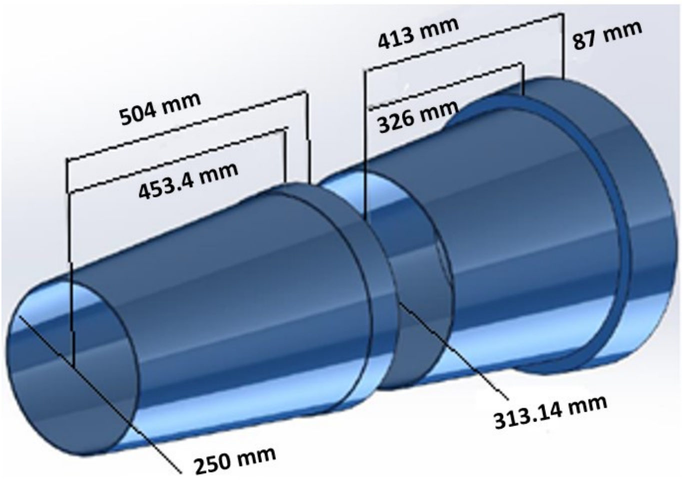


Figure 43: WindLab Diffuser

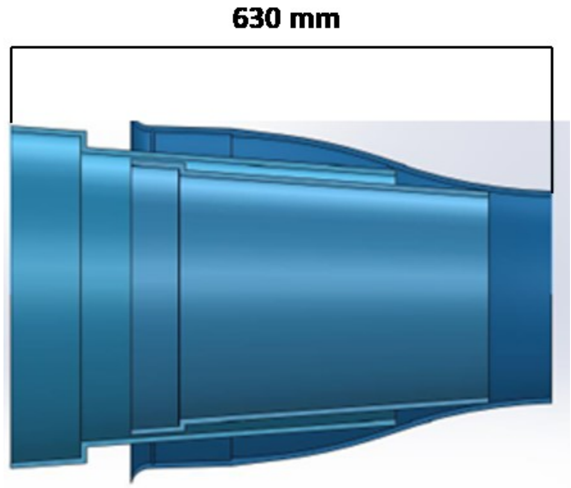


Figure 44: Nozzle and diffuser in transport modus

6.2.4.2 Wind turbine

With a height of 45 cm. and a total weight of 4.5 kg, the wind turbine model used in the WindLab (shown in figure 45) is a tailor-made, scale-sized mockup of a real windmill consistent of base, tower, hub, nacelle, rotor blades generator and an internal set of sensors registering air pressure, relative humidity, environmental temperature and pitch angle. In addition to its dimensional correctness, the turbine features a pitch angle control mechanism with a functionality to be described in section 6.3.4.4, which distinguish it from conventional models in the market.

Figure 45: WindLab's wind turbine

6.2.4.3 Back-end Data Acquisition System

WindLab’s hardware control and data acquisition system consists of a series of sensors, controllers and a micro processing unit that enable a real-time bidirectional data exchange and the interaction between user and system. Data to be registered by the sensors correspond mostly to either system control variables such as wind speed, simulated electric load and rotor blades’ pitch angle, all of them to be influenced by the user, or dependent variables consisting mostly in power output and rotor blades’ rpm attributable to a specific combination of control variables.

The core of the control and data acquisition system is embodied in an Arduino Due microcontroller board comprising a 32-bit ARM core microcontroller, 54 digital input / output pins, 12 log inputs, 4 hardware serial ports, 2 digital to analog converters, a USB port and a power jack (see figure 46). The Arduino is responsible to manage external input data generated by the user through the software component of the WindLab control system, to be described in the next section, and output information registered by the sensors mentioned above, which are located either in the wind turbine or directly attached to the Arduino through an expansion board. The communication protocol and control between software and hardware components is regulated by the Arduinos own firmware.

Both, the design and development of the control and data acquisition system, as well as the firmware programming were result of student projects conducted within the framework of this dissertation. The next sections will describe roughly the architecture and those components.

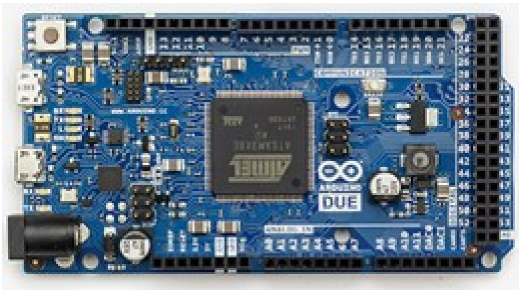


Figure 46: Arduino Due [ARD-16]

Wind Turbine's power output: Power generated by the wind turbine's generator is indirectly determined by the WindLab through the calculation of the product of current and voltage registered by the Arduino through its expansion board.

Voltage values are relatively straightforward to acquire as the Arduinos ADC can directly "read" up to 3.3 V values. However, due to the design requirements of the wind turbine, mainly regarding the target angular velocity of its rotor, it is nonetheless expected that the voltage input from the turbine will reach up to up three times this value, making necessary the introduction of voltage dividers prior to the Arduino's ADC.

Opposite to registering voltage, measuring current is conducted indirectly by applying Ohm's law in a voltage sink originated by a small resistance in a so-called four-wire measurement circuit. The four-wire circuit in the WindLab utilizes a small known resistance (0.1Ω) and the determination of the voltage drop through it to calculate current. An operational amplifier is incorporated to the circuit in order to amplify ten times the current signal up to a value readable by the Arduinos ADC current pin.

Rotor blades' angular speed: RPM are registered by the Arduino through a magnetic rotary encoder attached to the turbine's motor. The encoder is an electromechanical device able to sense rotating movement in either direction by generating quadratic waveforms in two or more channels, which are 90 degrees out of phase from each other. The rotary encoder included in the motor is a two-channel IE 2-1024 with a resolution of 1024 impulses / channel, a maximal frequency of 300 kHz and a maximum angular speed of 17578 RPM. However, due to its 5 V output signal, the data transmission from encoder to Arduino requires an intermediary buffer circuit with Schmitt trigger inputs to level-down the operating voltage to 3.3 V. A Fairchild' IC NC7WZ17 "TiniLogic UHS" data buffer was used for this purpose.

Control: When it comes to aerodynamic and electrical parameters affecting the turbines power output, there are several factors which are especially relevant for wind energy experts. Three of those, namely wind speed, electric load and rotor blade pitch angle have been included as controllable variables in the WindLab.

- Wind speed: The maximum wind speed of 12 $\frac{m}{s}$ established in the requirements catalogue is generated by an axial ventilator. The fan VA08-BP70 of SPAL Automotive is controlled by the Arduino microprocessor through a serial interface.

- Electric load: Wind turbines are not able to operate under "no-load" conditions, as doing so would inflict severe damage, even destruction, of the windmill as a whole. Therefore, an electrical load, also known as dump or diversion load, is necessary to regulate the speed up to which the rotor blades are going to be allowed to turn. The dump load can thus be defined as a physical-electrical component, such as a battery bank or the electricity grid that keeps the wind turbine working in its designed operating range [WIY-15]. In the WindLab this electrical load is simulated through a programmable current sink responsible to regulate the maximum generated current value. The current sink consists of an operational amplifier, an n-channel MOSFET (Q1) and a current sense resistor.

- Pitch Angle: The power output is also affected by the blade pitch angle, or the airfoil's angle of attack with respect to the relative wind angle [HEM-12]. Modern wind turbines are equipped with pitch control mechanisms that allow the turbine to modify the amount of lift force from the wind over the airfoil, thus increasing or decreasing its power generation capabilities [HEM-12]; [BOY-04].The WindLab features also an embedded electromechanical mechanism that allows it to control pitch angles of its rotor blades even during operation phases. The mechanism is based on a servomotor installed in the turbine hub controlled by the stepper motor driver SilentStepStick. The driver is in turn managed by the Arduino microprocessor.

6.2.4.4 Front-end interface

The computational architecture of the WindLab consists of an Arduino PC Board connected to a RS232 USB board, which is then wired to a Dell XPS 18 touchscreen PC. This PC acts as a bidirectional controlling / display front-end interface through which the user is able to steer variables such as wind speed, electric load and rotor blades pitch angle, as well as monitor power outputs and efficiency parameters.

The controlling architecture works as follows:

Electrical values generated from output sources are converted into low-level signal transferred by means of serial communication to the USB COM ports in the PC. From there, they are read by programmed libraries and interpreted by the controlling program through Application Programming Interface (API) abstraction layers. In the upper level, there is also an abstraction layer between the controlling program logic and the front-end interface This layer is written in JavaScript as a RESTful system so as to provide an http callable interface to set and extract data to-from the web based touchscreen and the low-level hardware controller logic. An advantage of using JavaScript is that every operation in the WindLab can be controlled and monitored through a web environment making it accessible from the Dell XPS 18 Desktop, but also in the future from any web or mobile device connected to the web enabling thus a combination of physical and remote teaching methods.

The interactive layer initially introduces the learner into a welcome screen guiding him / her throughout the experiment's menu, detailed in the next section, and the standard control interface where data gathered by the DAS is displayed in a user-friendly manner allowing interaction and control of the elements via touch screen.

6.2.4.5 Experiments

Every WindLab's experiment is conducted through the front-end interface described previously. A comprehensive description of each experiment is given below:

Introduction: Not being an experiment in the sense of data being collected and analyzed, the introduction consists of a virtual guided tour through the interface itself, and the WindLab components including the wind tunnel and wind turbine. This section familiarizes also the user with the control and operation of the mechanical, electric and software components of the WindLab. In this sense, the introduction section of the interface depicted in figure 47, allows the student to manipulate the tunnel's wind speed, as well as pitch angle and electric load of the wind turbine

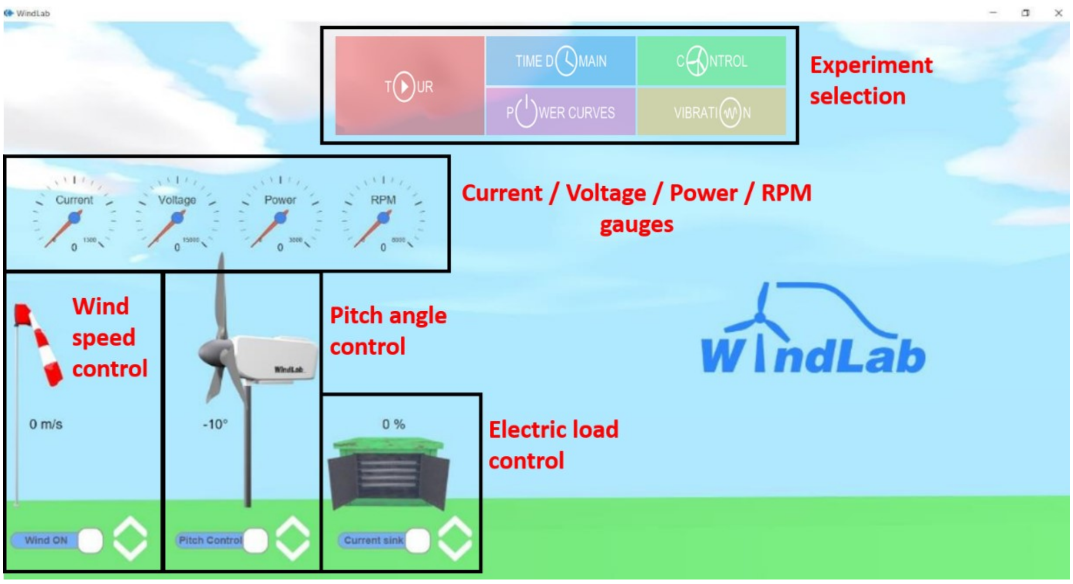


Figure 47: Introduction layout

During the introduction session, relevant phenomenological aspects like the visualization of airstream flows around the rotor by generating by means of fog generation inside the measuring chamber are also shown.

Time domain: Wind turbines are turbo-engines with variable outputs depending on the operational area in which they act. In order to understand fundamental concepts determining wind power generation, a "time domain" experiment has been included to explain the relationship between a rotor's power coefficient or efficiency (C_p), and its tip speed ratio (λ). Through the plotting of so-called C_P-λ curves, students will understand that λ is determined by parameters such as wind speed and the angle of attack, aka pitch angle, of the corresponding rotor airfoils. In real wind turbines, this pitch angle (β) is modified during operation to adjust to wind speed variations maintaining an optimum energy output.

The plotting of C_P-λ curves in the WindLab is achieved by means of a “speed-up test” in which the turbine rotor is brought from standstill to idling at a determined wind speed. Through the saving function of the interface, C_P-λ curves at different wind speeds are recorded and plotted by an integrated Matlab sub-function. The speed up is repeated then at different wind speeds in order to find the optimal operative tip speed of the turbine. Finally, the experiment is repeated this time varying the rotor blades’ pitch angle. By comparing the combined results of the experiments, users are able to determine the optimum λ and β values for a maximum power output.

Power curve: In the power curve section, the user is introduced to active power generation elements such as the generator. The main objective of the experiment is to determine power losses within the system by comparing rotational power coefficients to electric power coefficients. The experiment process is similar to the time domain experiment integrating now a variable generator load consistent of an electrical resistance. By modifying the resistance value and generating electricity the system approaches a new equilibrium of rotor torque and generator torque and thus rotor speed which consequently modifies the aerodynamic efficiency of the turbine.

During the experiment, the wind speed is set to 12 $\frac{m}{s}$, the pitch angle to 15°. The electric load of the generator is set to 0 %. As soon as the speed of the wind power plant reaches a predetermined value, the data saving process is started by clicking the "recording" function in the interface. Subsequently, hundred measurements are automatically recorded and stored, the arithmetic mean of these is saved and plotted by the Matlab integrated sub-function. After the first set of data is acquired, the load is gradually increased, depending on the required accuracy intervals from 1 %, 2 % or 5 % are possible. In parallel, the electric power is represented as a function of the speed in the interface. Once the load reaches 100 %, the last recording takes place, plots such as the one depicted in figure 48 are saved and the participants can proceed with the analysis.

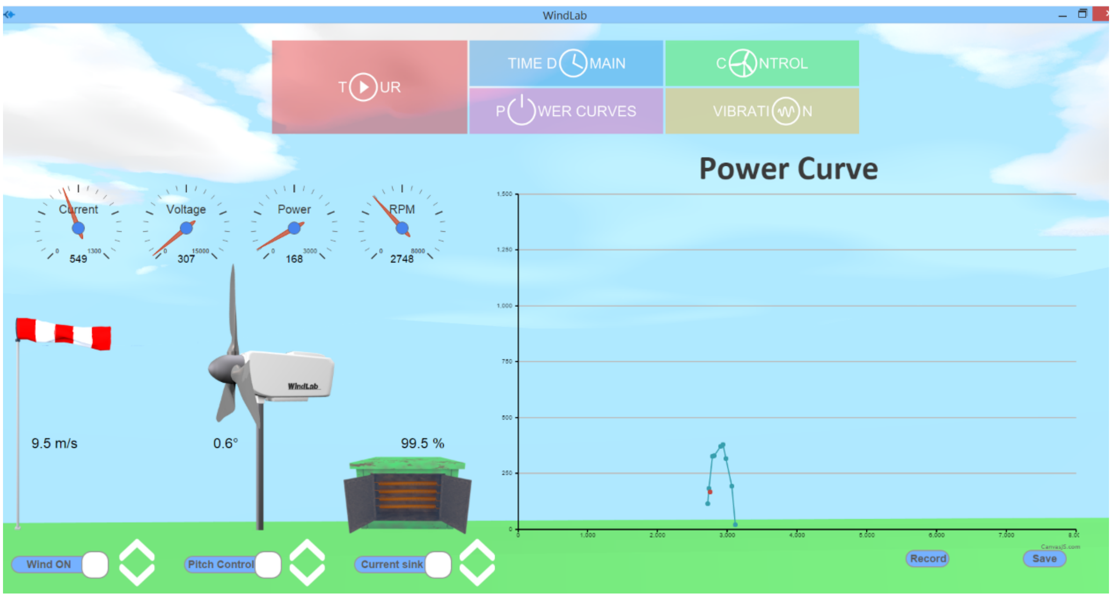


Figure 48: Power curve experiment

Rotor blade design: When introduced to this section, users of the WindLab are expected to be already familiar with relevant aerodynamic aspects responsible for the power generation in a wind turbine. In previous sections, concepts such as blades tip speed, pitch angle and power coefficient have been thoroughly explained.

Consequently, during this phase, users learn how the profile of mounted rotor blades influence these parameters. Arguably, the most important of these parameters is the tip speed ratio, which in turn is strongly influenced by the airfoils' geometry. According to [BUR-01] and [GRU-12] the most important parameters for rotor blades designers include:

- Blades length: Determines the "sweep area" or wind power capture diameter.
- Aerodynamic section: Cross-section profile of the blade, which creates lift and rotates the turbine.
- Planform shape: The planform gets narrower towards the end of the blade to avoid turbulences due to slow flowing wind.
- Airfoil thickness: Thickness increases towards the root to hamper mechanical loads and bending moments.
- Blade twist: A twist in the airfoil is required to maintain wind speeds along most of its trajectory outwards.
- Blade number: A maximum of three blades is considered to limit tip speed ratios to seven to ten times the wind speed.

Participants of the experiments design their own rotor blades. 3D prototypes of the designs are then printed through a stereolithographic process and attached to the turbine nacelle. The power curve experiment is then conducted anew in order to compare the power coefficient results against the standard blades. Exemplary blades produced by WindLab users are shown in figure 49.

Figure 49: Exemplary WindLab airfoil prototypes

6.2.4.6 Mobility

Mobility constraints applicable for the WindLab are basically delimited by cargo allowances of transportation means commonly accessible in developing countries. In case of intercontinental shipping, these constraints are defined by rules and regulations established by international organisms such as IATA. The design specifications defined in the requirements catalogue, clearly established the need for a device that could be transported as checked baggage in regular commercial flights as a means to reduce transportation costs and times. IATA regulations in this respect authorizes a maximum check luggage weight of 32 kg / 70 lbs. An international standard concerning luggage's size and shape dimensions does not exist, nonetheless the design specifications stressed the need to facilitate land transportation by means of medium-sized passenger cars and its handling by one person, which demands a minimization of space demand during the transportation modus.

The measuring chamber and its nested elements are then stored and handled in a customized transport case with 512 x 512 x 652 mm dimensions and a weight of 12 kg. The case consists of 6.5 mm lightweight polypropylene walls, a lower removable polypropylene cover hood, TSA accepted locks, three folding handles, adjustable feet and an internal rigid foam layer. The electronic set is stored in a second case with the same material features but with 512 x 512 x 228 mm dimensions and a weight of 9.6 kg. The electronics case, designed also to function as base for the larger one, include two 75 mm built-in corner rollers, plastic glides and connecting locks to secure both cases facilitating thus transportation of the whole system. Including the cases, the combined weight of WindLab components, depicted in figure 50, sums up 59.3 kg.

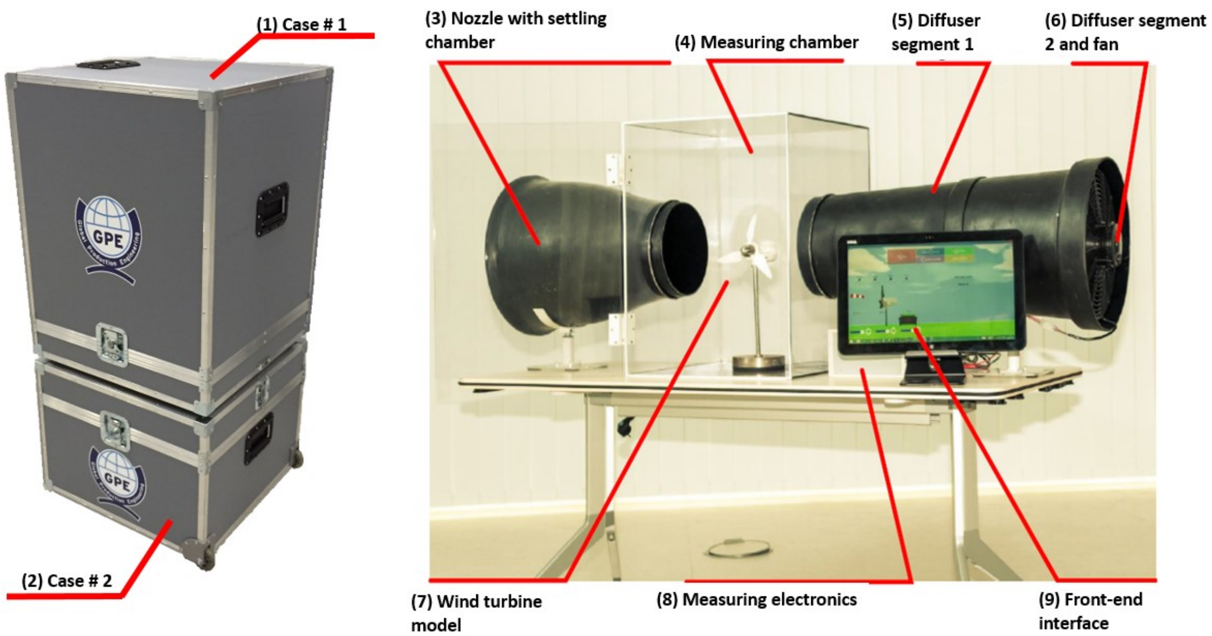


Figure 50: WindLab components; Left - Transport cases; Right - Tunnel, turbine, electronics and PC.

6.3 Practical course on sustainable manufacturing

A practical course has been developed as a means to provide higher education students with a strong foundation in the concepts, theories, and design engineering methodologies required to enable sustainable manufacturing. A non-formal format of the same course has also been developed to assist members of underdeveloped rural and informal urban settlements to generate value creation in their communities. The week-long practical course focuses in the conveyance of knowledge regarding production technologies, factory planning methods, production planning, quality-assurance and principles of sustainability in manufacturing, all thoroughly described in chapter 2, and deemed crucial for the development of manufacturing specialists' competences in section 2.1.5. The nature of the course is strongly based on constructivist and experiential learning approaches and encourages particularly active, sensitive and global learning styles. Following an introduction to the theory and concepts of manufacturing and sustainability, the practical component of the course challenges the participants to design, realize, manage, and operate real-life manufacturing processes within a Mobile Learning Factory for manufacturing (henceforth MLF). The MLF is equipped with tabletop machine tools and industrial auxiliary systems including handling devices and workstations to simulate real shop floor conditions.

The MLF is intended to serve as a low-cost mobile adaption of multi-million manufacturing learning facilities known as "learning factories", which have been comprehensively defined and described in a constantly growing literature including [LAM-95], [ELM-11], [WAG-12], [MAT-14], [KRE-14], and [CIR-14]. Conventional learning factories are gaining relevance in leading Higher Education Institutions in developed countries, however their immense investment, operation and maintenance costs, lack of technical and human resources, and limited contact to manufacturing industries, makes them currently inaccessible for instruction in impoverished regions of developing countries.

During the design of the MLF, a strong emphasis is put in the integration of sustainability methods. A thorough description of the course planning following the proposed IDMEE will follow.

6.3.1 What

Achieving sustainability in manufacturing is paramount for the accomplishment of UN's SDGs. Modifications in the engineering curricula suggested by field experts as a means to cope with the particular challenges of this sector have been addressed in chapter 2.1.3. Within the framework of the present dissertation, formal and non-formal practical courses in sustainable manufacturing were developed to enable graduates from engineering higher education programs to address modern industrial challenges, as well as members of underdeveloped communities in developing countries to create local socio-economic value. Both types of courses seek to, on the one hand familiarize learners with the value creation factors of Product, Process, Organization, Equipment and Human described in chapter 2.1.2, and on the other hand introduce methods and technologies aimed at reducing resources consumption in production, e.g. through the design and management of closed-loop product lifecycles. After the conclusion the course, learners are expected to be familiarized with conventional and sustainable production processes, technologies and methods, to be able to design and materialize value creation modules, and to improve existing productions systems and product quality. A set of concrete learning objectives to serve as strategical guideline for the development of the instruction courses is depicted in table 19.

Table 19: Learning objectives -mobile mini learning factory

Cognitive level	Learning objectives - By the end of the seminar you will be able to:
Knowledge / Comprehension	Recall and be able to define manufacturing terminology and concepts.
Knowledge / Comprehension / Application	Recall and explain specific production technologies and auxiliary systems. Be able to explain their functionality and operate them.
Knowledge / Comprehension / Application	Recall applicable manufacturing norms and guidelines. Be able to explain them and effectively employ them.
Evaluation	Be able to select appropriate production strategies according to company / business' objectives.
Application	Implement production tools and methods to enable production strategies.
Synthesis	Create factory layouts according to production strategies and methods.
Evaluation	Evaluate capacity planning in terms of material resources and personnel.
Application	Implement flexibility and changeability strategies within a factory.
Application	Implement concepts of ergonomics in workstation design processes.
Analysis / Application	Determine quality standards and implement measures to achieve them.
Analysis / Application	Determine inventories sizes and re-stock ordering points.
Application / Evaluation/ Synthesis	Determine sustainability potentials in the manufacturing process, apply technologies and methods to achieve sustainability, and devise own sustainability measures.
Evaluation	Assessment of proper production methods according to enterprises' business strategies.

6.3.2 Who

Target audience of the proposed practical course on sustainability practices in manufacturing consists on the one hand of undergraduate and graduate engineering students in developed and developing countries, who will contribute to fulfill the needs of national manufacturing industries in term of production specialists. On the other hand, the proposed course addresses members of rural and informal urban communities in developing countries as a means to incentive the creation of local value creation modules following a help for self-help approach.

In the first case, students of industrial, manufacturing, environmental and mechanical engineering are preferred due to their academic orientation towards the fields of production and sustainability. The practical course is oriented towards a holistic instruction in manufacturing including the integration of sustainable practices into conventional production systems and processes. The practical courses' ultimate objective is to train competent production specialists to attend the needs of local, national and international manufacturing companies. Technical and managerial competences are equally important in this case. Flexibility aspects within production and a deep insight in planning of resources and personnel capacities are mainstay components of the planned instruction.

Students of the TUB's international master's program "Global Production Engineering" (GPE) will serve as design reference for practical courses on sustainable manufacturing at a graduate level. GPE student's body consist of graduate international students mostly originating from developing countries. Most students of the program had already first contacts to manufacturing and are graduates from mechanical and industrial engineering programs in their home countries.

The intention of carrying out courses on sustainable manufacturing in impoverished communities in developing countries however, obeys the need to democratize education in the field of manufacturing as a means to contribute towards the achievement of global sustainability. The objective of the courses in this case is to enable members of local populations to generate socio-economic development through the generation of value creation modules and/or networks as a means to enrich their productive portfolio commonly limited to primary activities such as harvesting and collection. Embodied in a non-formal education event, as for being decoupled from formal educational programs, the involvement of local trainers is essential in this case with external experts facilitating knowledge exchange on a help-to-self-help context. Table 20 shows an example of topics to be taught according to the target audience.

Table 20: Example of teaching content. Academic vs. non- academic

Topic	Content	Engineering students	Community members
Introduction to manufacturing	Definition of manufacturing and assembly	X	X
	Manufacturing glossary	X	X
	Production technologies and auxiliary systems	X	X
	Norms and guidelines	X	
Production strategies	Make-to-stock, make-to-order, assemble-to-order	X	
	Mass production and push principle	X	X
	Lean manufacturing and pull principle	X	X
Lean manufacturing tools	Types and identification of Waste	X	X
	Value Stream Mapping; 5S; Kanban systems; Heijunka; Kaizen; Just in Time; One-Piece-Flow; Poka-Yoke; Single Minute Exchange of Die; Visual Factory	X	X
Introduction to factory planning	Definition of factory and factory segments	X	X
	Factory planning methodologies	X	
	Layout planning	X	X
Capacity planning	Equipment planning	X	X
	Material resource planning	X	X
	Personnel planning	X	
Change enablers in a factory	Changeability	X	
	Flexibility	X	
Workstation design and ergonomics	Workstation layout	X	X
	Physical, physiological and psychic ergonomics	X	X
Quality assurance and continuous improvement	Quality assurance basic definitions: Quality, yield, cost of quality, tolerances.	X	X
	DMAIC cycle	X	X
Supply chain	Key performance indicators: Restock ordering point; order fill rate; inventory management	X	X
Sustainable Manufacturing	Sustainable manufacturing premises: Resource and energy efficiency; design of closed loop production cycles.	X	X
	Reduce, recycle, reuse, remanufacture	X	X

6.3.3 How

A significant amount of engineering education researchers have claimed that education, especially in the fields of sciences and engineering, has neglected industry and national needs [STP-13]; [BAK-14]; [MIS-14]. Apelian credited this sentiment mainly to societal challenges experienced in the 21st century driven by the emergence of *"a connected, competitive, and entrepreneurial global economy, in which successful engineers increasingly need technical competency and professional skills that differ from what worked in the past"* [LAT-13]. Traditional instruction has failed to catch up with these demands, fostering conservative teaching models in which students acquire much factual knowledge, but little contact with real context and implementation scenarios.

In [REG-09], the authors summarized a set of differences that in their opinion were critical to explain the mismatch between classroom education and real-world professional demands. Arguably, the most notorious is the nature of the problems expected to be solved by the students or graduates. The authors argue that, while classroom problems are well structured, with defined solutions and created by lecturers based on previously covered material, problems faced by engineers in their professional life are commonly ill-defined, with solutions that vary with time and according to the context. According to the authors, these "wicked problems", as they chose to call them, are rarely dealt with during formal education events because their solution often implies the analysis of problems which cannot be foreseen, or are simply out of the scope of the given course. Authors in [RAZ-14] agree by claiming that manufacturing education cannot be limited to classroom lectures, as education practices followed so far have been deficient in provide the industry with specialists with multi-disciplinary and soft-skill competences [REZ-14].

The suggested higher education MLF practical course is meant to serve as a means to bridge the existing gap between higher education teaching practices in the field of manufacturing and the conveyance of technical and soft skills required by global enterprises with strong commitments towards a global sustainable development. The practical MLF course is structured as an intensive six-day block course, in which diverse learning theories and methods converge to create a holistic instructional event. The course will include conventional learning methods such as frontal teaching for the conveyance of introductory theoretical knowledge in the field of manufacturing, a gamification concept to maintain the interest of the course participants throughout the entire event, as well as constructivist and experiential learning approaches to build up technical and social competences commonly required in real life. The structure of the MLF course consists in six phases shown in figure 51. A brief description of the overall activities per phase is included below.

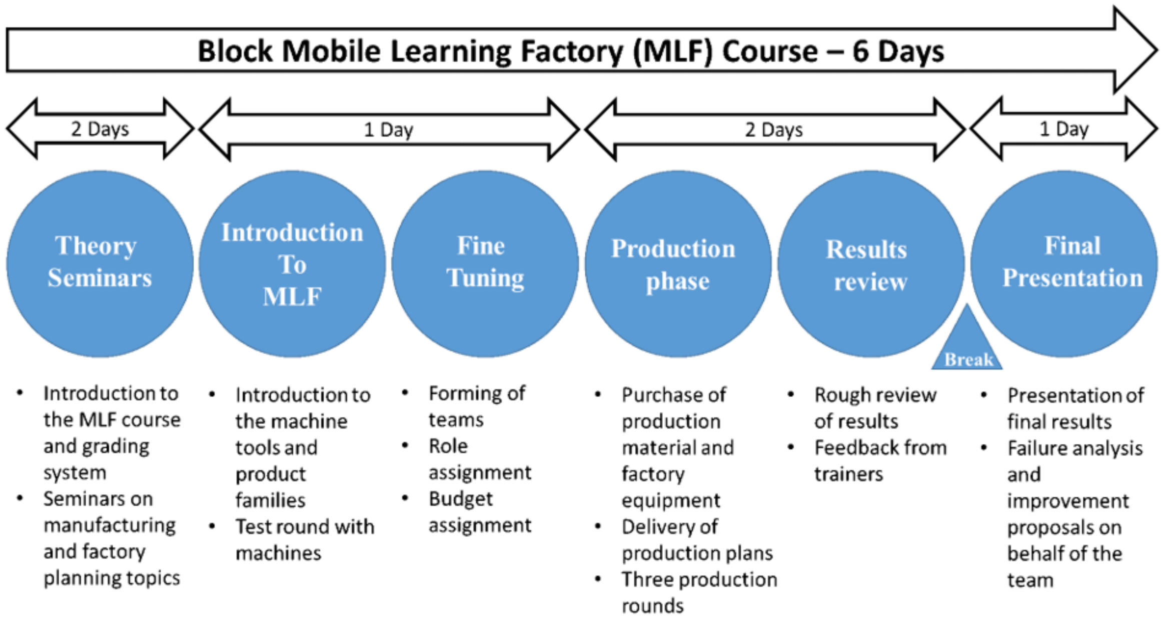


Figure 51: MLF course structure

- Theory seminars: Relevant topics on manufacturing, presented before in table 20, are presented to the audience by means of conventional frontal teaching. Presentations are conducted in a block format with a duration of fourteen hours. Also during this phase, a broad description of the MLF, its components, as well as its didactic approach is presented. Finally, participants of the course are introduced to its particular grading system. In this case, every student starts the course with a perfect grade mark, 1.0 as for the German grading system. However, participants are informed that failing to reach production objectives during the production phase, days 4-5 respectively, will have real-life consequences through grade deduction. Detailed information in this regard is deliberately ambiguous during this stage as further information is provided during the production phase.
- Introduction to the MLF: During the third day of activities, familiarization of the participants with relevant MLF elements, e.g. product, production technologies, handling devices, materials, and safety devices is conducted. In this phase, product families to be manufactured are presented along with their components and functionality. Additionally, machine tools are introduced to the participants, who will get the chance to operate them upon completion of a safety course.
- Fine tuning: Also during the third day, course participants are divided in autonomous teams. From this point on, the training staff will have their participation limited to event's moderator acting as the customer during the production phases. The team is thus responsible to make operational decisions by itself including those concerned to planning, managerial, purchasing and operational activities. Roles adopted by each team member during the production stages and beyond is determined by the group itself. Finally, a fictive budget for the procurement of machinery, raw materials, and handling devices is assigned per team.
- Production phase: Actual production takes place during the fourth and fifth day. Three production rounds with an average duration of three hours are conducted. In each round,

frame conditions regarding market demands, e.g. production plans, and production constrains are issued according to the didactic objective to be conveyed. At the beginning of each round, the teams are responsible of designing production layouts, selecting adequate machine tools, or planning capacities and inventories suitable to satisfy production demands. Each round ends then with a comparison between market demands and achieved production. The first two rounds of production focus on conveying methods of mass production, while the third one changes its demands to force the introduction of lean manufacturing methods. Important aspects of sustainability such as the creation of closed-loop material cycles are enforced by “customers” and fictive environmental regulations throughout the three rounds. Teams are also advised to ensure company’s profitability through the inclusion of recycling technologies.

- Results review: The fifth phase takes place after all production rounds are complete. Participants are required to review their results based on amount of production targets met and financial profitability of the factory. Trainers provide at this stage some feedback and highlight major issues observed as “external party”. Most probably, at least during the first production rounds, production objectives will be missed due to ill planning, operational issues with machine tools and handling systems, wrong inventories or capacity planning. The “production phase grade” is then calculated according to the production objectives missed.
- The final stage of the MLF course involves a thorough analysis on behalf of the team regarding what precisely went wrong during the botched production rounds, and which methods and tools could have been implemented to achieve the demanded objectives. The team is given time, usually some days, to conduct a profound assessment and present their conclusions in front of a panel of experts. The panel will permit then the team to disallow previous grade deductions suffered during the production round, if the team members are able to present a comprehensive round fail-analysis and suitable solutions. Missing the highest mark again would therefore not be a result of production mishaps but of a collective inability to determine their causes, consequences and countermeasures.

6.3.4 By which means

6.3.4.1 Design specifications

The determination of physical means required for the conduction of the proposed courses started with the identification of education technologies and other material requirements necessary for the achievement of the learning objectives presented in 6.3.1. Once more, following the Design or Select decision making process suggested in 5.1.5.1, a market research was conducted in order to determine if commercial systems were available that could fulfill the learning objectives proposed in 6.3.1 and serve learners’ audiences detailed in 6.3.2. In this sense, an online and literature search was conducted to identify adequate small-scale machine tools and abatable workstations necessary to develop a mobile mini learning factory in which students were able to develop their manufacturing competences.

In this case, commercially available technologies to fulfill every learning and functional requirement were found while conducting online searches. Companies such as desktop machine tools manufacturer BZT, the factory equipment producer ITEM, as well as the recycling equipment providers Bosch, and Borel committed to provide the instructional planners with technological means required for the conduction of the course as detailed in table 21. The company Haiko cases was commissioned with the realization of the MLF transportation concept.

Table 21: MLF learning objectives vs. technological requirements

Type	Objective	Means required
Didactic	Recall and be able to define manufacturing terminology and concepts.	
	Recall and explain specific production technologies and auxiliary systems. Be able to explain their functionality and operate them.	Inclusion of at least two types of production machines and two types of handling systems.
	Recall applicable manufacturing norms and guidelines. Be able to explain them and effectively employ them.	
	Be able to select appropriate production strategies according to company / business' objectives.	
	Implement production tools and methods to enable production strategies.	Inclusion of lean manufacturing enablers.
	Create factory layouts according to production strategies and methods.	
	Evaluate capacity planning in terms of material resources and personnel.	Selection of a product and raw materials.
	Implement flexibility and changeability strategies within a factory.	Inclusion of flexible and customizable working stations.
	Implement concepts of ergonomics in workstation design processes.	Inclusion of ergonomic accessories in workstations, e.g. extension arms, illumination sets.
	Determine quality standards and implement measures to achieve them.	Metrology - Inclusion of precision measuring devices.
	Determine inventories sizes and re-stock ordering points.	
	Determine sustainability potentials in the manufacturing process, apply technologies and methods to achieve sustainability, and devise own sustainability measures.	Inclusion of recycling technologies according to selected raw materials.
Structural	Mobility	Modular and robust transportation system capable of adding and removing components. Individual cases required for factory components.
	Dimensions	Maximum volume of 7 m^3.
	Weight	Maximum total weight of 1.5 Tons including transport system.
	Safety issues	Modification of devices to ensure student safety.
	Costs	25.000 € including transport system.

6.3.4.2 MLF product

The selection of the production technologies depends on the product characteristics. The MLF developed as prototype for this research based its planning in the production of a portable battery charger known as CliccLite.

The CliccLite is a portable solar battery developed by the Berlin-based company *Sonnenrepublik*, which can be used to charge small electronic devices such as cell phones. The CliccLite itself can be charged by a desktop or laptop computer through its integrated USB cable or through interchangeable miniature modular solar panels (see figure 52). The CliccLite device also features a LED white light to serve as portable flashlight.

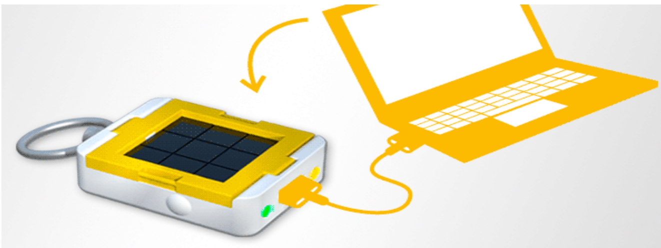


Figure 52: Sonnenrepublik's CliccLite [CLI-15]

The product families of the MLF are all product variations of the CliccLite battery neither designed nor sponsored by Sonnenrepublik and intend to serve solely as replicas for training and teaching purposes. In total, three product variants have been developed for the MLF course.

- Variant 1: Very similar to the basic CliccLite with minor changes such as lack of keyring and keyring shaft, and a modification in the lower case, in which a notch supporting the switch knob was removed and replaced by a 0.5 mm plateau to facilitate machining and assembly processes.
- Variant 2: Basically, the commercially available keyring CliccLite version with the same modifications as described in Variant 1.
- Variant 3: The CliccLite battery is turned into a flexible reading lamp with a flashlight feature.

A further common modification in all product variants is the selected production material. In the MLF, two base materials were selected according to their mechanical properties, which made them friendly to most desktop machine tools in the market but are also suitable to demonstrate resource-efficient closed loop material cycles in production.

- POM (Polyoxymethylene) was selected as the plastic base material for one product family as it demonstrates high resilient stiffness and strength, favorable sliding friction characteristics, high ability for machining, and great dimensional stability even at high temperatures. Furthermore, it can be relatively easily recycled and reused as raw material through heating processes.
- Spruce plywood was selected as second base material as it can be easily machined with conventional machine tools. The selection was made based on recyclability of the material and different possible applications of the recycled wood. Applications of recycled wood are vast ranging from paper pulp, soil erosion control agent, compost or mulch, and livestock animal feeding. However, recycled wood in the MLF will be used as garden mulches utilizing the second life cycle of the material.

As for the specific product families to be manufactured in the MLF, currently only the lower case is going to be locally produced while the rest of the components including upper case, solar cell, electronic components and grip arm for the reading lamp variant has been acquired from external suppliers. Most of the processes therefore correspond to the assembly of components for the final product. The value creation process depicted in figure 53 consist of the following processes:

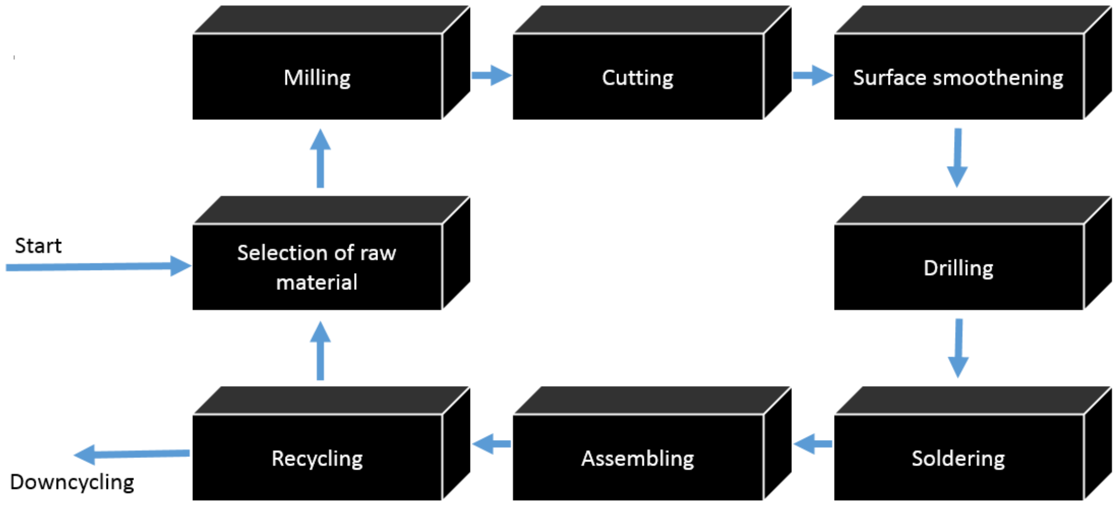


Figure 53: CliccLite's value creation process

6.3.4.3 MLF equipment

Machine tools and production equipment are mechanical devices by which components and complete products can be either manufactured or assembled. Once product families to be produced on-site are determined, one of the first decisions on a factory level is to define make-or-buy components of the finished products. In other words, which components are to be manufactured at the facility and which are to be outsourced. The decision is critical as it outlines which manufacturing machine tools and assembly production equipment are to be acquired.

The selection of manufacturing and assembly equipment in a factory, depends in most cases of technical, functional, ergonomic, economic and environmental criteria [SCE-10]. While considering the criteria for equipment selection of the MLF though, the mobility aspect, understood as long-distance transportability, is critical and supersedes almost any other criteria. This is especially relevant for manufacturing processes commonly conducted by large CNC machine tools, which in this case are to be substituted by portable desktop CNC machine tools broadly used in the lithographic and model-making industries.

Based on the production process shown in figure 53, commercially available machine tools and handling devices to be included in the MLF were appraised according to the selection method in 5.1.6.2. For the conduction of the milling process, a desktop BZT PFK-0203 PX milling machine was selected. Cutting and surface smoothing processes were to be performed with a conventional Dremel finishing set, while a Bosch PBD 40 portable drilling station was selected for the drilling process. Finally, digital Toolcraft stations were used as soldering tools, and a Borel oven CT – 250 19 and a Bosch wood chipper AXT rapid 2000 were acquired to conduct recycling and downcycling processes respectively. Characteristics of the selected production equipment and their selection process are documented in appendix 9.6.

Participants of the MLF course were responsible for the design and assembly of the workstations to be utilized during the course's production rounds. Working stations, simple handling systems, as well as accessories to achieve easy accessibility, adequate lighting, and noise reduction are put to the disposition of the production teams, leaving the realization of time study and motion analyses as part of their responsibilities. Modifications of the working station and the handling systems are encouraged as part of continuous improvement processes during the itineration of the production rounds. Two potential providers of workstation and handling systems, namely ITEM and Rexroth, were compared during the equipment procurement phase.

6.3.4.4 Transportation system

MLF transportation system was required to consider land shipment as a priority. However, intercontinental freight capabilities were also taken into account. During the design phase of the project, a series of transport modi were suggested and scrutinized in order to find the best possible shipping alternative. The selected option was based on an arrangement of standard-sized boxes to accommodate machine tools, working stations and ancillary materials. Standardization would allow the targeted MLF's modularization and further development. Focus was given on ergonomics and accessibility during loading and unloading operations as well as in securing the stability of the hardware stored. A pallet platform was designed to serve as support structure for the individual boxes as well as base for the forklift handling of the entire cube container. A provision for strapping the container with the pallet to ensure proper alignment of the boxes has been included in the planning to secure a stable and safe transportation during long distance shipment. Final transportation arrangement is depicted in figure 54.

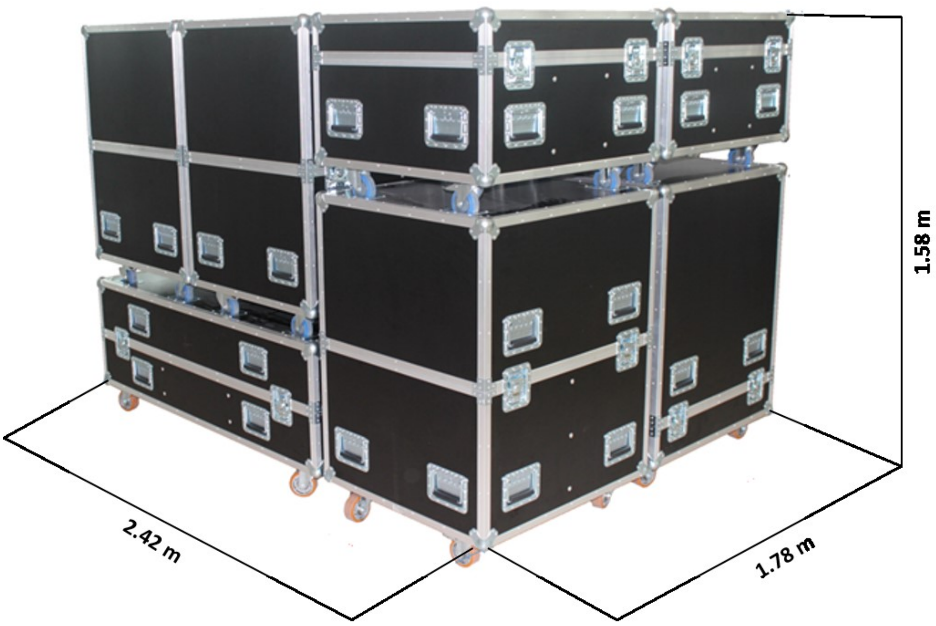


Figure 54: Arrangement of equipment inside the individual boxes

6.3.4.5 Pilot MLF course

A pilot MLF practical course was conducted in 2015 at the facilities of TUB's chair of assembly technologies and factory management. Course participants consisted of students of the international master's program "Global Production Engineering" (GPE) from developing countries. Previous experience in the field of production on behalf of the participants was assumed low, but this assertion needed to be corroborated during the first stages of the course. However, a common trait of the group participants was a strong interest concerning sustainable manufacturing practices in the solar industry that led them to participate in the course.

Following the course's structure shown in figure 51, the MLF course started with two days of theory seminars that included an introduction to the course, lectures on selected topics with regard to sustainability practices in manufacturing and factory planning (see table 20), as well as the conduction of a “welcome test”. The purpose of the welcome test was twofold. On the one hand, previous knowledge of the participants in production relevant fields could be assessed in order to adapt the discussion level to the participants’ current knowledge stand. On the other hand, obtained results can be used as initial reference while determining the course’s knowledge transfer success at the end.

The welcome test, with no influence on the final grade of the participants, consisted in ten basic-level questions regarding mostly production strategies, factory planning, supply chain management, and sustainable manufacturing topics were applied to the participants without prior notification. The results obtained by the group are shown in figure 55.

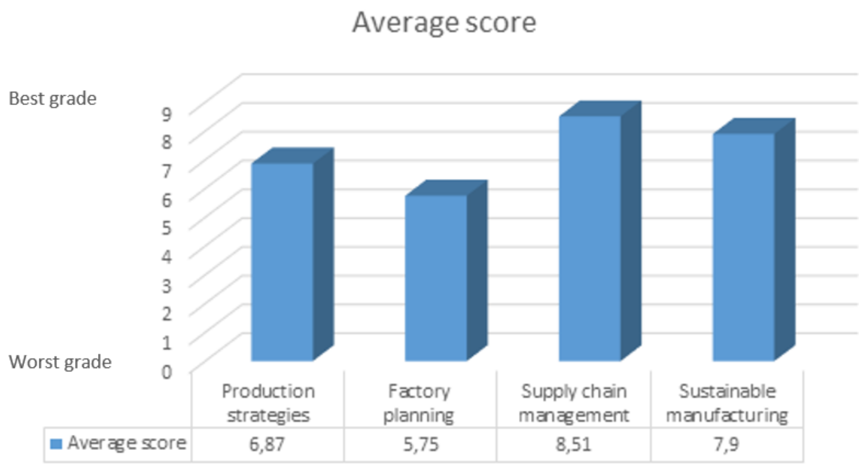


Figure 55: Average score - welcome test

In the third day, participants of the course were acquainted with the three CliccLite product families and their respective manufacturing and assembly processes. Machine tools and handling systems of the MLF were thoroughly introduced to the participants. The familiarization process comprised operation, maintenance, troubleshooting, and most importantly safety issues of the manufacturing and assembly tools utilized throughout the production process. Once the safe operation of all devices was secured, the teams were allowed to produce CliccLite samples to hone their machine operation skills and get a feeling of planning and production challenges to be faced during the production phase. Manufacturing key performance indicators such as cycle and throughput times, yield and process variability were also exemplarily reviewed during the sample product manufacturing phase. Finally, material and components costs, as well as product selling prices and recycling incentives were presented. The aim for the team was to achieve the largest possible profit, based on the selection of orders, sourcing of goods and devices, and consideration of sustainability criteria as a decision-making element.

The production phase, conducted during the fourth and fifth day, involved the manufacturing of CliccLite units in three production rounds under different framework constraints and market demands. Each production round had an average duration of three hours. For each round, participants were required to plan and / or modify their factory layout, and procure suitable machine tools, raw materials and consumables according to the variable conditions set by the training staff. The production phase was developed to follow a constructivist approach in which the teams were responsible to take real-world decisions with virtually no intervention on behalf the training staff and based solely in the knowledge acquired in previous stages. An experiential learning cycle was also introduced as students are expected to iteratively integrate observations of initial production rounds into subsequent rounds to generate process improvements despite a highly dynamic environment. The details of the individual production rounds are given below.

- Round one - Classic mass production: The first production round simulated a mass production scenario constrained to the manufacturing of large batches of product families. In this case, the milling station was limited to the manufacturing of 12-pieces sets, effectively pacing the production rate to this amount. Specific constraints of this run included the transfer of semi-finished work pieces to downstream processes only in batches equaling the initial batch size, assembly of mixed product families in downstream processes was not allowed, a raw material resupply time of forty-five minutes, and a production plan based merely on statistically-determined selling forecasts.

  Participants of the course, aware of mass production concepts such as division of labor and movable assembly lines designed a simple and straightforward factory layout with a linear production process and assigned "specialized personnel" to each workstation. The production output of the team during the first round was way below market demands being able to fulfill slightly over 40 % of the purchase orders issued by the customer at the end of the round. Biggest issues observed by the training team during this round included inventory overstock, operational problems in manufacturing and assembly processes, as well as a noteworthy disregard of quality-assurance activities and material recycling strategies. No quality checks were performed until the last assembly stage and recycling processes were not carried out despite economic incentives offered by the customer during the review of material and components prices and income generation possibilities conducted in the previous stage. Once the round concluded, during a feedback session with the training staff, the team draw following conclusions:

  - The team was surprised about the huge amount of work-in-progress (WIP) accumulated in their intermediate inventories.
  - Some team members complained about repetitive tasks and the need to produce "as fast as possible" in order to provide material to an idling downstream process. The team credited this fact to quality issues at the end of the assembly line, where several end products had to be discarded due to functional failures. The team failed however to realize that the quality issues attributed to the final assembly process were originated in upstream manufacturing stages.
  - Some team members complained about large idling periods in contrast to upstream processes.
  - Some team members complained about what they perceived as "weak" operation competences from colleagues in other working stations.
  - One of the biggest challenges the team faced, was to determine a production plan under batch size constraints that would "most likely" fulfill customers' demands at the end of the round. The team determined the inexistence of a "perfect" solution as they concluded a remaining production surplus could not be avoided regardless of the production plan and their line balancing attempts.
  - The team was confronted for the first time with the importance of counting with accurate throughput times in order to align them to approximate takt times and determine the suitability of the proposed factory layout.

- Round two - Modified mass production: The second round intended to introduce and show the advantages of some aspects of flexibility by allowing different batch sizes in root processes of all three product variants. The team was also entitled to implement a one-piece flow (OPF) approach in downstream processes as a means to experiment with production flexibility advantages and challenges. Specific constraints of this run included the batch production of 4, 6, and 12 pieces, OPF after the milling process, a raw material resupply time of forty-five minutes after a placed purchase order, and a production plan based merely on statistically-determined selling forecasts. The team also was given the chance to modify their factory and workstations' layout and rotate their operational staff.

For the conduction of this round, the team modified their initial layout by introducing parallel processes comprising soldering and board assembly tasks (see figure 56).

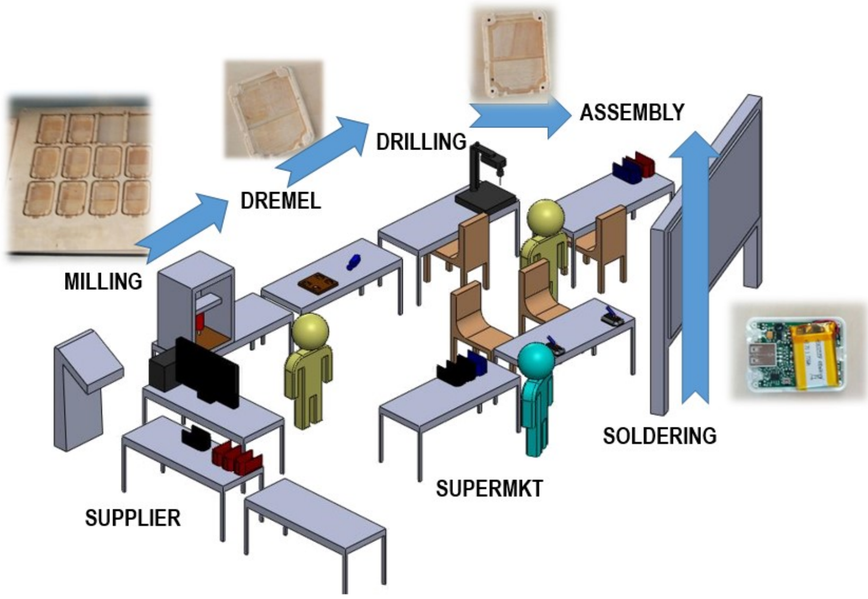


Figure 56: Students' layout of the second production round

Experiences gathered during the first production round led the team to implement further modifications in their production approach such as a continuous process improvement analysis of each workstation conducted by the responsible staff members, improved data gathering, job rotation, as well as the introduction of supermarkets and a supply chain department. After the conclusion of the round, a second feedback session was conducted with following results:

- The team noticed a drastic reduction of work-in-progress (WIP) in the downstream processes and was able to observe a consequent decrease of inventory costs.
- Now that production was not batch-bounded in each station, the team understood the flexibility potentials and challenges. Yet the uncertainty of the market demand remained and the team was forced to plan overproduction beforehand in order to cope with demand uncertainties.
- Despite the layout and process improvement, the team was unable to fully fulfill production demands at the end. Slightly over 60 % of the purchase orders were fulfilled in this occasion. Main reason for this was a low end-product yield rate due to quality issues. The failures were particularly credited to the soldering process.

- The team made its first attempt to incorporate recycling into their business scheme. However, due to market demand uncertainty the team opted to include only the wood chipper as recycling device based mainly on the ease of operation of the device.

- <u>Round three – Lean Manufacturing:</u> The third round introduced a pull-based production strategy. Specific constraints of this run included a pull-based production approach in which purchase orders were continuously issued by the customer, single pieces could be produced at the milling station, and a raw material resupply time of five minutes after a placed purchase order. The team also was again given the chance to modify their factory and workstations' layout, as well as to rotate their operational staff.

  For the conduction of this round, the team modified their layout by designing a U-cell process (see figure 57), which led to a reduction of operative staff and working area. Lean and quality assurance methods such as 5S, visual management and kaizen rounds conducted prior to production begin were additionally implemented as a means to tackle high discard rates experienced in previous rounds.

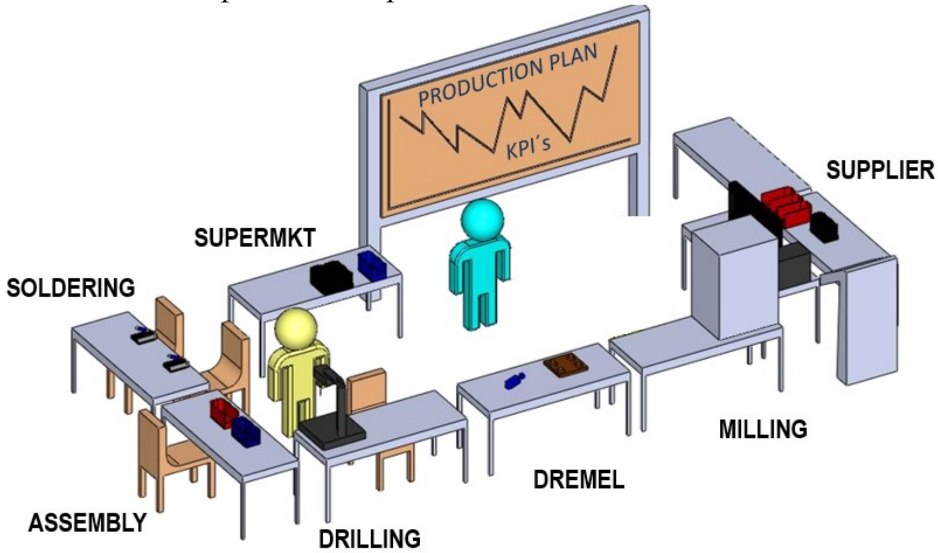


Figure 57: Students' layout of the third production round

  To cope with demand-driven production, further lean tools such as Kanban cards and line balancing according to takt times were implemented by the team as production pacemakers.

  Up to 85 % of the market demand was fulfilled by the team during the third production round. The team largely credited the improvement to a better operation of manufacturing and assembly technologies, flexibility in the production and the implemented OPF system. The team noticed additionally the advantages and challenges to work with low inventory control systems such as Kanban. The team was able to achieve profit for the first time due to reduced inventories, higher productivity, and efficient recycling.

The final phase of the course took place two weeks after the production round conclusion. It consisted of two activities. The first one was the assessment of results in terms of production targets achieved on behalf of the team. Root causes of failed production rounds on a workstation and factory level were categorized by the team as a whole. Conclusions of this analysis were summarized in a presentation held by selected team members to a panel of experts, who would evaluate the outcomes reached by the team and decide upon restituting grade deductions depending on the validity of the arguments and countermeasures suggested in the presentation.

Additionally, a “good bye test” to be solved individually by each team member was distributed during the conclusion of the course. In this examination, each participant was asked to answer ten questions in the fields of production strategies, factory planning, supply chain management and sustainable manufacturing. With a similar format but a substantially higher complexity degree than the “welcome” version, the “good bye test” intended to appraise the learning effect of the MLF hands-on approach by comparing original vs. acquired knowledge in the fields of manufacturing and factory planning. The results (shown in figure 58) showed a notorious improvement in the participants understanding especially in the fields production strategies and factory planning.

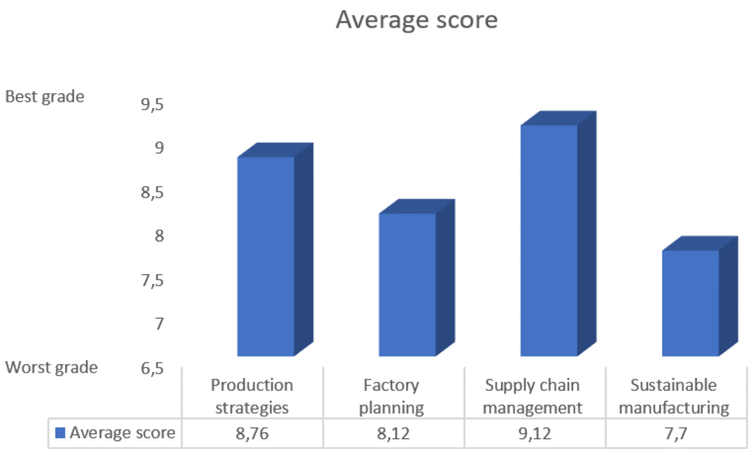


Figure 58: Good bye test results

7 Summary and outlook

Globalization trends are forcing a redefinition of engineering education. Formerly understood as the formal instruction of professionals in higher education institutions, engineering education is nowadays experiencing the effects of a global democratization of knowledge, in which teaching material and technological resources are becoming accessible to almost everyone. Supported by technical devices such as 3D printers, Arduino boards, desktop machine tools, as well as online didactic methods enhancing the quality and possibilities of distance learning, democratization of knowledge is facilitating decentralization of instruction and enabling non-elite members of developing countries' societies the access to information that was until recently considered as privilege of a few. This shift is good and needed due to its potential to turn low-productive society sectors into sources of higher value-creation and innovation. However, as with any new trend, there is a need to formalize structures and methods that allow the integration of new educational models and technologies in engineering curricula to maximize its potentials, especially if a meaningful contribution to a global sustainable development is expected.

This dissertation has claimed that conventional engineering education frameworks fell short in their attempts to contribute towards the achievement of sustainability goals by not fully harmonizing key instructional components such as learning objectives with pedagogic methods and educational technologies. A holistic instructional design model comprising the sheer dimensions "what", "who", "how", and "by which means" was therefore proposed as an instructional baseline for engineering educators to develop formal and non-formal instructional events. The proposed Instructional Design Model for Engineering Education (IDMEE) follows a sequential method, in which all four sheer dimensions are to be addressed by the designer as a means to ensure the quality of the instructional event, defined as the ratio between achieved learning outcomes on behalf of the learners and the course's original learning objectives.

Learning objectives, as for the proposed model, can be understood as educational vectors with a direction determined by the content of instruction ("what") and the magnitude in terms of instruction depth set by the target audience ("who"). Learning objectives can be classified in cognitive layers according to their level of complexity. Several taxonomies exist to identify these levels. However, this study utilized Bloom's cognitive taxonomy as reference due to its widespread usage in academic and education circles, as well as its cumulative hierarchical structure, which makes it easy to follow. According to Bloom, thinking and learning can be classified in six hierarchical levels of complexity. These levels, often depicted as a pyramid, characterize the natural order of cognition in a bottom-up manner. Instructors following this taxonomy, are expected to encourage students to climb from the lower pyramid echelons ("knowledge", "comprehension", and "application") to the most complex levels ("analysis", synthesis", and "evaluation") as a means to evolve from pure knowledge-recipient entities to agents of value creation. The level of complexity to be aimed by the instructor depends however on the type of learner/s addressed. Academic aspects such as level of education, educational background and previous knowledge in the particular field of instruction are important, yet the presented model stresses the need to give the same importance to social, cultural, and economic parameters while planning instruction in a globalized context.

Learning outcomes in turn, are defined in this dissertation as measurable effects of instruction on learners once the event is completed. Outcomes are commonly ascertained by means of evaluation processes upon the conclusion of the instruction, however they can also be determined according to the effects experienced by a community directly imputable to the instructional event. Two highly relevant factors influencing the quality of learning outcomes in an instructional event are the pedagogic approaches and educational technologies implemented during its conduction, which in turn are to be aligned to the learning objectives of the course. Pedagogic approaches of instruction comprise mainly learning theories and didactic models. Learning theories are attempts to describe how cognitive processes take place in the human brain. Modern learning theories have been proposed in the last hundred years by psychologists and pedagogues after studying how children and adults learn. Some of the best studied are the theories of behaviorism, cognitivism, constructivism and experiential learning. Researchers have demonstrated that each theory serves education purposes in young and adult audiences in a different manner. While psychological currents such as behaviorism favor development of early stages of knowledge, approaches such as cognitivism or constructivism elaborate on existing mental schemas to develop knowledge further Researchers in the field of engineering education have also often proved the validity of this theories in the conveyance of technical knowledge.

Didactic models on the other hand, refer to instruction methods commonly utilized in classroom for different purposes. Researchers have long associated learning theories with determined models. This way, classic didactic models such as frontal teaching have been linked to behaviorist approaches, and modern methods of instruction such as problem / project-based learning approaches have often been tagged as “constructivist per excellence”. However, this relation has not been proved to be absolute as instruction is seldom pure behaviorist, cognitivist or constructivist. Rather, a combination of methods is necessary according to what is exactly expected from the learner to achieve after instruction.

Finally, educational technologies (“by which means”) are defined in this dissertation as technological resources that facilitate learning. In the proposed instructional design model, educational technologies represent the virtual and / or physical means by which the knowledge to be conveyed (“what”) is transferred to a specific audience (“who”) in a specific manner (“how”) according to specific demands set by the learning objectives of the course. Alignment between all dimensions is necessary so that learning outcomes match initial learning objectives and the instruction succeeds. A systematic method to select or design educational technologies according to educational dimensions has been proposed and validated. The method adapts elements of well-known product selection / design methodologies adapting their evaluation criteria to the consideration of learning objectives and pedagogic methods deemed as proper to reach a specific audience.

The proposed Instructional Design Model for Engineering Education (IDMEE) has been used during the conduction of the present research study as a guideline to develop courses on manufacturing and energy generation, sectors which combined account for almost 50 % of Earth’s anthropogenic greenhouse gas emissions. These courses, designed to reach different audiences, aim on the one hand to disseminate new paradigms of production and consumption in which societal net welfare gains can be achieved through economic activities that reduce utilization and depletion of resources, and environmental pollution along the whole lifecycle. On the other hand, renewable energies are introduced as a technically and economically viable alternative to replace more polluting fossil fuels as global energetic sources.

As a means to contribute towards the achievement of UN’S SDGs No. 4, *quality education*; No. 7, *affordable and clean energy*; No. 9, *industry and infrastructure*; No. 12, *responsible production and consumption*; and No. 17*, partnerships for the goals*, these courses have been specifically designed to support instruction in developing countries. Conventional international collaboration methods between developed and developing countries, such as education of guest students in developed countries, train-the-trainer programs and setting of competence centers in partner (developing) countries, have been analyzed and compared to this end. The evaluation concluded that regardless undeniable advantages such as the infrastructural development in developing countries' urban centers, these approaches exhibit considerable drawbacks such as brain-drain furtherance and low-impact in rural and informal urban settlements. If global sustainable development is to be achieved however, the reach of education has to be broadened to those without access to quality education institutions commonly centralized in big urban centers.

An instructional strategy commonly utilized to reach these markets has been distance / remote education. Distance education is as old as correspondence courses. However, Information and Communication Technologies such as Internet have revolutionized this field through the integration of interactive teaching and learning platforms, which make immediate task feedback possible. Today, so-called Massive Open Online Courses (MOOCs) are notably taking off in developing countries. As implied in their name, MOOCs are online courses freely accessible to anyone with an internet connection. MOOCs structure consists mostly in short video lecture chunks, virtual examples, and tasks, which in some cases are immediately graded by the host application. Forums to discussion and question-answer sessions are also common. MOOCs however, have notorious downsides when it comes to distant technical education. Researchers have argued that overreliance on global MOOCs jeopardize own capacities to build local resources for education, research or knowledge development. Most importantly however, is the fact that most engineering educators concur in the essential role that physical laboratories play in the quality of instruction in technical fields. Future engineers they claim, are to be confronted with close-to-real-life experiences including the physical and virtual tools involved in their solution. Hands-on approaches during instruction phases are therefore indispensable and belong to any attempt to disseminate engineering knowledge.

Online attempts to substitute physical laboratories have been made. So-called virtual and remote laboratories have been developed by academic institutions as an attempt to, among others, counter physical infrastructure deficits in underdeveloped world regions. Nonetheless, when compared with real facilities, these technologies exhibit unsurmountable disadvantages such as simulated experiment outcomes, in the case of virtual laboratories, and limited accessibility, and protocol communication issues in the case of remote laboratories. Moreover, in both cases, the student has never physical contact with real components, limiting instruction to mere operational and analytical activities setting in most of the cases aside instructional activities such as planning, maintenance, implementation and most importantly understanding and further development of the components. Thus, if quality technical instruction in the fields of sustainable manufacturing and energy generation is to be conducted in underdeveloped regions in developing countries, mostly correspondent to rural and informal urban settlements, novel methods of instruction that facilitates the contact of the learner with modern educational technologies and laboratories are required.

The present dissertation suggests an approach, consistent in the utilization of mobile downscaled versions of conventional university laboratories capable to enable high quality, decentralized dissemination of technical knowledge independent of local infrastructural preconditions. Some of these mobile laboratories make use of Information and Communication Technologies, as well as modern educational technologies such as makerspaces' desktop machine tools, and Arduino boards to make possible the contact of engineering learners with sophisticated, yet economical high-end mobile laboratories. As a validation of the suggested approach, three mobile laboratories were designed and developed as part of this research. These laboratories comprised a mobile solar charging station for E-Bikes, a mobile wind energy laboratory, and a mobile learning factory for manufacturing. A comprehensive description of each laboratory including its design process, components and set of experiments has been included.

Advantages of the suggested approach are manifold. Firstly, the mobile feature of the laboratories facilitates their transportation and implementation in remote areas with minimum installation efforts and little infrastructure prerequisites. The introduced prototypes can be transported in small or medium-sized vehicles, or commercial flights as documented luggage, and their setup takes no longer than one hour. Secondly, utilization of commercially available education technologies makes these laboratories economically affordable for individual education institutions. Hence, it facilitates and encourages local multiplication and further development of local custom-made laboratories with local value creation opportunities. Most important is the possibility of conveyance of high-quality education with potential prompt benefits for underdeveloped communities. Studies conducted by international development agencies suggest that contact to renewable energies can facilitate the acceptance of these technologies in markets traditionally apprehensive to these technologies. On the other hand, instruction in sustainable production processes in impoverished communities can motivate the development of local value creation modules stimulating transformation of primary productive processes into higher, more profitable activities.

The laboratories and courses on sustainable manufacturing and energy generation developed as part of the present dissertation have been integrated into the curriculum of the international master program “Global Production Engineering” of the Technische Universität Berlin. The master’s program, with over 90 % of its students originating from developing countries, presents an experimental microcosm which has been utilized to draw first satisfactory conclusions in terms of acceptance of new learning methods and devices. This study acknowledges the need of implementation in developing countries addressing target audiences consistent in primary, secondary, tertiary education students as well as dwellers of rural and informal urban communities, as a means to validate the exposed theories.

Further development of the present research could include the diversification of the proposed IDMEE into other value-adding sectors. So far, the model focuses in the development of engineering competences under the educational umbrella of formal and non-formal educational systems based on the definition of learning objectives according to Bloom’s cognitive taxonomy. However, the utilization of similar taxonomies, e.g. Bloom’s psychomotor taxonomy, could serve as a similar bedrock to develop vocational training events.

Concerning the proposed mobility concepts for physical laboratories, servitization of Cyber-Physical Laboratories could be explored as a further mean to develop local economies and talent. Local producers exploiting relative low utilization of these facilities, could opt to develop shared ownership or leasing business models to cut off initial investments and maintenance costs.

8 References

[360-15] 360 Magazine. 2015. „Make Way for the Makers Movement”. 360 Magazine: Making Distance Disappear. http://www.steelcase.com/insights/articles/making-way-making-education/. (Latest access 16th January 2017).

[ABB-13] Abbot, S. 2013. “The Glossary of Education reform”. http://edglossary.org/education-system/. (Last visited November 10th. 2016).

[ABE-15] Abele, E. et al., 2015. „Learning Factories for Research, Education, and Training”. Procedia CIRP 32 (1): 1–6.

[AGG-90] Aggteleky, B.C.C., 1990. „Fabrikplanung: Werksentwicklung und Betriebsrationalisierung“. Hanser, München.

[ALE-84] Alesandrini, K. L. 1984., „Pictures and Adult Learning”. Instructional Science 13: 63–77.

[ALL-08] Alli, B.O., 2008. “Fundamental Principles of Occupational Health and Safety”. International Labour Force, Geneva.

[ALV-09] Alvin, M. 2009. „Learning theories and instruction”. https://mmalvin.files.wordpress.com/2009/12/learning-theory-matrix.pdf. (Latest access 16th January 2017).

[AKA-10] Akar, H., 2010. „Globalization and its challenges for developing countries: the case of Turkish higher education”. Asia Pacific Education Review 11 (3): 447–457.

[AMA-16] Amatrol. 2016. „Solar PV Installation Learning System – 950-SPF1”. http://www.amatrol.com/coursepage/950-spf1/. (Latest access 16th January 2017).

[AND-00] Anderson, L.W., Krathwohl, D.R., 2000. “A taxonomy for learning, teaching, and assessing: a revision of Bloom's taxonomy of educational objectives”. Longman, New York.

[ANN-16] Annetta, L., und Minogue, J., 2016. “Connecting Science and Engineering Education Practices in Meaningful Ways: Building Bridges”. Springer, München.

[ANS-14] Ansari, A., und Mourya, R.M., 2014. „Drag Force Analysis of Car by Using Low Speed Wind Tunnel”. International Journal of Engineering Research and Reviews 2 (4): 144–149.

[ARD-16] Arduino. 2016. „ArduinoBoardDue”. Arduino. https://www.arduino.cc/en/Main/ArduinoBoardDue. (Latest access 16th January 2017).

[ARL-96] Applied Research Laboratory - U. Michigan. 1996. „Definitions of Instructional Design”. http://www.umich.edu/~ed626/define.html. (Latest access 16th January 2017).

[ARM-16] Armfield. 2016. „C15: Computer Controlled Subsonic Wind Tunnel”. http://discoverarmfield.com/en/products/view/c15/computer-controlled-subsonic-wind-tunnel. (Latest access 16th January 2017)

[ARR-98] Arreola, R.A. 1998. „Writing Learning Objectives”. University of Tennessee, Memphis. https://www.uwo.ca/tsc/graduate_student_programs/pdf/LearningObjectivesArreola.pdf. (Latest access 16th January 2017).

[ASH-04] Ashford, N. 2004. „Major Challenges to Engineering Education for Sustainable Development: What has to change to make it Creative, Effective, and

Acceptable to the Established Disciplines”. Massachusetts Institute of Technology. https://esd.mit.edu/symposium/pdfs/papers/ashford.pdf. (Latest access 16th January 2017).

[ASL-14] Ashley, L.D., et.al., 2014 „The role and impact of private schools in developing countries: a rigorous review of the evidence”. University of Birmingham, London.

[ASM-15] Ashmore, Lyn, und Denise Robinson., 2015. “Learning, Teaching and Development: Strategies for Action”. SAGE, New York.

[AST-08] American Society for Training and Development, 2008. “Foundations and delivery: the basics to becoming a successful trainer”. ATD Press, Alexandria - Virginia.

[ASU-10] Arizona State University. 2010. „Guidelines for the Assessment of Learning Outcomes”. Arizona State University. http://www.niu.edu/assessment/manual/_docs/assessguide.pdf. (Latest access 16th January 2017).

[AZA-11] Azad, K.M., 2011. “Internet Accessible Remote Laboratories: Scalable E-Learning Tools for Engineering and Science Disciplines: Scalable E-Learning Tools for Engineering and Science Disciplines”. IGI Global, United States.

[BAC-11] Bacon, C.M., et.al., 2011. „The creation of an integrated sustainability curriculum and student praxis projects”. International Journal of Sustainability in Higher Education 12 (2): 193–208.

[BAE-15] Barrett, T., et al., 2015. A Review of University Maker Spaces. 2015 ASEE Annual Conference and Exposition Proceedings.

[BAJ-06] Barjak, F., 2006. „The Role of the Internet in Informal Scholarly Communication”. Journal of the American Society for Information Science and Technology 57 (10): 1350–67.

[BAK-14] Baker, L. 2014. „The Skills Mismatch”. London: Edge Foundation. http://www.edge.co.uk/media/130721/the_skills_mismatch_march_2014_final.pdf. (Latest access 16th January 2017).

[BAL-09] Balamuralithara, B., Woods, P.C.. 2009., „Virtual Laboratories in Engineering Education: The Simulation Lab and Remote Lab”. Computer Applications in Engineering Education 17 (1): 108–118.

[BAN-14] Barnes, C. 2014. „Education and Training - What’s the difference?”. ELearning Industry. Juni 13. https://elearningindustry.com/education-and-training-what-is-the-difference. (Latest access 16th January 2017).

[BAR-99] Barlow, J. B., Rae W.H., Pope, A., 1999. “Low-Speed Wind Tunnel Testing”. Wiley, Michigan.

[BAT-14] Bates, T. 2014. „Learning theories and online learning”. Online Learning and Distance Education Resources. http://www.tonybates.ca/2014/07/29/learning-theories-and-online-learning/. (Latest access 16th January 2017).

[BEC-10] Becker, F.S., 2010. „Why don’t Young People want to become Engineers? Rational Reasons for Disappointing Decisions”. European Journal of Engineering Education 35 (4): 349–66.

[BEJ-12] Benjamin, L. 2012. „A History of Teaching Machines”. American Psychologist 45(4): 551–552.

[BEL-11] Bellanca, J. A., 2011. „Navigating Social Networks as Learning Tools”. In “21st Century Skills: Rethinking How Students Learn”. Solution Tree Press, New York.

[BEN-04] Benchikh, O. 2004. „UNESCOS’s Global Renewable Energy Education and Training Programme (GREET Programme)”.

http://www.fvee.de/fileadmin/publikationen/Themenhefte/sf2004/sf2004_03_02.pdf. (Latest access 16th January 2017).

[BET-15] Bethke, R. 2015. „Should your institution move into the Augmentarium future?" eCampus News. http://www.ecampusnews.com/technologies/augmentarium-virtual-reality-122/. (Latest access 16th January 2017).

[BIL-95] Bilsel, A., Oral, O., 1995. "Role of education, science and technology in developing countries". Proceedings Frontiers in Education 1995 25th Annual Conference. Engineering Education for the 21st Century.

[BLA-96] Black, J., McClintock, R. 1996. „An Interpretation Construction Approach to Constructivist Design". In "Constructivist Learning Environments". Educational Technology Publications, New Jersey.

[BLE-13] Blewitt, J., Cullingford, C., 2013. "The Sustainability Curriculum: The Challenge for Higher Education". Earthscan, London.

[BLO-56] Bloom, B.S., 1956. "Taxonomy of Educational Objectives: The Classification of Educational Goals". D. McKay, Ann Arbor - Michigan.

[BMZ-14] BMZ, Federal Ministry for Economic Cooperation and Development. 2014. „The situation in developing countries". Federal Ministry for Economic Cooperation and Development. http://www.bmz.de/en/what_we_do/issues/Education/hintergrund/bildungsituation/index.html. (Latest access 16th January 2017).

[BOE-09] Boyer, K., Verma, R. 2009. „Operations and Supply Chain Management for the 21st Century." Cengage Learning, Mason - Ohio.

[BOD-86] Bodner, G. M., 1986. „Constructivism: A theory of knowledge". Journal of Chemical Education 63 (10): 873 - 915.

[BOK-14] Bokova, I., 2014. „Shaping the future we want: UN Decade of Education for Sustainable Development (2005-2014)". UNESCO. http://unesdoc.unesco.org/images/0023/002303/230302e.pdf. (Latest access 16th January 2017).

[BON-14] Bonk, C.J., Reynolds, T.H., Reeves, C., Lee, M., 2015. "MOOCs and Open Education Around the World". Routledge, New York.

[BOR-07] Borri, C., Maffioli F., 2007. "Re-Engineering Engineering Education in Europe". Firenze University Press, Firenze.

[BOREL-15] Borel. 2015. „CT 250-19 Conterm ovens 250 °C - CT 250 - Ovens (< 500 °C)", Borel Special furnaces.: http://www.borelswiss.com/ovens/ct-250/ct-250-19-etuves-conterm-250-c.html. (Latest access 16th January 2017).

[BOS-15] Bosch. 2015. „AXT Rapid 2200 | Häcksler | Garten", Elektrische Gartengeräte von Bosch. https://www.bosch-garden.com/de/de/bosch-gartengeraete/gartengeraete/axt-rapid-2200-3165140430555-199967.jsp. (Latest access 16th January 2017).

[BOT-12] Boston University. 2012. „Using Case Studies to Teach", Center for Teaching & Learning, Boston University. http://www.bu.edu/ctl/teaching-resources/using-case-studies-to-teach/. (Latest access 16th January 2017).

[BOU-13] Boumphrey, S., Bevis, E., 2013. "Reaching the Emerging Middle Classes Beyond BRIC". Brussels: Euromonitor International, Brussels.

[BOY-04] Boyle, G., 2004. "Renewable Energy". Oxford University Press, Oxford.

[BRA-15a] Bradshaw, P., Mehta, R.D. 2015. "Wind Tunnels – Diffuser". http://navier.stanford.edu/bradshaw/tunnel/diffuser.html. (Latest access 16th January 2017).

[BRA-15b] Bradshaw, P., Mehta, R.D. 2015. „Wind Tunnels - Settling Chamber". http://navier.stanford.edu/bradshaw/tunnel/settlingchamber.html. (Latest access 16th January 2017).

[BRE-14] Broekman, M., et al., 2014. „Open Education: A study in Disruption". Rowman & Littlefield International, London.

[BRG-04] Bruning, R. H., 2004. "Cognitive Psychology and Instruction". Pearson/Merrill/Prentice Hall, Ann Arbor - Michigan.

[BRH-07] Brough, J. E., et al., 2007. „Towards the Development of a Virtual Environment-Based Training System for Mechanical Assembly Operations". Virtual Reality 11 (4): 189–206.

[BRI-13] Briede, B. 2013. „A Constructivist Approach in Engineering Education". http://tf.llu.lv/conference/proceedings2013/Papers/109_Briede_B.pdf. (Latest access 16th January 2017).

[BRL-07] Bralla, J., 2007. „Handbook of Manufacturing Processes". Industrial Press, New York.

[BRM-13] Broman, L, Kandpal, T.J., 2013. „On the importance of PURE - Public Understanding of Renewable Energy". Acta Academiae Stromstadiensis.

[BRN-15] Brown, A. H., Green, T.D., 2015. "The Essentials of Instructional Design: Connecting Fundamental Principles with Process and Practice". 3 Ed. Routledge, New York.

[BRO-83] Brookfield, S.D., 1983. "Adult Learning, Adult Education and the Community". Milton Keynes, UK: Open University Press, London.

[BRU-87] Brundtland, G.H., 1987. „Our Common Future". United Nations Publishing, New York.

[BRW-84] Browne, J. D., et al., 1984. „Classification of Flexible Manufacturing Systems". FMS Magazine 5(6): 114 -117.

[BUK-14] Burke, B.N., 2014. „The ITEEA 6E Learning ByDesign Model: Maximizing Informed Design and Inquiry in the Integrative STEM Classroom". Technology and Engineering Teacher 73 (6): 14–19.

[BUR-01] Burton, T., et al., 2001. "Wind Energy Handbook". John Wiley & Sons, West Sussex.

[BUZ-82] Buzacott, J.A., 1982. „The fundamental principles of flexibility in manufacturing systems". Conference on Flexible Manufacturing Systems Proceedings. Brighton – United States.

[BYB-06] Bybee, R.W. et al. 2006. "The BSCS 5E Instructional Model: Origins, Effectiveness and Applications". Biological Science Curriculum Study, Colorado Springs.

[BZT-15] BZT. 2015. BZT Onlineshop :: CNC Fräsmaschinen und Graviermaschinen". BZT. http://www.bzt-cnc.de/. (Latest access 16th January 2017).

[CAE-00] Cánez, L.E., Platts, K.W., Probert, D.R. 2000. „Developing a framework for make or buy decisions", International Journal of Operations & Production Management 20 (11): 1313-1330.

[CAN-97] Cantor, J. A., 1997. "Experiential Learning in Higher Education: Linking Classroom and Community. Graduate School of Education and Human Development". The George Washington University, Washington D.C.

[CAR-10] Carr, N. G., 2010. "The Shallows: What the Internet Is Doing to Our Brains". W. W. Norton & Company, New York.

[CAS-10] Castro, M., Martin, S., 2010. „Trends of use of technology in engineering education". Proceedings IEEE EDUCON Education Engineering 2010 - The future of global Engineering Education, Madrid.

[CAY-02] Carney, R.N., Levin, J.R., 2002. „Pictorial Illustrations still improve Students' Learning from Text". Educational Psychology Review 14(1): 5-26.

[CED-06] CEDEFOP., 2006. „Typology of Knowledge, Skills, and Competences". European Commission, Luxemburg.

[CHA-06] Cha, H.J., et. al., 2006. „Learning Styles Diagnosis based on User Interface Behaviors for the Customization of Learning Interfaces in an Intelligent Tutoring System". In „Intelligent Tutoring Systems" 513-524. Springer, London.

[CHD-02] Chandrasekharam, D., Bundschuh, J., 2002. "Geothermal Energy Resources for Developing Countries". CRC Press, Lisse – The Netherlands.

[CHE-09] Chen, H., Ho, J.C., Kocaoglu, D.F., 2009. „A Strategic Technology Planning Framework: A Case of Taiwan's Semiconductor Foundry Industry". IEEE Transactions on Engineering Management 56 (1): 4-15.

[CHE-10] Chen, X., Song, G., Zhang, Y., 2010. „Virtual and Remote Laboratory Development: A Review". In "Earth and Space 2010" 3843–3852. American Society of Civil Engineers, Washington D.C.

[CHE-13] Chen, S., Soldner, M., 2013. „STEM Attrition: College Students' Paths into and out of STEM Fields". National Center for Education Statistics, U.S. Department of Education, Washington, D.C.

[CHM-08] Champeau, R. 2008. „UCLA study finds that searching the Internet increases brain function". UCLA Newsroom. http://newsroom.ucla.edu/releases/ucla-study-finds-that-searching-64348. (Latest access 16th January 2017).

[CHN-00] Chan, F.T.S., Chan, M.H., Tang, N.K.H., 2000 „Evaluation methodologies for technology selection", Journal of Materials Processing Technology 107 (1-3): 330–337.

[CHO-11] Chowdhury, H., Alam, F., 2012. „Engineering education in Bangladesh – an indicator of economic development". European Journal of Engineering Education 37 (2): 217–228.

[CHP-04] Chapman, D., Mählck, L., 2004. "Adapting Technology for School Improvement: A global Perspective". UNESCO, New York.

[CHP-15] Chapman, S, Cantrell, P. 2015. „What is an Instructional Designer?" http://teaching.colostate.edu/tips/tip.cfm?tipid=70. (Latest access 16th January 2017).

[CHR-96] Chryssoluris, G. 1996. „Flexibility and its measurement". CIRP Annals, Paris.

[CHU-12] Chubb, I., Findlay, C. Du, L., 2012. „Mathematics, Engineering & Science in the National Interest". Office of the Chief Scientist, Canberra.

[CHV-14] Cheville, A., 2014. „A Century of Defining Engineering Education". In 121st American Society for Engineering Education Annual Conference, Indianapolis.

[CHY-09] Cheryl J. D., et.al., 2009. „Addressing the time lag dilemma in curriculum renewal towards engineering education for sustainable development". International Journal of Sustainability in Higher Education 10 (2): 184–99.

[CIR-04] CIRP., 2004. "CIRP Dictionaries of Production Engineering". Springer, Berlin Heidelberg.

[CIS-14] Cisco, „Internet of Things (IoT)". 2014. *Cisco*, 2014. http://www.cisco.com/c/en/us/solutions/internet-of-things/overview.html. (Latest access 16th January 2017).

[CIT-16] Center for Instructional Technology & Training. 2016. „Gagne's 9 Events of Instruction". University of Florida. http://citt.ufl.edu/tools/gagnes-9-events-of-instruction/. (Latest access 16th January 2017).

[CLI-15] Clicc. 2015. „Clicc - the world’s smallest USB solar charger”. Clicc Shop. http://www.clicc.de/en/. (Latest access 16th January 2017).

[COH-14] Cohn, C. 2014. „Build vs. Buy: How to Know When You Should Build Custom Software Over Canned Solutions“. Forbes – online. http://www.forbes.com/sites/chuckcohn/2014/09/15/build-vs-buy-how-to-know-when-you-should-build-custom-software-over-canned-solutions/. (Latest access 16th January 2017).

[COL-03] Collins, J.W., 2003. The Greenwood Dictionary of Education. Greenwood Publishing Group, Westport – United States.

[COO-74] Coombs P. H., Ahmed, M., 1974. “Attacking Rural Poverty”. World Bank Research Publications, Connecticut –United States.

[COP-70] Cooper, C., 1970. „The Transfer of Industrial Technology of the Under-Developed Countries”. Institute of Development Studies Bulletin, Washington D.C.

[CRI-00] Crisp, B., Swerissen, H., Duckett S.J., 2000. “Four approaches to capacity Building in Health: Consequences for Measurement and Accountability”. Health Promotion International 21 (5): 99-107.

[CSP-15] CSP today. 2015. „Installed CSP capacity now over 4.5 GW”. http://social.csptoday.com/markets/installed-csp-capacity-now-over-45-gw. (Latest access 16th January 2017).

[CUR-04] Curbelo A., 2004. „UNESCO’s Global Renewable Energy Education and Training Program in a Latin American View”. UNESCO, New York.

[DAB-00] Dabour, N. 2000. „The Role of Foreign Direct Investment (FDI) in Development and Growth in OIC Members”. Journal of Economic Cooperation 21 (3): 27–55.

[DAV-15] Davoli, F., et.al., 2015. „LABNET: Towards Remote Laboratories with Unified Access”. IEEE Transactions on Instrumentation and Measurement 55 (5): 1551-1558.

[DEH-15] Despatch. 2015. „Industrial Ovens and Furnaces | Despatch“, Despatch industries. http://www.despatch.com/. (Latest access 16th January 2017).

[DEI-11] Deichmann, U., et.al., 2011. „The economics of renewable energy expansion in rural Sub-Saharan Africa”. Energy Policy 39 (1): 215–27.

[DEL-14] Deloitte. 2014. „Challenges and Solutions for the Digital Transformation and use of Exponential Technologies”. Deloitte Magazine. http://www2.deloitte.com/content/dam/Deloitte/ch/Documents/manufacturing/ch-en-manufacturing-industry-4-0-24102014.pdf. (Latest access 16th January 2017).

[DEP-16] De Paul Teaching Commons. 2016. „Course Objectives & Learning Outcomes”. Course Objectives & Learning Outcomes - DePaul University Teaching Commons. http://resources.depaul.edu/teaching-commons/teaching-guides/course-design/Pages/course-objectives-learning-outcomes.aspx. (Latest access 16th January 2017).

[DER-09] Del Río, P.D., Burguillo, M., 2009. “An empirical analysis of the impact of renewable energy deployment on local sustainability”. Renewable and Sustainable Energy Reviews 13: 1314–1325.

[DES-07] Desha, C.J, et. al., 2007. „The Importance of Sustainability in Engineering Education: A Toolkit of Information and Teaching Material”. Engineering Training and Learning Conference Proceedings. Brisbane.

[DES-09] Desha, C.J., Hargroves, K., Smith, M.H., 2009. „Addressing the time lag dilemma in curriculum renewal towards engineering education for sustainable development". International Journal of Sustainability in Higher Education 10 (2): 184-199.

[DESA-13] Department of Economic and Social Affairs (DESA), U.N., 2013. "World Economic and Social Survey 2013: Sustainable Development Challenges". United Nations Publication, New York.

[DESA-14] Department of Economic and Social Affairs (DESA), U.N., 2014. "World Urbanization Prospects – The 2014 Revision". United Nations Publication, New York.

[DESA-15] Department of Economic and Social Affairs (DESA), U.N., 2015. "World Population Prospects – The 2015 Revision". United Nations Publication, New York.

[DET-11] Deterding, S., Dixon, D., 2011. „Gamification: Towards a Definition". CHI 2011 Gamification Workshop Proceedings. San Jose.

[DEV-08] Devine-Wright, P., 2008. „Reconsidering public acceptance of renewable energy technologies: A critical review". In "Delivering a low-carbon Electricity System: Technologies, Economics and Policy". Cambridge University Press, UK.

[DEW-16] Dewey, J., 1916. "Democracy and Education: An Introduction to the Philosophy of Education". Macmillan, Massachusetts.

[DGS-13] DGS., 2013. "Planning and Installation of Photovoltaic Systems". 3.Edition. Earthscan, Berlin.

[DIA-10] Diaz-Dorado, E., et.al., 2010. „Influence of the shadows in photovoltaic systems with different configurations of bypass diodes". SPEEDAM 2010.

[DIC-90] Dick, W.O., Carey, L., Carey J.O., 1990. "The Systematic Design of Instruction". Allyn & Bacon, New York.

[DIK-13] Dickson, M. H., Fanelli, M., 2013. "Geothermal Energy: Utilization and Technology". Routledge, New York.

[DIM-11] Dimopoulos, C., Katzis, K., Hawwash, K., 2011. „Attracting Students to Engineering Education Studies: A survey of Practices". First World Engineering Education Flash Week. Lisbon.

[DIN-8580] Deutsches Institut für Normung. 2009. „DIN 8580:2003-09". DIN.

[DIT-16] Dictionary.com. 2016. „Familiarization". http://www.dictionary.com/browse/familiarization. (Latest access 16th January 2017).

[DOC-14] Docquier, F., 2014. „The brain drain from developing countries". Universite Catholique de Louvain, Louvain-la-Neuve - Belgium.

[DOW-16] Downes, S. 2016. „Half an Hour: Connectivism as Learning Theory". http://halfanhour.blogspot.com/2014/04/connectivism-as-learning-theory.html. (Latest access 16th January 2017).

[DPA-12] DPAD., 2012. „World Economic Situation and Prospects 2012 - Statistical annex". http://www.un.org/en/development/desa/policy/wesp/wesp_current/2012country_class.pdf. (Latest access 16th January 2017).

[DRE-07] Drew, J., Esposito, M., Perakslis, C., 2007. „Utilization of Robotics in Higher Education". Information Systems Education Journal 4 (2): 1-13.

[DUF-92] Duffy, T.M., Jonassen, D.H., 1992. „Constructivism: New Implications for Instructional Technology". In Constructivism and the Technology of Instruction. Lawrence Erlbaum Associates, Inc., New Jersey.

[DUF-13] Duffy, T.M., Jonassen, D.H., 2013. „Constructivism and the Technology of Instruction: A Conversation". Routledge, New York.

[DUH-08] Duh, H. B. L., Zhou, F. Billinghurst, M., 2008. „Trends in Augmented Reality Tracking, Interaction and Display: A Review of Ten Years of ISMAR”. 7th IEEE/ACM International Symposium on Mixed and Augmented Reality Proceedings 193-202.

[DUS-14] Duscha, V., et.al., 2014. „Employment and Groth Effects of Sustainable Energies in the European Union”. Fraunhofer ISI, Karlsruhe.

[EBE-08] Ebel, F., S., et.al. “Fundamentals of automation technology”. Festo Didactics. Denkendorf: Festo Didactic GmbH Co. https://lehrerfortbildung-bw.de/faecher/nwt/fb/atechnik/grundlagen/en/kapitel/563060_Fundamentals_of_automation_technology.pdf. (Last visited 04th Nov. 2016).

[EBR-UK] Ebert, K. Unknown. „Behaviorism vs. Constructivism in the Technological Secondary Education Classroom”. Theories of Educational Technologies. https://sites.google.com/a/boisestate.edu/edtechtheories/behaviorism-vs-constructivism-in-the-technological-secondary-education-classroom-1. (Last visited 19th November 2016).

[EC-08] European Commission., 2008. „Recommendation of the European Parliament and of the Council of 23 April 2008 on the Establishment of the European Qualifications Framework for Lifelong Learning”. European Commission, Brussels.

[EC-09] European Commission., 2009. „Gender Differences in Educational Outcomes. Study on the Measures Taken and the Current Situation in Europe”. Brussels: European Commission, Brussels.

[EC-15] European Commission., 2015. „Science Education for Responsible Citizenship”. Brussels: European Commission, Brussels.

[ECK-97] Eckelmann, H., 1997. „Einführung in die Strömungsmeßtechnik“. Vieweg Teubner Verlag, Wiesbaden.

[EDI-16a] EDIBON. 2016. „Computer controlled Photovoltaic Solar Energy Unit EEFSC”. http://www.edibon.com/products/catalogues/en/units/energy/alternativeenergies/EESFC.pdf. (Latest access 16th January 2017).

[EDI-16b] EDIBON. 2016. „MINI-EEEC Computer Controlled Wind Energy Basic Unit”. http://www.edibon.com/products/catalogues/en/units/energy/alternativeenergies/MINI-EEEC.pdf. (Latest access 16th January 2017).

[EDI-16c] EDIBON, „TA50/250C. Computer Controlled Aerodynamics Tunnel“. http://www.edibon.com/products/catalogues/en/units/fluidmechanicsaerodynamics/aerodynamicsbasic/TA50-250C.pdf. (Latest access 16th January 2017).

[EDN-15] Education News. 2015. „Oculus Rift Technology May Improve Online Learning”. Education News. Juni 18. http://www.educationnews.org/online-schools/oculus-rift-technology-may-improve-online-learning/. (Latest access 16th January 2017).

[EDU-15] EDUCASE. 2015. „EDUCAUSE Learning Initiative 7 Things You Should Know About Flipped Classrooms”. Educase Learning Initiative. https://net.educause.edu/ir/library/pdf/eli7081.pdf. (Latest access 16th January 2017).

[EEA-14] European Energy Agency., 2014. „Trends and Projections in Europe 2014”. European Environmental Agency, Luxemburg.

[EEA-15] European Energy Agency., 2015. „Renewable energy in Europe - approximated recent growth and knock-on effects”. European Environmental Agency, Luxemburg.

[EEP-16] Electrical Engineering Portal. 2016. „9 Reasons for automation of manufacturing processes | EEP”. EEP - Electrical Engineering Portal. http://electrical-engineering-portal.com/9-reasons-for-automation-of-manufacturing-processes. (Latest access 16th January 2017).

[EHR-01] Ehrenberg, R., et.al., 2001. „Class size and student achievement”. Psychological Science in the Public Interest 2 (1): 1–30.

[ELA-09] Elawady, Y.H., Tolba, A.S., 2009. „Educational Objectives of Different Laboratory Types: A comparative Study”. International Journal of Computer Sciences and Information Security 6 (2): 89-96.

[ELM-09] ElMaraghy, H. 2009. “Changeable and reconfigurable manufacturing systems”. Springer, London.

[ELN-89] El-Namaki, M.S.S. 1989. „Developing and promoting technology and technical skills in small-scale rural manufacturing enterprises”, Food and Agriculture Organization of the United Nations (FAO), New York.

[ELV-07] Elvira, M, Davila, A., 2007. “Managing Human Resources in Latin America: An Agenda for International Leaders”. Routledge, New York.

[ENE-16] Energypedia. 2016. „Technical Training for Renewable Energies and Energy Efficiency in Brazil”. https://energypedia.info/wiki/Technical_Training_for_Renewable_Energies_and_Energy_Efficiency_in_Brazil. (Latest access 16th January 2017).

[EP-05] European Parliament., 2005. “Establishing a framework for the setting of ecodesign requirements for energy-using products and amending”. European Parliament, Brussels.

[EPA-16] Environmental Protection Agency. 2016. „Global Greenhouse Gas Emissions Data“. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data. (Last visited 19th November 2016).

[ERT-93] Ertmer, P., Newby, T., 1993. „Behaviorism, Cognitivism, Constructivism: Comparing Critical Features from an Instructional Design Perspective”. Performance Improvement Quarterly 6 (4): 50–72.

[EST-05] Estes, A.C., Welch, R.W., Ressler, S.J., 2005 „The ExCEEd Teaching Model“. Journal of Professional Issues in Engineering Education and Practice 131 (4): 218-222.

[EU-15] EU. 2015., „2020 climate & energy package - European Commission”. European Union Climate Action, Luxemburg.

[EUR-09] EUREC., 2009. „Research Priorities for Renewable Energy Technology by 2020 and Beyond”. European Renewable Energy Research Centres, Brussels.

[EUS-13] Eurostat. 2013. „Greenhouse gas emissions by economic activity, EU-27, 2000 and 2012”. Eurostat. http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Greenhouse_gas_emissions_by_economic_activity,_EU-27,_2000_and_2012_(%25_of_total_emissions_in_CO2_equivalents)_YB15.png. (Last visited 18th November 2016).

[EWE-10] EWEA., 2010. „Wind at work: Wind energy and job creation in the EU”. The European Wind Association, Brussels.

[EWI-11] Ewing, B.D., et.al., 2011. „The Ecological Footprint Atlas 2010”. Global Footprint Network, Oakland.

[EWK-16] Education Wikipedia. 2016. “Instructional Design Models”. http://edutechwiki.unige.ch/en/Instructional_design_model. (Last visited Nov. 11th 2016)

[FAL-09] Falcao, A.F.O., 2009. „Wave energy utilization: A review of the technologies". Renewable and sustainable energy reviews 14 (1): 899-918.

[FED-90] Fedows, K., 1990. „Lasting improvements in manufacturing performance: In search of a new theory". Journal of Operations Management 9, 168–184.

[FEI-02] Feisel, L.D., Peterson, G., 2002. „A colloquy on learning objectives for engineering education laboratories". In Proceedings ASEE Annual Conference and Exposition, Montreal.

[FEI-05] Feisel, L.D., Rosa, A.J., 2005. „The Role of the Laboratory in Undergraduate Engineering Education". Journal of Engineering Education 94, 121–130.

[FEL-87] Felder, R.M., Silverman, L., 1987. „Learning and Teaching Styles in Engineering Education". Journal of Engineering Education 78 (7).

[FEL-97] Felder, R.M., Soloman, B.A. 1997. „Index of Learning Styles Questionnaire". Index of Learning Styles Questionnaire. http://www.engr.ncsu.edu/learningstyles/ilsweb.html. (Latest access 16th January 2017).

[FEL-05] Felder, R.M., Brett, R., 2005. „Understanding Student Differences". Journal of Engineering Education 94: 57–72.

[FEL-11] Felder, R.M., 2011. „Engineering Instructional Development: Programs, Best Practices, and Recommendations", Journal of Engineering Education 100 (1): 89-122.

[FEL-13] Felder, R.M., Hadgraft, R.G., 2013. „Educational Practice and Educational Research in Engineering: Partners, Antagonists, or Ships Passing in the Night?". Journal of Engineering Education 102 (3): 339–345.

[FID-14] Fidalgo-Blanco, A., Sein-Echaluce, M.L., García-Peñalvo, F.J., 2014. „Methodological Approach and Technological Framework to Break the Current Limitations of MOOC Model". Journal of Universal Computer Science 21: 712–34.

[FLA-14] Flavin, C. et al., 2014. "Study on the Development of the Renewable Energy Market in Latin America and the Caribbean". Interamerican Development Bank, Washington D.C.

[FLE-96] Flechsig K.H., 1996. „Kleines Handbuch didaktischer Modelle". Managerseminare Verlag, Eichenzell - Neuland.

[FLO-15] Flott. 2015. „TB 10 STW electronic - Arnz FLOTT GmbH Werkzeugmaschinen". TB 10 STW. http://www.flott.de/en/flott/products-metal-machine-tools/flott-drilling-machinery/single-phase-230v-ac/tb-10-stw-electronic. (Latest access 16th January 2017).

[FOR-98] Forrester, D, Jantzie, N. 1998. „Learning Theories". Learning Theories. https://www.academia.edu/7455235/Learning_Theories. (Latest access 16th January 2017).

[FORBES-11] Forbes. 2011. „Just How Much Are Engineers In Demand? Very Much So". Forbes / Tech. http://www.forbes.com/sites/tomiogeron/2011/12/21/just-how-much-are-engineers-in-demand-very-much-so/. (Latest access 16th January 2017).

[FRA-15] Fraunhofer ISE., 2015. „Photovoltaics report". Fraunhofer ISE, Freiburg.

[FRE-12] Freeman, S.P. 2012. „Budgetary Priorities in Latin America: Military, Health and Education Spending". SIPRI Insights on Peace and Security. http://books.sipri.org/files/insight/SIPRIInsight1102.pdf. (Latest access 16th January 2017).

[FSU-16] Fresno State University. 2016. „Blooms Taxonomy Action Verbs". Blooms Taxonomy Action Verbs.

http://www.fresnostate.edu/academics/oie/documents/assesments/Blooms%20 Level.pdf. (Latest access 16th January 2017).

[FUC-07] Fuchs, R., 2007. "Global Warming - Impacts and Consequences of Global Warming". GRIN Verlag, Konstanz.

[GAA-11] Galarraga, I., Gonzalez-Eguino, M., Markandya, A., 2011. "Handbook of Sustainable Energy". Edward Elgar Publishing, Cheltenham - UK.

[GAG-05] Gagne, R.M., et al., 2005. „Principles of instructional design". Performance Improvement 44 (2): 44–46.

[GAL-13] Gallaugher, J., 2013. "Information Systems: A Manager's Guide to Harnessing Technology". Flatworld Knowledge, Minnesota.

[GAO-00] U.S. General Accounting Office., 2000. "School facilities: America's schools not designed or equipped for the 21st century". GAO report GAO/HEHS.

[GAR-12] Garetti, M., Taisch, M., 2012. „Sustainable manufacturing: trends and research challenges". Production Planning & Control: The Management of Operations 23 (2–3): 83–104.

[GAS-05] Gasch, R., Twele, J., 2005. „Auslegung von Windturbinen nach Betz und Schmitz". In Windkraftanlagen, 179–217. Vieweg Teubner Verlag, Wiesbaden.

[GEB-12] Gebhardt, A., 2012. "Understanding Additive Manufacturing: Rapid Prototyping - Rapid Tooling - Rapid Manufacturing". Carl Hanser Verlag, Aachen.

[GEN-15] Genlab Limited, „Industrial Ovens and Laboratory Ovens - Industrial Ovens, Laboratory Ovens and Incubator Manufacturers: Genlab".Genlab limited. http://www.genlab.co.uk/. (Latest access 16th January 2017).

[GEO-04] Georgiev, T., Georgieva, A., Smrikarov, A. 2004. „M-learning - a New Stage of E-Learning". CompSysTech '04 international conference on Computer systems and technologies Proceedings.

[GEY-11] Geyer, H. S., 2011. "International Handbook of Urban Policy: Issues in the Developing World". Edward Elgar Publishing, Cheltenham - UK.

[GFN-10] Global Footprint Network. 2010. "Ecological_Footprint_Atlas 2010". http://www.footprintnetwork.org/images/uploads/Ecological_Footprint_Atlas_2010.pdf. (Last visited 15th November 2016).

[GFN-16] Global Footprint Network. 2016. "Ecological Wealth of Nations". http://www.footprintnetwork.org/ecological_footprint_nations/. (Last visited 15th November 2016).

[GIB-08] Gibbins, J., Chalmers, H., 2008. „Carbon capture and storage". Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project, 36 (12): 4317–4322.

[GLA-03] Gläser, J., 2003. „What Internet Use does and does not Change in Scientific Communities". Science Studies 16 (1): 38–51.

[GOE-05] Goetzberger, A., Hoffmann, V.U., 2005. „Photovoltaic Solar Energy Generation". Springer, London.

[GOF-15] Goff, L., et.al., 2015. "Learning Outcomes Assessment: A Practitioner's Handbook". Higher Education Quality Council of Ontario, Ontario.

[GOI-10] Goli, S., Pandey, A. 2010. „Is India getting older before getting rich? Beyond demographic assessment". In "Challenges of the Twenty First Century: A transdisciplinary Perspective". Macmillan Advanced Research Series, New Delhi.

[GOL-14] Gold, S. 2014 „The Competitive Edge: Manufacturing's Multiplier Effect -- It's Bigger Than You Think", Industry Week. http://www.industryweek.com/global-economy/competitive-edgemanufacturings-multiplier-effect-its-bigger-you-think. (Latest access 16th January 2017).

[GOLC-16] GOLC, „International Association of Online Engineering (IAOE) & Global Online Laboratory Consortium (GOLC)“ [Online]. http://online-engineering.org/GOLC_about.php. (Last visited 18th November 2016).

[GON-13] Gonzalez Hernandez, M. A., et.al. 2013. „Design Methodology for a Quick and Low-Cost Wind Tunnel”. In Wind Tunnel Designs and Their Diverse Engineering Applications,. InTech. http://www.intechopen.com/books/wind-tunnel-designs-and-their-diverse-engineering-applications/design-methodology-for-a-quick-and-low-cost-wind-tunnel. (Last visited 4th November 2016).

[GPE-15] Global Production Engineering. 2015. „GPE - New Energy Technologies: Module and Course Description”. Technische Universität Berlin. http://www.gpe.tu-berlin.de/fileadmin/user_upload/download/GPE_Intake_2016_Module_Catalogue_NET.pdf. (Last visited 4th November 2016).

[GRA-07] Graf, S., Viola, S.R., Leo, T., K., 2007. “In-Depth Analysis of the Felder-Silverman Learning Style Dimensions”. Journal of Research on Technology in Education 40, 79–93.

[GRE-62] Greschenkron, A., 1962. “Economic Backwardness in historical perspective”. Frederick A. Praeger, New York.

[GRN-09] Grundig, C.G., 2009. „Fabrikplanung: Planungssystematik - Methoden – Anwendungen“. Hanser, München.

[GRO-10] Groover, M.P., 2010. “Fundamentals of Modern Manufacturing: Materials, Processes, and Systems”. John Wiley & Sons, Chicago.

[GRU-11] Grube, P., et al., 2011 „A Metadata Model for Online Laboratories”, IEEE EDUCON Engineering Education Proceedings, Amman.

[GUN-16a] Gunt. 2016. „ET 250 Messen an Solarmodulen“. http://www.gunt.de/index.php?option=com_gunt&task=gunt.list.category&category_id=669&product_id=186&Itemid=119&lang=de. (Latest access 16th January 2017).

[GUN-16b] Gunt 2016. „HM 170 Open Wind Tunnel“. http://www.gunt.de/index.php?option=com_gunt&task=gunt.list.category&product_id=769&lang=en. (Latest access 16th January 2017).

[GUN-16c] Gunt. 2016. „ET 220 Energy Conversion in a Wind Power Plant”. http://www.gunt.de/index.php?option=com_gunt&task=gunt.list.category&product_id=183&lang=en. (Latest access 16th January 2017).

[GUN-16d] Gunt. 2016. „HM 226 Wind Tunnel for Visualisation of Streamlines”. http://www.gunt.de/index.php?option=com_gunt&task=gunt.list.category&product_id=819&lang=en. (Latest access 16th January 2017).

[GUR-12] Gurit. 2012. „Wind Turbine Blade Aerodynamics“ http://www.gurit.com/files/documents/2aerodynamicspdf.pdf. (Latest access 16th January 2017).

[GUT-11] Guthrie, G., 2011. “The Progressive Education Fallacy in Developing Countries: In Favour of Formalism”. Springer Science & Business Media, New York.

[GUY-09] Guy, R., 2009. “The Evolution of Mobile Teaching and Learning”. Informing Science, California.

[GWE-15a] Global Wind Energy Council., 2015. „Global Wind Statistics 2014“. Global Wind Energy Council, Brussels.

[GWE-15b] Global Wind Energy Council., 2015. „How much electricity can one wind turbine generate?”. Global Wind Energy Council, Brussels.

[HAA-15] Haas. 2015. „Haas Automation, Inc. | CNC Machine Tools | Best in CNC Milling and Lathe Value“, Haas Automation Inc. http://int.haascnc.com/home.asp?intLanguageCode=1033. (Latest access 16th January 2017).

[HAE-12] Häberlin, H., 2012. “Photovoltaics: System Design and Practice”. Wiley, UK.

[HAM-11] Hamrol, A., Kowalik, D., Kujawińsk, A., 2011. „Impact of Selected Work Condition Factors on Quality of Manual Assembly Process”. Human Factors and Ergonomics in Manufacturing & Service Industries 21 (2): 156–163.

[HAN-06] Haan, G., 2006. „The BLK ‘21’ programme in Germany: a ‘Gestaltungskompetenz’-based model for Education for Sustainable Development”. Environmental Education Research 12 (1): 19–32.

[HAR-04] Harris, E., 2004. „Building scientific capacity in developing countries”. EMBO Reports 5 (1): 7–11.

[HAR-09] Harris, K.L., 2009. „International trends in establishing the standards of academic achievement in higher education: An independent report and analysis”. Australian Universities Quality Agency, Melbourne.

[HAS-15] Haski-Leventhal, D., Pournader, M., McKinnon, A., 2015. „The Role of Gender and Age in Business Students’ Values, CSR Attitudes, and Responsible Management Education: Learnings from the PRME International Survey”. Journal of Business Ethics 1–21.

[HEA-14] Herrmann, E. 2014. „MultiBrief: Grouping students: Heterogeneous, homogeneous and random structures”. http://exclusive.multibriefs.com/content/grouping-students-heterogeneous-homogeneous-and-random-grouping-structures/education. (Latest access 16th January 2017).

[HEI-09] Heizer, J., Render, B., Rajashekhar., 2009. “Operations Management”. Pearson Education, New York.

[HEM-12] Hemami, A., 2012. “Wind Turbine Technology”. Cengage Learning, Clifton Park – United States.

[HER-13] Herreid, C.F., Schiller N.A., 2013. „Case Studies and the Flipped Classroom”. Journal of College Science Teaching 42 (5): 62–66.

[HES-08] Hesselbach, J., et.al., 2008. „Energy Efficiency through optimized coordination”. In 15th CIRP International Conference on Life Cycle Engineering proceedings. Sydney, Australia.

[HEY-14] Heyer, S., 2014. „Community-based Design of Process Chains for Manufacturing and Recycling”. Dissertation Technische Universität Berlin, Berlin.

[HOF-11] Hofstede, G. 2011. „Dimensionalizing Cultures: The Hofstede Model in Context”. Online Readings in Psychology and Culture. http://scholarworks.gvsu.edu/cgi/viewcontent.cgi?article=1014&context=orpc. (Latest access 16th January 2017).

[HOO-16] van Hooft, C., 2016. „Globalising innovation: How developing countries can be competitive in a tech-driven world“. Cambridge Globalist, Cambridge.

[HOU-04] Houseman, O., Tiwari, A., Roy, R., 2004. „A methodology for the selection of new technologies in the aviation industry“. Cranfield University, Cranfield - UK.

[HU-01] Hu, J., E Kannatey E., 2001. „Assembly and welding processes and their monitoring and control". In The Mechanical Systems Design Handbook. CRC Press, Dallas.

[HUN-15] Hung, C.Y., Lee, W.Y., 2015 „A proactive technology selection model for new technology: The case of 3D IC TSV". Technological Forecasting and Social Change 103 (1): 191–202.

[HWA-14] Hwang, G.J. 2014. „Definition, framework and research issues of smart learning environments - a context-aware ubiquitous learning perspective" Smart Learning Environments 1 (4).

[IDC-12] Instructional Design Central., 2012. „Instructional Design Models and Methods". Instructional Design Central, Michigan. http://www.instructionaldesigncentral.com/htm/IDC_instructionaldesignmodels.htm. (Latest access 16th January 2017).

[IEA-12a] IEA., 2012a. „Bioenergy Roadmap". International Energy Agency, Paris.

[IEA-12b] IEA., 2012b. „Technology Roadmap: Hydropower". Paris: International Energy Agency, Paris.

[IEA-12c] International Energy Agency., 2012. „Energy Technology Perspectives 2012". Energy Technology Perspectives. Paris: International Energy Agency, Paris.

[IEA-15] IEA., 2015. „Medium-Term Renewable Energy Market Report 2015". Paris: International Energy Agency, Paris.

[IEA-16] IEA., 2016. „RD&D Budget". IEA Energy Technology RD&D Statistics. International Energy Agency, Paris.

[IEE-12] Institute of Electrical and Electronics Engineers. 2012. „IEEE Reference Guide for Instructional Design". https://www.ieee.org/education_careers/education/university_programs/index.html. (Latest access 16th January 2017).

[IKS-15] IKS Photovoltaik. 2015. „Solar Trainer Profi", 2015. http://www.iks-photovoltaik.de/fileadmin/iks/pdf/STP_EN%20kl.pdf. (Last visited 020th November 2016).

[IRE-09] IRENA. 2009. „Conference on the Establishment of the International Renewable Energy Agency". Bonn: International Renewable Energy Agency. https://www.irena.org/documents/uploadDocuments/IRENA_FC_conference_report_26_01_2009.pdf. (Last visited 4th November 2016)

[IRE-12] IRENA. 2012. „Capacity Building Strategic Framework for IRENA (2012 – 2015)". UAE: International Renewable Energy Agency. https://www.irena.org/DocumentDownloads/Publications/Capacity_Building_Strategy.pdf. (Last visited 4th November 2016).

[IRE-14a] IRENA. 2014a. „Ocean Thermal Energy Technology Brief". International Renewable Energy Agency. http://www.irena.org/DocumentDownloads/Publications/Ocean_Thermal_Energy_V4_web.pdf. (Last visited 4th November 2016).

[IRE-14b] IRENA. 2014b. „Renewable Energy in Manufacturing: A Technology Roadmap for REmap2030". International Renewable Energy Agency. http://www.irena.org/REmap/REmap%202030%20Renewable-Energy-in-Manufacturing.pdf. (Last visited November 4th 2016).

[IRE-14c] IRENA. 2014c. „Tidal Energy Technology Brief". International Renewable Energy Agency. http://www.irena.org/documentdownloads/publications/tidal_energy_v4_web.pdf. (Last visited November 4th 2016).

[IRE-14d] IRENA. 2014d. „Wave Energy Technology Brief”. International Renewable Energy Agency. http://www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf. (Last visited November 4th 2016).

[IRE-15a] IRENA. 2015. „Dismantling the Barriers to a Renewable-Based Knowledge Economy”. International Renewable Energy Agency. http://www.renewableenergymagazine.com/article/dismantling-the-barriers-to-a-renewablesbased-knowledge-20130328. (Last visited November 4th 2016).

[IRE-15b] IRENA. 2015. „Renewable energy and jobs - Annual review 2015“. Abu Dhabi: International Renewable Energy Agency. http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=585. (Last visited November 4th 2016).

[IRE-16a] IRENA. 2016. „Renewable Energy Benefits: Measuring the Economics”. International Renewable Energy Agency. http://www.irena.org/DocumentDownloads/Publications/IRENA_Measuring-the-Economics_2016.pdf. (Last visited November 4th 2016).

[IRE-16b] IRENA. 2016. „IRENA’s Renewable Energy Learning Partnership (IRELP)”. http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=44&CatID=109&SubcatID=447. (Last visited 18th November 2016).

[ISE-16] ISE NCSU. 2016. „Industrial Engineering defined”. Department of industrial and System Engineering at the North Carolina State University. http://www.ise.ncsu.edu/undergraduate/docs/isecareers.pdf. (Latest access 16th January 2017).

[ISI-16] iSixSigma. 2016. „What Is Six Sigma?” What is Six Sigma. Februar 12. http://www.isixsigma.com/new-to-six-sigma/getting-started/what-six-sigma/. (Latest access 16th January 2017).

[ISO-9000] ISO. 2005. „ISO/TR 9000:2005 – Quality Management”. International Organization for Standardization.

[ISO-14040] ISO. 2006. „ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework”. International Organization for Standardization.

[ISO-14062] ISO. 2002. „ISO/TR 14062:2002 - Environmental management -- Integrating environmental aspects into product design and development”. International Organization for Standardization

[ISP-10] ISPRE., 2010. „Research and Development on Renewable Energies: A Global Report on Photovoltaic and Wind Energy”. The International Science Panel on Renewable Energies, Paris.

[JAC-09] Jackson, T., 2009. “Prosperity without growth: Economics for a finite planet”. Earthscan, United States.

[JAK-13] Jackson, R., 2013. „Global Climate Change: Effects”. Climate Change: Vital Signs of the Planet, United States.

[JAN-13] Januszewski, et.al., 2013. “Educational Technology: A Definition with Commentary”. Routledge, New York.

[JAO-16] Jacobs, K. 2016. „Bridging the rift between classroom and online learning”. http://news.psu.edu/story/359805/2015/06/15/research/bridging-rift-between-classroom-and-online-learning. (Latest access 16th January 2017).

[JAR-13] Jared, K., 2013. “Pedagogical Applications and Social Effects of Mobile Technology Integration”. IGI Global, Pennsylvania.

[JAW-13] Jawahir, I.S., 2013. „Innovation in sustainable manufacturing education”. In 11th Global Conference on Sustainable Manufacturing, Berlin.

[JEN-01] Jennings, P., Lund, C. 2001. „Renewable Energy Education for Sustainable Development”. Elsevier, Australia.

[JEN-09] Jennings, P., 2009. „New directions in renewable energy education”. Renewable Energy for Sustainable Development in the Asia Pacific Region, 34 (2): 435–39.

[JHA-07] Jha, C.S., 2007. „Engineering Education in Developing Countries: social relevance versus international comparability”. European Journal of Engineering Education 14 (2): 113–19.

[JIA-11] Jiang, S., Qi, X., 2011. „Exploration of Enhancing Students’ Professional Ability and Innovation Ability with Manufacturing Knowledge“. Energy Procedia 13 (1): 2432–2437.

[JOE-10] Jones, P., Selby, D., Sterling, S.R., 2010. “Sustainability Education: Perspectives and Practice Across Higher Education”. Earthscan, New York.

[JOH-11] Johri, A., Olds, B.M., 2011. „Situated Engineering Learning: Bridging Engineering Education Research and the Learning Sciences“. Journal of Engineering Education 100 (1): 151-185.

[JOH-14] Johri, A., Olds, B.M., 2014. “Cambridge Handbook of Engineering Education Research”. Cambridge University Press, Cambridge.

[JON-91] Jonassen, D.H., 1991. „Evaluating Constructivistic Learning”. Educational Technology 31 (9): 28–33.

[JON-03] Jonassen, D.H., 2003. “Learning to Solve Problems with Technology: A Constructivist Perspective”. Merrill, New Jersey.

[JOS-07] Johnston, A., 2007. „Final education for sustainable development: Final report of international action research project”. OECD, Paris.

[JOV-08] Jovane, F., H. et.al., 2008. „The incoming global technological and industrial revolution towards competitive sustainable manufacturing”. CIRP Annals - Manufacturing Technology 57 (2): 641–659.

[JUK-13] Juknys, R., Liobikienė, G., Dagiliūtė, R., 2014. “Sustainability of catch-up growth in the extended European Union”. Journal of Cleaner Production 63: 54–63.

[JUN-21] Jung, C., 1921. “Psychological types”. Routledge, New Jersey.

[KAL-67] Kaldor, N., 1967. “Strategic Factors in Economic Development. New York State School of Industrial and Labor Relations”. Cornell University, New York.

[KAN-14] Kandpal, T.C., Broman, L., 2014. „Renewable energy education: A global status review”. Renewable and Sustainable Energy Reviews 34: 300–324.

[KAR-11] Karner, F.W., Härtel, G. 2011. „Theory and Taxonomies of Serious Games”. ENTREExplorer. http://www.entrexplorer.com/pdf/Theory_and_Taxonomies_of_Serious_Games.pdf. (Latest access 16th January 2017).

[KAS-12] Katsioloudis, P., Fantz, T., 2012. „A Comparative Analysis of Preferred Learning and Teaching Styles for Engineering, Industrial, and Technology Education Students and Faculty”. Journal of Technology Education 23 (1).

[KAT-09] Katehi, L., Pearson, G., Feder, M., 2009. „The Status and Nature of K-12 Engineering Education in the United States”. National Academy of Engineering, Washington.

[KAU-10] Kaushish, J. P., 2010. Manufacturing Processes. Prentice-Hall India, New Delhi.

[KEC-15] Kecebas, A., Alkan, A., 2015. „The education and training of renewable energy resources for sustainable development in Turkey”. Mugla Journal of Science and Technology 1 (1).

[KEE-11] Keesee, G.S. 2011. „Learning Theory and Instructional Design/Technology”. Teaching and Learning Resources. http://teachinglearningresources.pbworks.com/w/page/19919565/Learning%20 Theories. (Latest access 16th January 2017).

[KEL-10] Kelly, P., 2010. „Rapid Urbanization and Mega Cities: The Need for Spatial Information Management“.International Federation of Surveyors Publication 48 (1).

[KER-15] Keramida, M., 2015. „Behaviorism in Instructional Design for eLearning: When and How to Use”. http://elearningindustry.com/behaviorism-in-instructional-design-for-elearning-when-and-how-to-use. (Latest access 16th January 2017).

[KET-84] Kettner, H., Schmidt, J., Greim, H.R., 1984. „Leitfaden der systematischen Fabrikplanung“. Hanser, München.

[KIB-67] Kimble, G.A., 1967. “Foundations of Conditioning and Learning”. Appleton-Century-Crofts, New York.

[KIM-10] Kim, W., et al., 2010. „The dual analytic hierarchy process to prioritize emerging technologies”. Technological Forecasting and Social Change 77 (4): 566–577.

[KLI-09] Klinger, C.M., 2009. „Behaviorism, cognitivism, constructivism, or connectivism? Tackling mathematics anxiety with ‚isms‘ for a digital age“. Proceedings Adult Learning Mathematics Conference. London.

[KNE-12] Kneill-Boxley, S., 2012. „Towards a mobile learning strategy to support Higher Education”. Innovative Practice in Higher Education. http://journals.staffs.ac.uk/index.php/ipihe/article/view/2. (Latest access 16th January 2017).

[KNI-07] Knight, J., 2007. „An Internationalization Model: Responding to new Realities and Changes”. In Higher Education in Latin America: The International Dimension. The World Bank, Washington D.C.

[KOB-08] Kobayashi, R., 2008. “New Educational Technology”. Nova Publishers, Tokyo.

[KOH-14] Koshal, D., 2014. “Manufacturing Engineer’s Reference Book”. Butterworth-Heinemann, Los Angeles.

[KOL-84] Kolb, D.A., 1984. “Experiential Learning: Experience as the Source of Learning and Development”. FT Press, Michigan.

[KOO-09] Koohang, A., Riley, L., Smith, T., 2009. „E-Learning and Constructivism: From Theory to Application”. Interdisciplinary Journal of E-Learning and Learning Objects 5: 91–109.

[KOS-13] Kosmadoudi, Z., et.al., 2013. „Engineering Design Using Game-Enhanced CAD: The Potential to Augment the User Experience with Game Elements”. Computer-Aided Design 45 (3): 777–95.

[KRA-02] Krathwohl, D.R., 2002. „A revision of Bloom’s Taxonomy: An Overview”. Theory into Practice 41 (4).

[KRU-05] Krause, E., 2005. “Fluid Mechanics”. Springer-Verlag, Berlin.

[LAH-78] Lanham, C. D., 1978. “Review of Review of Education and Culture in the Barbarian West, Sixth through Eighth Centuries, Pierre Richard;, von Pierre Riché”. The Journal of Library History (1974-1987) 13 (1): 72–74.

[LAM-97] Lamancusa, J.S., Jorgensen, J.E., Zayas-Castro, J.C., 1997. „The Learning Factory - A New Approach to Integrating Design and Manufacturing into the Engineering Curriculum”. Journal of Engineering Education 86 (2): 103–12.

[LAN-16] Langevin 2016. „5 Ways Learner Analysis Will Impact Instructional Design”. Langevin Learning Services. http://www.langevin.com/blog/2012/09/17/5-ways-learner-analysis-will-impact-instructional-design/. (Latest access 16th January 2017).

[LAR-14] Larmer, J. 2014. „Project-Based Learning vs. Problem-Based Learning vs. X-BL”. Edutopia. http://www.edutopia.org/blog/pbl-vs-pbl-vs-xbl-john-larmer. (Latest access 16th January 2017).

[LAT-13] Latanision, R.M., 2013., “The Bridge: Linking Engineering and Society”. 2 (43). National Academy of Engineering, Washington D.C.

[LAV-12] Lavopa, A., Szirmai, A., 2012. „Industrialization, employment and poverty”. International Finance Corporation - World Bank Group, Washington D.C.

[LEH-12] Lehto, M.R., Landry, S.J., 2012. „Introduction to Human Factors and Ergonomics for Engineers”. CRC Press, New York.

[LEO-02] Leonard, D.C., 2002. “Learning Theories, A to Z”. Greenwood Publishing Group, Connecticut.

[LEU-06] Leung, F.K.S., et.al., 2006. „Mathematics Education in Different Cultural Traditions- A Comparative Study of East Asia and the West: 13th ICMI Study”. Springer Science & Business Media, London.

[LEW-15] Lewis, N., et.al., 2015. “A distance measurement platform dedicated to electrical engineering”. IEEE Transactions on Learning Technologies 2(4): 312-319.

[LI-05] Li, X., 2005. „Diversification and localization of energy systems for sustainable development and energy security”. Energy Policy 33 (17): 2237–43.

[LI-12] Li, W., Grossman T., Fitzmaurice, G., 2012. „GamiCAD: A Gamified Tutorial System for First Time AutoCAD Users”. 25th Annual ACM Symposium on User Interface Software and Technology Proceedings.

[LIE-09] Liersch, J., Wiens, S., 2015. „GPE Lecture: Wind energy turbines“. Technische Universität Berlin, Berlin.

[LIM-09] Liming, H., 2009. „Financing rural renewable energy: A comparison between China and India”. Renewable and Sustainable Energy Reviews 13 (5): 1096–1103.

[LMC-14] LMC. 2014. „Makerspaces: What Are They?” Libraries & Maker Culture: A Resource Guide. http://library-maker-culture.weebly.com/what-are-they.html. (Latest access 16th January 2017).

[LNU-16] Lucas Nülle. 2016. Lucas Nülle, „EPH 2 Photovoltaik Advanced“. https://www.lucas-nuelle.de/217/apg/5677/EPH-2-Photovoltaik-Advanced.htm. (Latest access 16th January 2017).

[LOU-12] Lou, S.J., et al., 2012 „Construction of A Creative Instructional Design Model Using Blended, Project-Based Learning for College Students”. Creative Education 3 (7): 1281-1290.

[LUQ-03] Luque, A., Hegedus, S., 2003. “Handbook of photovoltaic science and engineering”. Wiley, Sussex.

[MA-16] Ma, J. 2016. „How Unconventional, Experiential Learning Is Reshaping Higher Education”. Forbes. http://www.forbes.com/sites/jasonma/2015/05/15/how-unconventional-experiential-learning-is-reshaping-higher-education/. (Latest access 16th January 2017).

[MAC-09] Machotka, J., Nedic, Z., 2009. „Collaboration in Remote Laboratory: Vision for the Future”. Proceedings 6th WSEAS International Conference on Engineering Education, 80–84. EDUCATION’09. Stevens Point – United States.

[MAL-15] Malevanov, E., Novoselova, S., Pevstova, E., 2015. „Technologies Didactic Content of the Higher School Students Intellectual Potential Development”. Journal of Sustainable Development 8 (3).

[MAM-99] Mamgain, V., 1999. „Are the Kaldor-Verdoorn laws applicable in the newly industrializing countries”. Review of Development Economics 3 (3): 295–309.

[MAN-18] Mann, C.R., 1918. „A Study of Engineering Education”. The Carnegie Foundation for the Advancement of Teaching, New York.

[MAR-15] Markopoulos, A.P., Fragkou, A., Kasidiaris, P.D., Davim, J.P., 2015. “Gamification in engineering education and professional training”. International Journal of Mechanical Engineering Education 43: 118–131.

[MAT-16] Mathiesen, K., 2016. „Lack of engineers delaying vital water projects in developing countries“. The Guardian, 15-Jan-2016. https://www.theguardian.com/global-development-professionals-network/2016/jan/15/lack-of-engineers-delaying-vital-water-projects-in-developing-countries. (Latest access 16th January 2017).

[MAV-11] Mavrikios, D. et al., 2011. „On industrial learning and training for the factories of the future: a conceptual, cognitive and technology framework”. Journal of Intelligent Manufacturing 24 (3): 473–485.

[MAY-12] Manyika, J., et.al. 2012. „Manufacturing the Future: The Next Era of Global Growth and Innovation. http://www.mckinsey.com/business-functions/operations/our-insights/the-future-of-manufacturing. (Last visited 4th November 2016).

[MCD-13] McDonough, D., 2013. „Similarities and Differences between Adult and Child Learners as Participants in the Natural Learning Process”. Psychology 4 (3): 345–48.

[MCE-12] McEvoy, A.J., Markvart, T., 2012. “Practical Handbook of Photovoltaics: Fundamentals and Applications”. Academic Press, London.

[MCF-13] McFarland, R., Reise, C., Postawa, A., Seliger, G., 2013. “Learnstruments in Value Creation and Learning Centered Work Place Design,”. In Proceedings of the Global Conference on Sustainable Manufacturing 2013, Berlin.

[MCG-05] McGowan, F., Sauter, R., 2005. „Public Opinion on Energy Research: A Desk Study for the Research Councils”. University of Sussex, Sussex.

[MCK-09] McKinsey & Company. 2009. „Pathways to a Low-Carbon Economy“. McKinsey & Company Publication, Chicago.

[MEH-79] Mehta, R.D., Bradshaw, P., 1979. „Design rules for small low speed wind tunnels”. The Aeronautical Journal of the Royal Aeronautical Society 1: 443-449.

[MER-04] Merrill, D., 2004. „First Principles of Instruction”. Educational Technology Research and Development 50 (3): 43-59.

[MID-15] Middleton, A., 2015. “Smart learning: teaching and learning with smartphones and tablets in post compulsory education”. The U.K. Media-Enhanced Learning Special Interest Group (MELSIG). http://melsig.shu.ac.uk/?page_id=503. (Last visited 04th November 2016).

[MIL-05] Milanović, B., 2005. “Worlds Apart: Measuring International and Global Inequality”. Princeton University Press, New Jersey.

[MIR-15] Miremadi, M., et. al., 2015. „The Age of Smart, Safe, Cheap Robots Is Already Here”. Harvard Business Review, Massachusetts.

[MIS-14] Mishra, A. 2014. „Growing mismatch between graduate skills, market needs”. University World News. http://www.universityworldnews.com/article.php?story=20140204171742828. (Latest access 16th January 2017).

[MOE-07] Moreno, L., et.al., 2007. „Applying a constructivist and collaborative methodological approach in engineering education”. Computers & Education 49 (3): 891–915.

[MOR-09] Morris, Richard. 2009. “Fundamentals of Product Design”. AVA Academia, Lausanne.

[MOU-13] Moula, E., et.al., 2013. „Researching social acceptability of renewable energy technologies in Finland”. International Journal of Sustainable Built Environment 2 (1): 89–98.

[MUG-11] Mughal, F., Zafar, A., 2011. „Experiential Learning from a Constructivist Perspective: Reconceptualizing the Kolbian Cyle”. International Journal of Learning and Development 1 (2).

[MUL-11] Mulvaney, D., 2011.” Green Energy: An A-to-Z Guide”. SAGE, Paris.

[MUN-12] Munoz-Hernandez, G. et.al., 2012. „Modelling and Controlling Hydropower Plants”. Springer Science & Business Media, Puebla - Mexico.

[MUS-16a] Munsel, M. 2016. “Latin America Solar Market on Pace to Install 2.2GW of PV in 2016, Grow 55% Year-Over-Year”. Grrentech Media. https://www.greentechmedia.com/articles/read/latin-america-solar-market-on-pace-to-install-2.2-gw-of-pv-in-2016-grow-55. (Last visited 20th November 2016).

[MUS-16b] Munsel, M. 2016. “3 Fast Facts About Latin America’s Solar Market”. Greetech Media. https://www.greentechmedia.com/articles/read/three-fast-facts-about-latin-americas-solar-market. (Last visited 20th November 2016)

[MWA-06] Mwakali, J. 2006. „Feasibility of Conserving Energy through Education: The Case of Uganda as a Developing Country”. Proceedings International Conference on Advances in Engineering and Technology (AET2006). Elsevier. http://www.sciencedirect.com/science/article/pii/B9780080453125500431. (Last visited 04th November 2016)

[MWG-10] Multilateral Working Group on Implementing the Major Economies Forum Global Partnership’s Technology Action Plans for Wind and Solar Technologies, 2010. „A long term strategy on joint capacity building - Success factors for a long term strategy”. MWG, Madrid.

[NAE-04] National Academy of Engineering., 2004. „The Engineer of 2020: Visions of Engineering in the New Century”. National Academy of Engineering, Washington D.C.

[NAE-06] National Academy of Engineering., 2006. „Engineering for the Developing World”. National Academy of Engineering, Washington D.C.

[NAH-09] Nahmias, S., 2009. “Production and operations analysis”. McGraw Hill, New York.

[NAK-11] Nakata, Y., Miyazaki, S., 2011. „The Labor Market for Japanese Scientists and Engineers: Is the Labor Market externalized? What has happened at their Workplace“, Japan Labor Review 8 (3): 95–117.

[NAM-14] National Association of Manufacturers. 2014. „Facts About Manufacturing”. http://www.nam.org/Newsroom/Facts-About-Manufacturing/. (Latest access 16th January 2017).

[NAS-95] National Academy of Sciences. 1995. “Unit Manufacturing Processes: Issues and Opportunities in Research”. National Academy Press – Washington D.C.

[NASA-15] NASA. 2015. „Wind Tunnel Design”. National Aeronautics and Space Administration - Wind Tunnel Design. https://www.grc.nasa.gov/www/k-12/airplane/tunnozd.html. (Latest access 16th January 2017).

[NAU-12] Naudé, W., Szirmai, A., 2012. „The importance of manufacturing in economic development: Past, present and future perspectives”. Maastricht Economic and Social Research Institute on Innovation and Technology, The Netherlands.

[NCE-15] NCES. 2015. „Education expenditures by country”. The condition of education. http://nces.ed.gov/programs/coe/indicator_cmd.asp. (Latest access 16th January 2017).

[NEA-99] Neap, H. Shevket, A., Celik, A., 1999. „Value of a Product: A Definition”. International Journal of Value-Based Management 12 (2): 181–191.

[NED-15] Nedic, Z., Machotka, N., Nafalski, A., 2015. „Remote laboratories versus virtual and real laboratories”. In Proceedings Frontiers in Education Conference, Westminster Colorado.

[NEG-12] Negro, S. O., Floortje A., Hekkert. P.M. 2012. „Why does renewable energy diffuse so slowly? A review of innovation system problems”. Renewable and Sustainable Energy Reviews 16 (6): 3836–46.

[NEI-67] Neisser, U., 1967. “Cognitive Psychology: Classic Edition”. Psychology Press, New York.

[NEM-15 Nemeth, J. 2015. „Georgia Tech, Emory unite to train health care roboticists”. http://news.emory.edu/stories/2015/10/health_care_robotics/campus.html. (Latest access 16th January 2017).

[NET-04] Netz, Y, Raviv, S., 2004. „Age Differences in Motivational Orientation toward Physical Activity: An Application of Social-Cognitive Theory”. The Journal of Psychology 138 (1): 35–48.

[NEU-06] Neu, D, et.al., 2006. “Informing” technologies and the World Bank”. Accounting, Organizations and Society 31 (7): 635–62.

[NEW-91] Newborough, M., P., et.al., 1991. „Primary- and secondary-level energy education in the UK”. Applied Energy 40 (2): 119–56.

[NGA-15] Ngaile, G., Wang, J., Gau, J.T., 2015. “Challenges in teaching modern manufacturing technologies”. European Journal of Engineering Education 40 (4): 432–449.

[NIE-11] Nielsen, L., 2011. „Classifications of Countries Based on Their Level of Development: How it is Done and How it Could be Done”. International Monetary Fund, Washington D.C.

[NIN-16] Nino, F.S., 2016. „Education”. United Nations Sustainable Development Goals http://www.un.org/sustainabledevelopment/education/. (Latest access 16th January 2017).

[NIX-01] Nixon, E.K., Lee, D., 2001. „Rapid Prototyping in the Instructional Design Process”. Performance Improvement Quarterly 14 (3): 95–116.

[NMC-15] NMC. 2015. „Horizon report 2015: Higher education edition”. Horizon Report. New Media Consortium. http://cdn.nmc.org/media/2015-nmc-horizon-report-HE-EN.pdf. (Latest access 16th January 2017).

[NMC-16] NMC. 2016. „Horizon Report: 2016 Higher Education Edition”. Horizon Report. New Media Consortium. http://cdn.nmc.org/media/2016-nmc-horizon-report-he-EN.pdf. (Latest access 16th January 2017).

[NRC-15] National Research Council., 2015. „Interim Report on 21st Century Cyber-Physical Systems Education”. National Research Council, Washington D.C.

[NRE-15a] National Renewable Energy Laboratory, 2015a. „Geothermal Electricity Production Basics”. National Renewable Energy Laboratory, Washington D.C.

[NRE-15b] National Renewable Energy Laboratory, 2015b. „Renewable electricity futures study”. National Renewable Energy Laboratory, Washington D.C.

[NSF-15] National Science Foundation. 2015. „Cyber-Physical Systems“ http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503286. (Latest access 16th January 2017).

[OECD-13] OECD, 2013. „How many students study abroad and where do they go?” Education at glance 2013: Highlights. OECD, Paris.

[OECD-14] OECD, 2014. „Research co-operation between Developed and Developing Countries in the Area of Climate Change Adaption and Biodiversity”. OECD, Paris.

[OECD-15] OECD, 2015. Education at a Glance 2015. Education at a Glance. OECD Publishing, Paris.

[OECD-16] OECD, 2016. „OECD Better Life Index”. OECD, Paris.

[OKP-02] Okpala, Comfort O., 2002. „Educational Resources, Student Demographics and Achievement Scores”. Journal of Education Finance 27 (3): 885–907.

[OLA-15] Oladayo, R. 2015. „Rural Depopulation: The Planning Implications for the Development of Urban Lagos”. http://www.regionalstudies.org/uploads/Oladayo_Ramon_IBRAHIM_PDF.pdf. (Last visited 19th November 2016).

[OLI-13] Olivier, J.G.J, et.al., 2013. „Trends in global co2 emissions-2013-report”. Netherlands Environmental Assessment Agency, The Hague.

[OMA-03] O Malley, C., et.al. 2005. „Guidelines for learning/teaching/tutoring in a mobile environment”. http://kn.open.ac.uk/public/getfile.cfm?documentfileid=7488 (Last visited 19th November 2016).

[OXF-16] Oxford Dictionary. 2016. „Definition of value in English”, https://en.oxforddictionaries.com/definition/value. (Last visited 19th November 2016).

[ORD-14] Orduña, P., et al., 2014. „Towards federated interoperable bridges for sharing educational remote laboratories”. Computers in Human Behavior 30 (1): 389–395.

[ORM-12] Ormrod, J.E., 2012. “Human learning”. Pearson, Boston.

[OSU-02] O’Sullivan, D., 2002. “Framework for managing business development in the networked organisation“.Computers in Industry 47 (1): 77–88.

[OSU-09] O’Sullivan, D., Rolstadås, A., Filos, E., 2009. “Global education in manufacturing strategy”. Journal of Intelligent Manufacturing 22 (5): 663–674.

[PAH-96] Pahl, G., Beitz, W., 1996. “Engineering Design: A Systematic Approach”. Springer Verlag, London.

[PAI-16] P.A. Hilton. 2016. „RE540 Photovoltaic Trainer“. http://www.p-a-hilton.co.uk/products/RE540-Photovoltaic-Trainer. (Latest access 16th January 2017).

[PAL-15] Palacios, J. et al., 2015. “Development of a Mobile Wind Laboratory for Teaching Purposes in Emerging Countries”. International Conference on Interactive Mobile Communication, Technologies and Learning, Thessaloniki.

[PAO-13] Pao, H.T., Fu, H.C. 2013. „Renewable energy, non-renewable energy and economic growth in Brazil”. Renewable and Sustainable Energy Reviews: 381–392.

[PAP-12] Pappano, L. 2012. „The Year of the MOOC NY Times”. The New York Times. http://edinaschools.org/cms/lib07/MN01909547/Centricity/Domain/272/The%20Year%20of%20the%20MOOC%20NY%20Times.pdf. (Latest access 16th January 2017).

[PAR-04] Park, J., 2004. „International and Intersectoral R&D Spillovers in the OECD and East Asian Economies”. Economic Inquiry 42 (4): 739-757.

[PAR-15] Park, K.S., 2015. „Instructional Design Models for Blended Learning in Engineering Education”. International Journal of Engineering Education 31(2): 476-485.

[PED-13] Pedley, M. 2013. „Tilt Sensing Using Linear Accelerometers”. Freescale Semiconductor. http://www.freescale.com/files/sensors/doc/app_note/AN3461.pdf. (Latest access 16th January 2017).

[PEO-11] Pedota, L., 2011. „Indigenous Intercultural Universities in Latin America: Interpreting Interculturalism in Mexico and Bolivia”. Loyola University, Chicago.

[PER-13] Petroff, A. 2013. „Engineers get rich as talent war heats up”. http://money.cnn.com/2013/07/25/news/economy/engineering-jobs-pay/. (Latest access 16th January 2017).

[PET-89] Peters, J., 1989. „Manufacturing in Mechanical Engineering Education in Developing Countries”. European Journal of Engineering Education 14 (2): 135–139.

[PET-07] Peters, K., 2007. „M-Learning: Positioning Educators for a Mobile, Connected Future”. The International Review of Research in Open and Distributed Learning 8 (2).

[PHI-15] Philibert, C. 2015. „Three Reasons Why Renewable Energy Is So Important to the Power Industry”. https://www.gepowerconversion.com/inspire/three-reasons-why-renewable-energy-so-important-power-industry. (Latest access 16th January 2017).

[PIQ-15] Piquer, J. et al., 2015. „Neurosurgery Education and Development program to treat hydrocephalus and to develop neurosurgery in Africa using mobile neuro-endoscopic training”. Journal of Neurosurgery Pediatrics 1 (1): 1–8.

[POL-01] Poli, C., 2001. “Design for Manufacturing: A Structured Approach”. Butterworth-Heinemann, Oxford.

[POS-11] Postawa, A., Kleinsorge, M., Krüger, J., Seliger, G., 2011. „Automated Image Based Recognition of Manual Work Steps in the Remanufacturing of Alternators”. In “Advances in Sustainable Manufacturing”. Springer, Berlin.

[PRB-13] Population Reference Bureau., 2013. “2013 World Population Data Sheet”. Population Reference Bureau, Washington D.C.

[PRO-12] Provost, C. 2012. „Developing countries face growing secondary education challenge”. the Guardian. http://www.theguardian.com/global-development/poverty-matters/2011/oct/25/developing-countries-secondary-education-challenge. (Latest access 16th January 2017).

[PRX-15] Proxxon. 2015. „PROXXON“. http://www.proxxon.com/en/. (Latest access 16th January 2017).
[PTC-15] PTC. 2015. „Ergonomics/Human Factors”. PTC. http://www.ptc.com/cad/3d-design/ergonomics-human-factors. (Latest access 16th January 2017).
[PUG-91] Pugh, S., 1991. “Total Design: Integrated Methods for Successful Product Engineering”. Addison-Wesley Publishing Company, Michigan.
[PUR-10] Purushothaman, V.K. 2010. „Wind Tunnels”. https://www.academia.edu/2937181/Wind_Tunnels. (Latest access 16th January 2017).
[QUI-00] Quinn, C. 2000. “Learning in the new economy”. http://www.linezine.com/2.1/features/cqmmwiyp.htm. (Latest access 16th January 2017).
[RAJ-07] Rajput, R. K., 2007. “A Textbook of Manufacturing Technology: Manufacturing Processes”. Firewall Media, New Delhi.
[RAO-95] Raouf, A., Ben-Daya, M., 1995. “Flexible Manufacturing Systems: Recent Developments”. Elsevier, Amsterdam.
[RAP-03] Rappaport, S. 2003. „Why we’ve failed to integrate technology effectively in our schools”, *eSchool News*. http://www.eschoolnews.com/2003/08/01/why-weve-failed-to-integrate-technology-effectively-in-our-schools/. (Latest access 16th January 2017).
[RAY-15] Raypa. 2015. „autoclaves, instrumentación y equipos para laboratorios“. Raypa Laboratory equipment. http://www.raypa.com/. (Latest access 16th January 2017).
[REA-15] Real Sociology. 2015. „Is a Western Style of Education Appropriate for Developing Countries?”. http://realsociology.edublogs.org/2015/11/08/is-a-western-style-of-education-appropriate-for-developing-countries-education-and-development-post-33/. (Latest access 16th January 2017).
[REC-15] Recalde, M.Y., 2015. „The Different Paths for Renewable Energies in Latin American Countries: The Relevance of the Enabling Frameworks and the Design of Instruments”. Wiley, London.
[REG-09] Regev, G., Gause, D.C., Wegmann, A., 2009. „Experiential Learning Approach for Requirements Engineering Education”. Requirements Engineering 14 (4): 269–87.
[REI-89] Reigeluth, C. M., 1989. „Educational Technology at the Crossroads: New Mindsets and New Directions”. Educational Technology Research and Development 37 (1): 67–80.
[REI-13] Reigeluth, C.M., 2013. “Instructional Design Theories and Models: An Overview of Their Current Status”. Routledge, New York.
[REN-15] REN21., 2015. „Global Status Report - Renewables 2015“. Renewable Energy Policy Network for the 21st Century, Paris.
[RENAC-12] Renewables Academy. 2012. „TREE | RENAC International“ http://www.renac.de/en/current-projects/tree.html. (Last visited 18th November 2016).
[RENAC-14] Renewables Academy. 2014. „ReGrid 2011 - 2014 Capacity Building on Integration of Large Amounts of Renewable Energy in Electricity Grids”. http://www.renac.de/en/reference/reference/192-regrid-2011-2014-capacity-building-on-integration-of-large-amounts-of-renewable-energy-in.html. (Last visited 18th November 2016).
[RENAC-15] Renewables Academy. 2015. „Capacity Development on Renewable Energy and Grid Integration (CapREG) - RENAC International“.

http://www.renac.de/en/current-projects/capreg.html. (Last visited 18th November 2016).

[RES-07] Reisser, R.A., Dempsey, J.V., 2007. „Trends and issues in instructional design and technology”. Education Tech Research 55 (2): 193-196.

[REW-15] Renewable Energy World, 2015. „Bio Energy”. http://www.renewableenergyworld.com/bioenergy/tech.html. (Last visited 18th November 2016).

[REZ-14] Rentzos, L., Chryssolouris, G., 2014. „Integrating Manufacturing Education with Industrial Practice Using Teaching Factory Paradigm: A Construction Equipment Application”, Procedia CIRP 17 (1): 189–194.

[RHE-02] Rheingold, H., 2002. “Smart Mobs: The Next Social Revolution”. Perseus Publishing, United States.

[RIE-11] Rienties, B., et.al. 2011. „Understanding Academic Performance of International Students: The Role of Ethnicity, Academic and Social Integration”. Higher Education 63 (6): 685–700.

[RIL-96] Riley, F.J., 1996. “Assembly Automation: A Management Handbook”. Industrial Press Inc, New York.

[ROC-83] Rockstroh, W., 1983. „Die technologische Betriebsprojektierung: Gestaltung von Fertigungswerkstätten“. VEB Verlag Technik, Bonn.

[ROD-13] Rodriguez. I. 2013 „Hay 1 ingeniero por cada 100 mexicanos”. Industria - Manufactura.mx. http://www.manufactura.mx/industria/2013/10/21/hay-1-ingeniero-por-cada-100-mexicanos. (Latest access 16th January 2017).

[ROJ-09] Rojter, J., 2009. „PBL and Constructivism in Engineering Education”, In Proceedings of the 37th SEFI Conference, Rotterdam.

[ROL-15] Roland. 2015. „Milling Machines | CNC Machines | 3D Printers and Milling Machines | Roland DGA“. Roland. https://www.rolanddga.com/products/3d. (Latest access 16th January 2017).

[ROS-07] Rolstadås, A., Moseng , T., 2007. „Global education in Manufacturing: Basic Framework, Industrial Survey and Possible Implementation”. CRC Press, New York.

[ROT-15] Rotwerk. 2015. „Rotwerk GmbH ***Maschinen, Zubehör, Ersatzteile***“, Rotwerk. 2015 http://www.rotwerk.de/. (Latest access 16th January 2017).

[RYD-03] Ryder, M. 2003. „Instructional Design Models”. http://thingsorganic.tripod.com/Instructional_Design_Models.htm. (Latest access 16th January 2017).

[SAC-08] Sachs, J., 2008. “Common Wealth: Economics for a Crowded Planet”. Penguin Press, Pennsylvania.

[SAG-12] Sangrà, A, Vlachopoulos, D., Cabrera, N., 2012. „Building an Inclusive Definition of E-Learning: An Approach to the Conceptual Framework”. The International Review of Research in Open and Distributed Learning 13 (2): 145–159.

[SAN-11] Sancristobal, E., et.al., 2011. „Remote labs as learning services in the educational arena”. IEEE Global Engineering Education Conference (EDUCON) Proceedings.

[SAR-14] Sargent, J., 2014. „The U.S. Science and Engineering Workforce: Recent, Current, and Projected Employment, Wages, and Unemployment”. Congressional Research Service, Washington, D.C.

[SCE-10] Schenk, M., Wirth, S., Müller, E., 2010. „Factory Planning Manual. Berlin, Heidelberg”. Springer, Berlin Heidelberg.

[SCH-11] Schuh, G., et.al., 2011. „Status-Condition based planning for processes, resources and industrial buildings”. POMS 22nd Annual Conference Proceedings.

[SCI-12] Science Buddies. 2012. „Science Buddies: How to Build and Use a Subsonic Wind Tunnel”. Science Buddies. http://www.sciencebuddies.org/science-fair-projects/wind-tunnel-toc.shtml. (Latest access 16th January 2017).

[SCL-13] Schiller, B. 2013. „The World’s Biggest Wind Turbine Has Blades The Length Of A Football Field”. Co.Exist. Januar 9. http://www.fastcoexist.com/1681150/the-worlds-biggest-wind-turbine-has-blades-the-length-of-a-football-field. (Latest access 16th January 2017).

[SCM-01] Schumacher, J.O., Wetting, W., 2001. „Device Physics of Silicon Solar Cells”. In “Clean Electricity from Photovoltaics”. Imperial College Press, London.

[SCO-13] Schönsleben, P., Büchel, A., 2013. „Organizing the Extended Enterprise” IFIP TC5 / WG5.7 International Working Conference on Organizing the Extended Enterprise Proceedings.

[SCU-12] Schunk, D. H., 2012. „Learning Theories: An Educational Perspective”. Pearson, New York.

[SEI-16] Solar Energy Industries Association, 2016. „Solar Industry Facts and Figures”.. http://www.seia.org/research-resources/solar-industry-data. (Latest access 16th January 2017).

[SEI-13] Seiler, S., 2013. „Current trends in remote and virtual lab engineering. Where are we in 2013?”. International Journal of Online Engineering, 9(6).

[SEL-07] Seliger, G., 2007., „Nachhaltige industrielle Wertschöpfungsnetze“. Produktionstechnisches Kolloquium 2007 Tagungsband. Berlin.

[SEL-10] Seliger, G., 2010. „Emerging Markets bei materiellen Grenzen des Wachstums - Chancen nachhaltiger Wertschöpfung“. In „Wertschöpfung und Beschäftigung in Deutschland“. Springer, Hannover.

[SEL-11] Seliger, G, Reise, C., Bilge, P., 2011. „Curriculum Design for Sustainable Engineering”. In “Advances in Sustainable Manufacturing”. Springer Science & Business Media Berlin.

[SEL-12] Seliger, G., 2012. “Sustainable Manufacturing for Global Value Creation”. Springer, Berlin Heidelberg.

[SEL-15] Seliger, G., 2015. „Lecture: Factory Planning Methodology“. Technische Universität Berlin.

[SEY-97] Seymour, E., 1997. “Talking About Leaving: Why Undergraduates Leave the Sciences”. Westview Press, Colorado.

[SHA-05] Sharples, M., Taylor, J., Vavoula, G., 2005. „Towards a Theory of Mobile Learning”. mLearn 2005 Proceedings.

[SHA-06] Sharples, M., Taylor, J., Vavoula, G., 2006. „A Theory of Learning for the Mobile Age”. In “The Sage Handbook of ELearning Research”. Sage Publications, New York.

[SHE-05] Sherren, K., 2005. „Balancing the Disciplines: A Multidisciplinary Perspective on Sustainability Curriculum Content”. Australian Journal of Environmental Education. 1 (1): 97–106.

[SHH-06] Shehabuddeen, N., Probert, D. Phaal, R., 2006. „From theory to practice: challenges in operationalizing a technology selection framework”. Technovation. 26 (3): 324–335.

[SHI-12] Shipp, S., N Lal, G.B., Scott, J. 2012. „Emerging Global Trends in Advanced Manufacturing”.

https://www.wilsoncenter.org/sites/default/files/Emerging_Global_Trends_in_Advanced_Manufacturing.pdf. (Last visited 4th November 2016).

[SHO-15] ShopBot. 2015. „ShopBot Desktop“. http://www.shopbottools.com/mProducts/desktop.htm. (Latest access 16th January 2017).

[SIE-04] Siemens, G. 2004. „Connectivism: A Learning Theory for the Digital Age”. International Journal of Instructional Technology and Distance Learning 2 (3).

[SIE-11] Siemens Industry. 2011. „Siemens Launches Plantville — An Innovative Gaming Platform to Showcase Products and Solutions for Industry and Infrastructure”. PR Newswire. http://www.prnewswire.com/news-releases/siemens-launches-plantville--an-innovative-gaming-platform-to-showcase-products-and-solutions-for-industry-and-infrastructure-118571809.html. (Latest access 16th January 2017).

[SIM-02] Simpson, T.L. 2002. „Dare I Oppose Constructivist Theory?” The Educational Forum 66 (4): 347–54.

[SIN-09] Singh, M.M., 2009. “Technology-Assisted Problem Solving for Engineering Education: Interactive Multimedia Applications”. Engineering Science Reference, Pennsylvania.

[SKI-69] Skinner, W., 1969. „Manufacturing—Missing Link in Corporate Strategy”. Harvard Business Review, Boston.

[SKI-74] Skinner, B. F., 1974. “About Behaviorism”. Knopf Doubleday Publishing Group, Detroit.

[SME-12] Society of Manufacturing Engineers (SME). 2012. “Workforce Imperative: A Manufacturing Education Strategy”. http://www.abet.org/wp-content/uploads/2015/04/workforce-imperative-manufacturing-education-strategy.pdf. (Latest access 16th January 2017).

[SNE-85] Snelbecker, G. E. 1985. “Learning Theory, Instructional Theory, and Psychoeducational Design”. University Press of America, Pennsylvania.

[SNY-14] Snyder, S. 2014. „Villanova: Improved student performance in flipped classes”. http://articles.philly.com/2014-09-28/news/54380476_1_lecture-classroom-engineering. (Latest access 16th January 2017).

[SOR-10] Sørensen, B., 2010. “Renewable Energy: Physics, Engineering, Environmental Impacts, Economics & Planning”. Academic Press, Massachusetts.

[SPU-86] Spur, G., Stöferle, T., 1986. „Handbuch der Fertigungstechnik: Fügen, Handhaben und Montieren“. Hanser, München.

[SRI-06] Srivastava. 2006. “Teacher in Emerging Indian Society”. APH Publishing, New Delhi.

[STE-11] Stein, S. J., Shephard, S., Harris, I., 2011. „Conceptions of E-Learning and Professional Development for E-Learning Held by Tertiary Educators in New Zealand”. British Journal of Educational Technology 42 (1): 145–65.

[STI-14] Stirling, D. 2014. „Motivation in education”. Learning Development Institute. http://www.learndev.org/dl/Stirling_MotEdu.pdf. (Latest access 16th January 2017).

[STO-99] Stoll, H. W. 1999. “Product Design Methods and Practices”. CRC Press, New York.

[STP-13] Stephens, R., 2013. „Aligning Engineering Education and Experience to Meet the Needs of Industry and Society”. In “The Bridge: Linking Engineering and Society” 31–34. National Academy of Engineering, Washington D.C.

[STR-00] Strauss, S., 2000. „Theories of cognitive development and their implications for curriculum development and teaching”. In “Routledge international companion to education” 33–50. Routledge, London.

[STV-07] Streveler, R.A., Borrego, M., Smith, K.A., 2007. „Moving from the Scholarship of Teaching and Learning to Educational Research: An example from Engineering“. To Improve the Academy 1 (25): 139–149.

[SUL-15] Sultan N., Al-Lail, H.J., 2015. “Creative Learning and MOOCs: Harnessing the Technology for a 21st Century Education”. Cambridge Scholars Publishing, Cambridge.

[SWE-02] Swearengen, J.C. et al. 2002 „Globalization and the Undergraduate Manufacturing Engineering Curriculum“. Journal of Engineering Education 91 (2): 255–261.

[SZI-12a] Szirmai, A., Naudé, W., Haraguchi, N., 2012. „Structural change, poverty reduction and industrial policy in the BRICS”, United Nations Industrial Development Organization, New York.

[SZI-12b] Szirmai, A., Verspagen, B., 2012. „Manufacturing and economic growth in developing countries, 1950–2005“. Structural Change and Economic Dynamics 34 (2): 46–59.

[TAV-03] Tavana, M., 2003. „CROSS: A Multi-criteria Group-Decision-Making Model for Evaluating and Prioritizing Advanced-Technology Projects at NASA“. Interfaces. 33 (3): 40-56.

[TAW-12] Tawfik, M., et al., 2012. „Shareable educational architectures for remote laboratories”. Technologies Applied to Electronics Teaching (TAEE) 1 (1): 122–127.

[TED-05] Teacher and Educational Development., 2005. „Effective Use of Learning Objectives for Learning and Assessment”. University of New Mexico, New Mexico.

[TET-16] The Economic Times. 2016. „Definition of' ‚Product”. The Economic Times. http://economictimes.indiatimes.com/definition/product. (Latest access 16th January 2017).

[THE-15] The economist. 2015. „Whose brains are draining?”. The Economist. Juli. http://www.economist.com/blogs/graphicdetail/2015/07/daily-chart. (Latest access 16th January 2017).

[THM-08] Thomas, C., Jennings, P., Lloyd, B., 2008. „Issues in Renewable Energy Education”. Australian Journal of Environmental Education 24 (1): 67–73.

[THO-10] Thorvald, P, Brolin, A., Högberg, D., 2010. „Using Mobile Information Sources to Increase Productivity and Quality”. In “Advances in Cognitive Ergonomics”. CRC Press, New York.

[TID-05] Tidd, J., Bessant, J., Pavitt, K., 2005. “Managing Innovation: Integrating Technological, Market and Organizational Change”. Wiley, New York.

[TIE-15] Tierney, J. 2015. „How Makerspaces Help Local Economies”. The Atlantic, April 17. http://www.theatlantic.com/technology/archive/2015/04/makerspaces-are-remaking-local-economies/390807/. (Latest access 16th January 2017).

[TOD-98] Todaro, M.P., 1998. „Education and Development”. Pearson, Boston.

[TOD-12] Todaro, M.P., Smith, S.C., 2012. “Economic Development”. Addison-Wesley. Boston.

[TOL-06] Tolio, T, Valente, A. 2006. „An approach to design the flexibility degree in flexible manufacturing systems”. 16th Int. Conference on flexible automation and intelligent manufacturing Proceedings. University of Limerik, Ireland.

[TOM-10] Tompkins, J. A., et.al., 2010. "Facilities Planning". John Wiley & Sons, New York.

[TPV-16] The PV Market Alliance. 2016. „Global PV Market Report". http://www.pvmarketalliance.com/the-report/. (Latest access 16th January 2017).

[TRA-05] Traxler, J. 2005., „Defining mobile learning". IADIS International Conference Mobile Learning 2005. Sydney.

[TRC-13] Tracey, R. 2013. „The Definition of a MOOC". eLearning Industry. September 2. https://elearningindustry.com/the-definition-of-a-mooc. (Latest access 16th January 2017).

[TRE-12] Tremblay, Lalancette, K.D., Roseveare, D., 2012. „Assessment of Higher Education Learning Outcomes - AHELO". OECD, Paris.

[TRY-12] Tryggvason, T., Apelian, D., 2012. „Meeting New Challenges: Transforming Engineering Education". In "Shaping our World: Engineering for the 21st Century". John Wiley & Sons, Canada.

[TSU-10] Tsujita, Y., 2010. „Deprivation of Education: A Study of Slum Children in Delhi, India". In "U.N. Education for All Global Monitoring Report 2010". UNESCO, New York.

[TUK-16] The University of Kansas. 2016. „Instruction/Cognitive Strategies". KU The University of Kansas. http://www.specialconnections.ku.edu/?q=instruction/cognitive_strategies. (Latest access 16th January 2017).

[TWB-00] The World Bank., 2000. „Higher Education in Developing Countries: Peril and Promise". The World Bank, New York.

[TWB-13] The World Bank. 2013. „Country and Lending Groups". http://data.worldbank.org/about/country-and-lending-groups. (Latest access 16th January 2017).

[TWB-14] The World Bank. 2014. „Manufacturing, value added (% of GDP)". http://data.worldbank.org/indicator/NV.IND.MANF.ZS. (Latest access 16th January 2017).

[TWB-16] The World Bank. 2016. „Indicators | Data", The World Bank Indicators. http://data.worldbank.org/indicator/. (Latest access 16th January 2017).

[UN-66] United Nations., 1966. „International Covenant on Economic, Social and Cultural Rights". United Nations Publishing, New York.

[UN-02] United Nations., 2002. "Report of the World Summit on Sustainable Development". United Nations Publishing, New York.

[UN-13] United Nations., 2013. „Global trends and challenges to sustainable development post 2015". In "World Economic and Social Survey 2013". United Nations Publishing, New York..

[UN-15] UN General Assembly., 2015. „Transforming our World: The 2030 Agenda for Sustainable Development". United Nations Publishing, New York.

[UN-16] United Nations., 2016. „Sustainable Development Goals". Sustainable Development Knowledge Platform. United Nations Publishing, New York.

[UNC-14] UNCTAD., 2014. „Transfer of Technology and Knowledge Sharing for Development: Science, Technology and Innovation Issues for Developing Countries". United Nations Conference on Trade and Development, New York.

[UNE-06] UNEP. 2006. „Ways to Increase the Effectiveness of Capacity Building for Sustainable Development". United Nations Environment Programme, New York.

[UNE-09a] UNESCO. 2009. „Global Renewable Energy Education and Training - GREET“. http://portal.unesco.org/science/en/ev.php-URL_ID=7866&URL_DO=DO_TOPIC&URL_SECTION=201.html. (Last visited 18th November 2016).

[UNE-09b] UNESCO., 2009. „Trends in Global Higher Education: Tracking an Academic Revolution”. UNESCO, New York.

[UNE-10] UNESCO., 2010. „Engineering: issues, challenges and opportunities for development”. UNESCO, New York.

[UNE-14] UNESCO., 2014. „UNESCO Africa Engineering Week”. UNESCO, New York.

[UNE-15a] UNESCO., 2015. „Education: Government expenditure per student in PPP $”. UNESCO Institute for Statistics, New York.

[UNE-15b] UNESCO., 2015. “UNESCO science report: towards 2030”. UNESCO Publishing, New York.

[UNE-16a] UNESCO., 2016a. „Most influential theories of learning”. UNESCO, New York.

[UNE-16b] UNESCO., 2016b. „New agreement to measure global citizenship and sustainable development education”. UNESCO, New York.

[UNI-12] United Nations Industrial Development Organization., 2012. “Industrial Development in Least Developed Countries”. UNIDO, New York.

[UPH-06] Upham, P., Shackley, S., 2006. „Stakeholder opinion of a proposed 21.5 MWe biomass gasifier in Winkleigh, Devon: Implications for bioenergy planning and policy”. Journal of Environmental Policy & Planning 8 (1): 45–66.

[USD-16] US Department of Commerce, NIST. 2016. „Cyber-Physical Systems Homepage”. http://www.nist.gov/cps/. (Latest access 16th January 2017).

[VDI-12] Verein Deutscher Ingenieure e.V. 2012. „Ingenieure auf einen Blick: Ewerbstätigkeit, Innovation, Wertschöpfung“. https://www.vdi.de/fileadmin/vdi_de/redakteur/dps_bilder/SK/2012/2012_-_Ingenieure_auf_einen_Blick.pdf. (Latest access 16th January 2017).

[VDI-2869] Verein Deutscher Ingenieure e.V. 2009. „Richtliniendetails VDI 2869: Montage und Handhabungstechnik“.

[VEE-92] Veer, G., Bagnara, C., Kempen, G., 1992. “Cognitive Ergonomics: Contributions from Experimental Psychology”. Elsevier, Amsterdam.

[VIE-10] Viertel, E., 2010. „Vocational Education for Sustainable Development: An Obligation for the European Training Foundation”. European Journal of Education 45 (2): 217–35.

[VOD-15] Vodovozov, V., Raud, Z., Lehtla, T., 2015. „Active learning in remote electrical drive laboratory”. 2015 IEEE Global Engineering Education Conference (EDUCON) Proceedings. Tallin, Estonia.

[WAG-12] Wagner, U., AlGeddawy, T., ElMaraghy, H., 2012. „The State-of-the-Art and Prospects of Learning Factories“. Procedia CIRP 3 (1): 109–114.

[WAI-15] [1] WaterAid, 2015„Releasing the flow“. http://www.wateraid.org/what-we-do/our-approach/research-and-publications/view-publication?id=1982a81b-1dc1-4e63-b2f2-00cb791a7210&sc_lang=en. (Latest access 16th January 2017).

[WAL-14] Walk, M., Aurich, J.C., 2014. „Integrated Desktop Machine Tool for Manufacturing and Application of Ultra-small Micro Pencil Grinding Tools“. Procedia CIRP 14 (1): 333–338.

[WAR-96] Ward, P., Bickford, D., Leong, C. 1996. „Configuration of manufacturing strategy, business strategy, environment and structure". International Journal of management 22 (4): 597–626.

[WAT-24] Watson, J.B. 1924. „Behaviorism". Transaction Publishers, Boston.

[WEF-12] World Economic Forum. 2012. „Enabling Sustainable Global Manufacturing". http://www3.weforum.org/docs/WEF_GAC_EnablingSustainableGlobalManufacturing_Report_2012.pdf. (Last visited 4th November 2016).

[WEF-15] World Economic Forum. 2015. „The Human Capital Report 2015". http://www3.weforum.org/docs/WEF_Human_Capital_Report_2015.pdf. (Last visited 4th November 2016).

[WEN-87] Wenke, K.G. 1987. „Theorie der Wertschöpfung und der Wertschöpfungsrechnung". Dissertation Universität Mainz. http://www.econis.eu/PPNSET?PPN=02290395X. (Last visited 4th November 2016).

[WES-91] West, C. K., Farmer, J.A. Wolff, P.M., 1991. "Instructional Design: Implications from Cognitive Science". Pearson Custom Pub, Pennsylvania.

[WID-15] Wind Science. 2015. „Energy science: Wind turbine manufacturing". http://www.wind-science.org/iresen/page/wind-turbine-manufacturing.html. (Latest access 16th January 2017).

[WIE-07] Wiendahl, H.-P., et al., 2007. „Changeable Manufacturing - Classification, Design and Operation". CIRP Annals - Manufacturing Technology 56, 783–809.

[WIE-15] Wiendahl, H.P., Reichard, J., Nyhuis, P. 2015. „Handbook Factory Planning and Design". Springer, London.

[WIK-16] Wikipedia. 2016. „Education". Wikipedia, the Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Education&oldid=722746950. (Latest access 16th January 2017).

[WIL-10] Wilkins, G. 2010. "Technology Transfer for Renewable Energy". Taylor & Francis, Boston.

[WIN-90] Winn, W., 1990. „Some implications of cognitive theory for instructional design". Instructional Science 19 (1): 53–69.

[WIY-15] Windynation. 2015. „Wind Turbine Dump and Diversion Loads: What They Do and How to Choose the Right System". Windynation clean-power to the people. https://www.windynation.com/jzv/inf/wind-turbine-dump-and-diversion-loads-what-they-do-and-how-choose-right-s. (Latest access 16th January 2017).

[WLE-10] Wleklinski, N. 2010. „Skinner's Teaching Machine and Programmed Learning Theory". http://people.lis.illinois.edu/~chip/projects/timeline/1954teaching_machine.html. (Latest access 16th January 2017).

[WUE-05] Wuerfel, P., Hrsg., 2005. "Physics of Solar Cells". Wiley-VCH Verlag GmbH, Weinheim.

[WWF-12] WWF. 2012. „Living planet report 2012: Biodiversity, biocapacity and better choices". http://d2ouvy59p0dg6k.cloudfront.net/downloads/1_lpr_2012_online_full_size_single_pages_final_120516.pdf. (Latest access 16th January 2017).

[YIM-07] Yim, H.J., 2007. "Consumer Oriented Development of Ecodesign Products". Vulkan-Verlag GmbH, Dissertation TU Braunschweig.

[YOU-09] Young, S.T. 2009. "Essentials of Operations Management". SAGE, California.

[ZHA-13] Zhao, H., 2013. “Synthetic Biology: Tools and Applications”. Academic Press, Illinois.

[ZHU-16] Zhu, Z.T., Yu, M.H., Riezebos, P., 2016. „A research framework of smart education”. Smart Learning Environments 3 (1).

[ZIC-11] Zichermann, G. 2011. „Intrinsic and Extrinsic Motivation in Gamification”. Gamification Co. http://www.gamification.co/2011/10/27/intrinsic-and-extrinsic-motivation-in-gamification/. (Latest access 16th January 2017).

[ZOG-08] Zografakis, N., et.al., 2008. „Effective education for energy efficiency”. Energy Policy 36 (8): 3226–32.

9 Glossary

Anthropogenic	Man-made
Assembly	Assembly processes are defined as activities that serve the ultimate purpose of joining geometrically defined subcomponents into a final product where amorphous operating and ancillary materials are commonly required [WIE-15]
Augmented reality	Technology that merges information or images with video-streaming from a web cam with a result similar to virtual reality but using real-world images in real time [DU-08]; [CAS-10].
Behaviorism	Psychological learning theory that links every human or animal behavior, including learning, to a concrete stimulus or set of stimuli.
Capacity building	Development of a country's human, scientific, technological, organizational, institutional and resource capabilities [UNE-06].
Changeability	Capacity of a factory to physically modify the elements of a production system by adding and/or replacing in it machines, modules, handling systems or complete lines [ELM-09]
Cognition	Cognition is a broad term used to distinguish the abstract, reasoning components of mind/brain from other psychological functions such as affect/emotion, sensation and the like [COL-03].
Cognitive process	Process describing the act people use in perceiving, reasoning, understanding, and judging the environment and the information they receive [COL-03]
Cognitivism	Psychological learning theory ascribing knowledge to learning strategies and previous stored information known as schemas. These schemas are continuously enriched by sensorial inputs, processed by the mind and stored for later use [SNE-85]
Competences	The proven ability to use knowledge, skills and personal, social and / or methodological abilities, in work or study situations and in professional and personal development [EC-08]
Connectivism	Modern learning theory largely focusing in modified mental processes and communication paradigms originated by the use of modern information and communication technologies.
Constructivism	Psychological learning theory contending that individuals form or construct much of what they learn or understand [BRG-04]
Democratization of Knowledge	Spread of knowledge (usually through technologic means) among common people that was considered prerogative of academic elites.

Didactics	Means and methods by which knowledge is conveyed from owner to recipient. Also referred as to the study of teaching. Synonym: pedagogy [COL-13].
Didactic models	Principles, strategies, methods and mechanisms of instruction between learners and teacher [FLE-96].
Didactic principles	Referred to as the application of learning theories, learning styles and didactic models proposed by psychologists, pedagogues and engineering educators to enable efficient knowledge conveyance.
E-learning	An approach to teaching and learning, representing all or part of the educational model applied, that is based on the use of electronic media and devices as tools for improving access to training, communication and interaction and that facilitates the adoption of new ways of understanding and developing learning [SAG-12].
Education	Education refers to a broadly inclusive term referring to a process of fostering cognitive, physical, social, emotional or moral growth and development in individuals or groups. It is goal directed, implies a values system and may proceed in a formal, non-formal, or informal manner [COL-03].
Education System	Refers to public schooling, and more commonly from kindergarten through high school programs. Schools or school districts are typically the smallest recognized form of "education system" and countries are the largest. Simply put, an education system comprises everything that goes into educating public-school students at the federal, state, or community levels [ABB-13].
Educational dimensions	IDMEE's four dimensions comprising instructional content (What); target audience (Who); Didactic principles (How); and Educational technologies (By which means).
Educational technology	The study and ethical practice of facilitating learning and improving performance by creating, using, and managing appropriate technological processes and resources [JAN-13].
Ergonomics	Study of people at work [LEH-12].
Experiential learning	Psychologic learning theory learning that situates experiences, and the reflections upon them, as core of any learning process. Contrary to constructivist ideas however, experiential learning's does not necessarily seek to create experiences in order to generate knowledge, but rather aims to understand the manners in which experiences motivate learners and promote their learning preferences [UNE-16a].
Factory planning	Planning of shop floor layouts in accordance to manufacturing strategies and philosophies

Familiarization	To make, oneself or another, well-acquainted or conversant with something [DIT-16].
Flexibility	Manufacturing company's capability of producing a number of distinct products in a shop floor environment where opportunities for production variability exist [RAO-95]
Formal Education	The hierarchically structured, chronologically graded 'education system', running from primary school through the university and including, in addition to general academic studies, a variety of specialized programmes and institutions for full-time technical and professional training [COO-74].
Gamification	The utilization of game design elements in non-game contexts [DET-11].
Higher Education Institutions	Universities, colleges, seminaries, and institutes of technology that convey tertiary education
Human factors in manufacturing	Study of human-machine systems with an emphasis on the human aspect [LEH-12]
Informal education	The truly lifelong process whereby every individual acquires attitudes, values, skills and knowledge from daily experience and the educative influences and resources in his or her environment - from family and neighbors, from work and play, from the market place, the library and the mass media [COO-74].
Informal urban communities	Unplanned settlements and areas where housing is not in compliance with current planning and building regulations. Usually communities with defective basic services and populated by poor inhabitants. Synonym: Slums.
Instruction	Guided lessons and materials used to teach a subject. It is characterized as a systematic approach to impart knowledge or developing skills. Synonym: Teaching [COL-03].
Instructional design	Systematic process that is employed to develop education and training programs in a consistent and reliable fashion [RES-07].
Instructional Design Model	Systematic methodological approaches to accomplish learning objectives by means of structured instructional events. In more abstract terms an *instructional design model* is a design rule for a given instructional design approach or a given pedagogic strategy [EWK-16].
Instructional event	Lectures, seminars or exercises conducted to deliver instruction.

K-12 education	Primary and secondary education (Kindergarten through twelfth degree).
Knowledge	The result of an interaction between intelligence, or the capacity to learn, and a situation, or opportunity to learn. Knowledge includes theory and concepts, as well as tacit knowledge gained as a result of the experience of performing certain tasks [CED-06]
Knowledge spillover	Intended or non-intended knowledge transmission from one party to another, which facilitates the development of technological improvements by the latest, based on the former's innovation.
Knowledge transfer	transfer of knowledge that is conducted between parties with big knowledge or technological disparities [UNC-14].
Learning styles in engineering education	Learning model that classifies students according to where they fit on a number of scales pertaining to the ways they receive and process information [FEL-87]
Learning	Acquisition of knowledge.
Learning objectives	Measurable results attained by a learner and attributable to her / his participation in an instructional event [COL-03]
Learning outcomes	Express a present or observed state of a learner after participating in an instructional event, in which he or she is assessed under fairly objective conditions [DEP-16].
Learning theories	Conceptual psychological frameworks describing how information is absorbed, processed, and retained during learning [ORM-12]. Some of the best-known theories include behaviorism, cognitivism, constructivism and experiential learning theories.
Learning styles	Personal preferred modes of learning influenced by intellectual preferences, culture or environment [FEL-87]
M-learning	E-learning through mobile computational devices [QUI-00].
Manufacturing	The entirety of interrelated economic, technological and organizational measures directly connected with the processing /machining of materials, i.e. all functions and activities directly contributing to the making of goods [CIR-04].
Net enrolment Ratio	Defined as the enrolment of the official age-group for a given level of education expressed as a percentage of the corresponding population [UNE-16b].
Non-formal education	Any organized educational activity outside the established formal system - whether operating separately or as an important feature of some broader activity - that is intended to serve identifiable learning clienteles and learning objectives [COO-74].

Occupational Health and Safety	Science of anticipation, recognition, evaluation and control of hazards arising in or from the workplace that could impair the health and wellbeing of workers [ALL-08].
Open education	Term used to describe institutional practices to communalize knowledge commonly offered in education institutions
Pedadogy	s. Didactics
Photovoltaic effect	Emergence of an electric voltage between two electrodes attached to a solid or liquid substrate upon shining light [GOE-05].
Power Distance Index	Index expressing the degree to which the less powerful members of a society accept and expect that power is distributed unequally. People in societies exhibiting a large degree of Power Distance accept a hierarchical order in which everybody has a place and which needs no further justification. In societies with low Power Distance, people strive to equalize the distribution of power and demand justification for inequalities of power [HOF-11]
Primary education	Primary level of western education systems commonly comprising the first six years of compulsory education.
Problem-based learning	Practical learning that requires the acquisition of knowledge to address a particular problem [ROJ-09].
Production System	A group of technical production facilities (e.g. machines, manual work stations, automatic plants, material flows), which are linked with each other for a certain type of production, including the existing reactions between them (CIRP 2004).
Production methods	Processes and techniques used to manufacture a product [KAU-10].
Project-based learning	The application of existing knowledge to new situations, which leads to the acquisition of practical skills [ROJ-09].
Quality	The degree to which a set of inherent characteristics of a product, fulfill requirements [ISO-9000].
Reconfigurability	s. changeability.
Remote labs	Internet platforms that allow users to carry out experiments online, which normally would only be conducted at physical laboratories. These experiments use real components or instrumentation at a different location from where they are being controlled or conducted [SEI-13]; [CHE-10].
Rural communities	A rural community comprises a group of inhabitants who live a rustic or country non-urban lifestyle

Secondary education	Secondary level of western education systems commonly comprising from the seventh till the twelfth years of education.
Skills	Level of performance, in the sense of accuracy and speed in performing particular tasks. Skilled performance has long been a subject of psychological studies, which consider both physical psychomotor abilities and mental cognitive abilities [CED-06].
Smart education	Context-aware ubiquitous learning, which is centered in the learner but strongly dependent on smart technologies and environments [HWA-14]; [MID-15].
Social benefits of education	Social benefits of education refer to the benefits a society gets through the education of an individual, such as the benefits of a more literate society or the economic output from his/her activities [TOD-12].
Social cost of education	Refer the opportunity cost to society as a whole, resulting from the need to finance costly educational expansion at higher levels when this funds might prove more productive in other economy sectors [TOD-12].
Target audience	In education, subset of learners addressed by the instructional event. Also, understood as who will be taught.
Teaching	Defined as actions by which a person intends that another person learn a certain content of knowledge [COL-03].
Teaching content	Referred to as the subject of instruction. Also understood as what is to be taught.
Tertiary education	Education, following secondary education at a school, at a college or university [COL-03].
Training	Instruction that is planned and focused and focused on the acquisition of skills and knowledge for a specific task or purpose. In contrast to education, training is undertaken for extrinsic purposes and practical ends, e.g. career preparation, while education is intrinsically valuable and is lifelong and continuous [COL-03].
Training centers	Specialized teaching facilities focused in the development of concrete academic and non-academic competences such as sales, installation, and maintenance.
Value	The regard that something is held to deserve; the importance, worth, or usefulness of something [OXF-16].

Value Creation Factors	Five factors contributing to the creation of value in manufacturing. Equipment, Human, Process, Product, Organization [SEL-07]. The five factors combined comprise a value creation module.
Virtual reality	Computer-generated environments that simulate the physical presence of people and objects to generate realistic sensory experiences [NMC-15].
Virtual laboratories	Internet platforms not linked to any physical hardware that virtualize real-life experiments by software means that intend to create a close-as-possible environment as the real scenario [SEI-13]. Synonym: Simulation labs.

10 Appendixes

10.1 Appendix: PV solar charging station

10.1.1 Market research

The table below introduces some of the most popular commercially available PV training stations in the market. Very few of them exhibit physical mobility characteristics such as light weights and modular expansion features, and yet limit with it the amount of possible experiments to be conducted and reduce the test component size to a cell level. The didactic method employed in each laboratory is based in experiments carried out under expert supervision with conventional measurement instrumentation and are limited to characterization of PV cells and panels without any specific core implementation area. In case of the PV charging stations found in the literature, none of them is intended to be used as didactic system. This implies that system components are mostly inaccessible to the user, and monitoring information is mostly limited to the vehicle's state of charge.

Table 22: Commercially available PV laboratories

Company - Model	Description	Weight and Dimensions [L x W x H mm]	Possible Experiments
 [EDI-16a]	- 2 polycrystalline panels - 8 halogen lamps (400 W) - Battery charger & battery - Computer Control Unit - Temperature, radiation, current & voltage sensors	310 kg; 2200 x 1200 x 2005	- Determination of solar panel characteristics - I-V- & P-V-Curve - Saturation Current - Temperature influence on open circuit voltage - Comparing of parallel and series connection of solar panels
 [GUN-16a]	- Polycrystalline panel - Battery - Solar charge controller - Two 20 W lamps - DC-AC inverter - „AC Voltage measurements module“ - „Grid Connection Inverter Kit“	50 kg; solar panel 730 x 510 x 1150 Grid Connection Inverter Kit 550 x 410 x 820 Rack 645 x 325 x 925	- I-V first quadrant curve without illuminating the solar cell - Detection of inverse (or saturation) current
 [PAI-16]	- Polycrystalline panel (80 W) - Battery charge controller - Battery (110 Ah) - Temperature, radiation, current & voltage sensors - Optional items (data acquisition; Solar Simulator)	42 kg; 750 x 527 x 1200	- Dependency of efficiency and solar radiation - Effect of angle of latitude - Dependency of temperature - System performance under load
 [LNU-16]	- Polycrystalline panel (10 W) - Halogen lamp (500 W) - Angle adjustment of light and solar panel - Solar charge controller - Battery (7 Ah) - “Interactive Lab Assistant”	120 kg: work station 1250 x 700 x 1995	- “Testing optimum alignment of solar panel” - Dependency of shadow - Function of a bypass diode
 [AMA-16]	- Two Solar Panels - Four halogen lamps - Angle adjustment	215 kg; 1830 x 710 x 1830	- Connection, operation, programming, and troubleshooting of AC/DC and grid-tie systems” - PV Maintenance - Performance - PV Array Connection - Safety
 [IKS-15]	- Wall charts with components according to experiments - Small solar cells	Variable according to modules	- Characterization of diodes, cells and small-sized modules - Irradiation and temperature effects on modules - Tilt-angle effect on power output - Shading effect - Simulation of series and parallel connection - On and off grid operation

10.1.2 Development of alternatives and concept evaluation

Rough draft alternatives of a PV solar station for E-Bikes generated during IDMEE's Design stage are exhibited below.

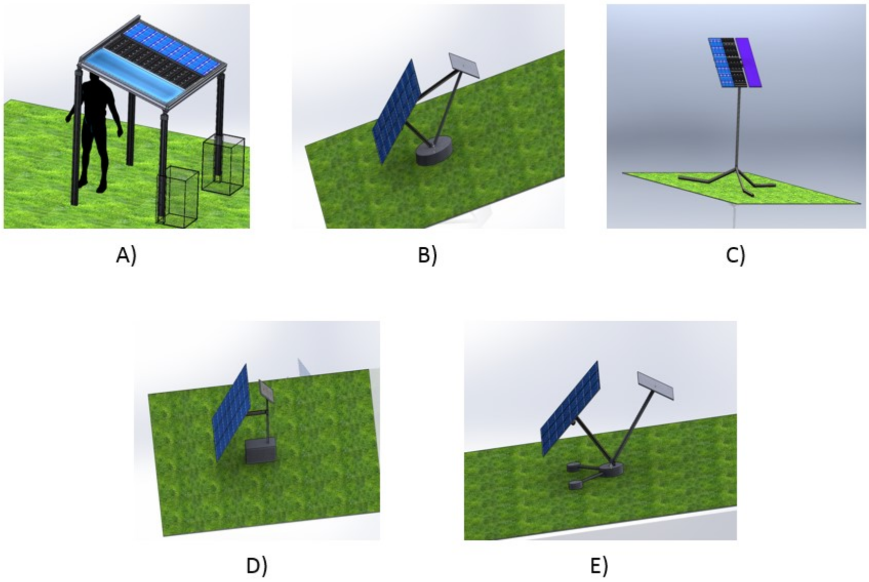


Figure 59: Concept drafts mobile PV solar station

The selection process was conducted by means of a Pugh diagram presented below. Selection criteria and their respective weights were elaborated according to the structural requirements of the device. According to the analysis, alternative "c" was selected as the most suitable design option mostly due to its modularity and robustness traits. The system was nonetheless also visually appealing and relatively easy to assemble and disassemble.

Table 23: Concept alternatives' evaluation

Variant	Weight in kg (30%)	Ease to disassemble in # of pieces (30%)	Robustness and stability in Beaufort rate (20%)	Component accessibility (10%)	Aesthetics (10%)	Total
A)	1 (0.3)	3 (0.9)	4 (0.8)	3 (0.3)	3 (0.3)	2.6
B)	**3 (0.9)**	**2 (0.6)**	**3 (0.6)**	**3 (0.3)**	**4 (0.4)**	**2.8**
C)	3 (0.9)	3 (0.9)	1 (0.2)	1 (0.1)	2 (0.2)	2.3
D)	3 (0.9)	3 (0.6)	3 (0.6)	3 (0.3)	3 (0.3)	2.7
E)	3 (0.9)	3 (0.6)	2 (0.4)	3 (0.3)	4 (0.4)	2.6

10.2 Appendix: Back-end PCB Schematic PV Solar station

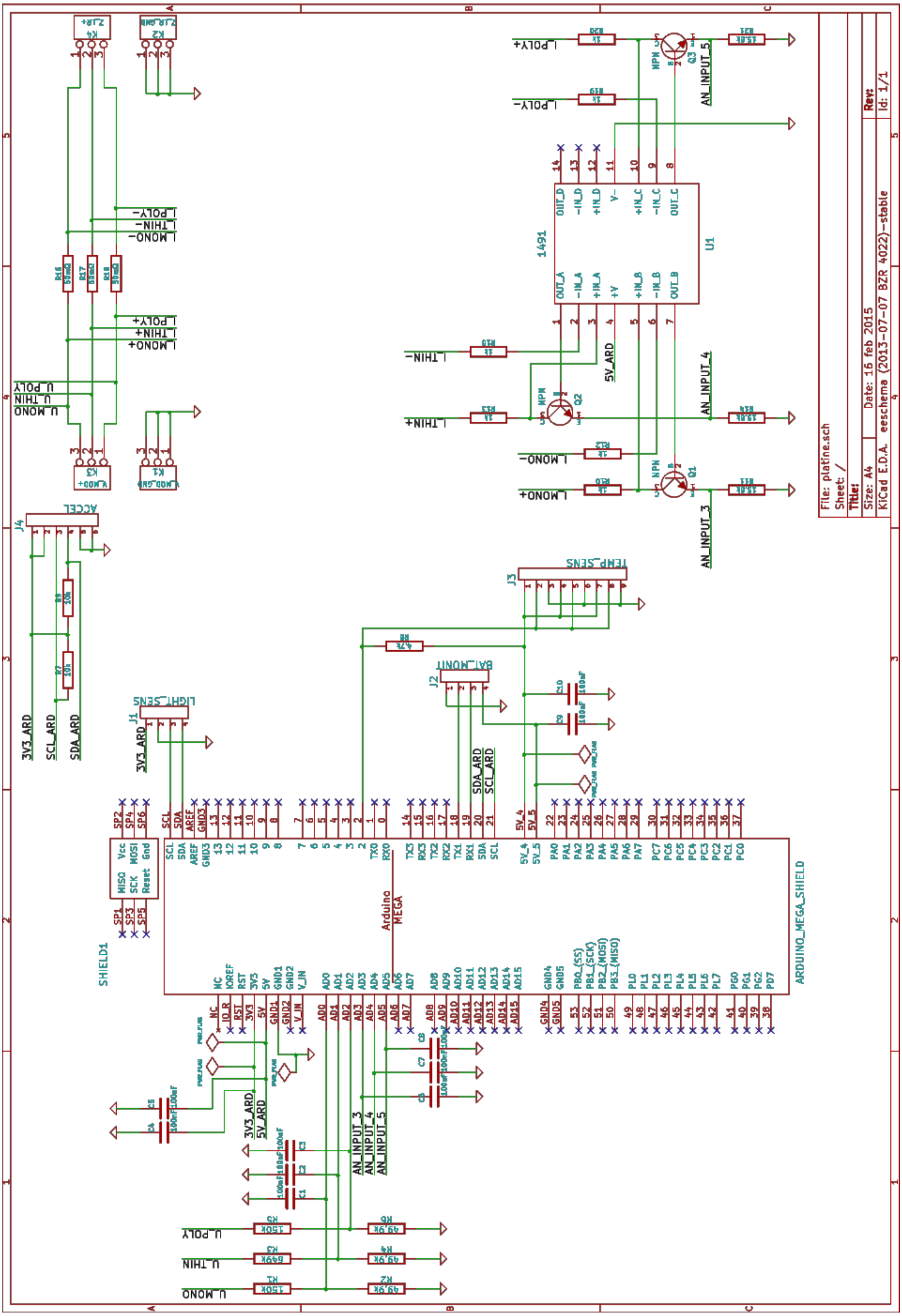


Figure 60: Back-end PCB schematic mobile PV charging station

10.3 Appendix: Back-end monitor program

```
#include <OneWire.h>
#include <DallasTemperature.h>
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_TSL2561_U.h>
#include <Adafruit_ADXL345_U.h>

/* Assign a unique ID to the Light Intensity and Accelerometer sensors*/
Adafruit_TSL2561_Unified tsl = Adafruit_TSL2561_Unified(TSL2561_ADDR_FLOAT,
12345);
Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified(12345);

/*Displays some basic information on the Lux sensor */
void displayLightSensorDetails(void)
{
 sensor_t sensor;
 tsl.getSensor(&sensor);
 Serial.println("------------------------------------");
 Serial.print  ("Sensor:       "); Serial.println(sensor.name);
 Serial.print  ("Driver Ver:   "); Serial.println(sensor.version);
 Serial.print  ("Unique ID:    "); Serial.println(sensor.sensor_id);
 Serial.print  ("Max Value:    "); Serial.print(sensor.max_value); Serial.println(" lux");
 Serial.print  ("Min Value:    "); Serial.print(sensor.min_value); Serial.println(" lux");
 Serial.print  ("Resolution:   "); Serial.print(sensor.resolution); Serial.println(" lux");
 Serial.println("------------------------------------");
 Serial.println("");
 delay(500);
}

/* Configures the gain and integration time for the TSL2561*/
void configureSensor(void)
{
 tsl.enableAutoRange(true);            /* Auto-gain ... switches automatically between 1x and
16x */

 /* Changing the integration time gives you better sensor resolution (402ms = 16-bit data) */
 tsl.setIntegrationTime(TSL2561_INTEGRATIONTIME_13MS);      /* fast but low
resolution */

 /* Update these values depending on what you've set above! */
 Serial.print  ("Gain:         "); Serial.println("Auto");
 Serial.print  ("Timing:       "); Serial.println("13 ms");
 Serial.println("------------------------------------");
 Serial.println("------------------------------------");
}

/*Displays some basic information on the Accel sensor*/
void displayAccelSensorDetails(void)
```

```
{
  sensor_t sensor;
  accel.getSensor(&sensor);
  Serial.println("------------------------------------");
  Serial.print  ("Sensor:       "); Serial.println(sensor.name);
  Serial.print  ("Driver Ver:   "); Serial.println(sensor.version);
  Serial.print  ("Unique ID:    "); Serial.println(sensor.sensor_id);
  Serial.print  ("Max Value:    "); Serial.print(sensor.max_value); Serial.println(" m/s^2");
  Serial.print  ("Min Value:    "); Serial.print(sensor.min_value); Serial.println(" m/s^2");
  Serial.print  ("Resolution:   "); Serial.print(sensor.resolution); Serial.println(" m/s^2");
  Serial.println("------------------------------------");
  Serial.println("");
  delay(500);
}

void displayDataRate(void)
{
  Serial.print  ("Data Rate:    ");

  switch(accel.getDataRate())
  {
    case ADXL345_DATARATE_3200_HZ:
      Serial.print  ("3200 ");
      break;
    case ADXL345_DATARATE_1600_HZ:
      Serial.print  ("1600 ");
      break;
    case ADXL345_DATARATE_800_HZ:
      Serial.print  ("800 ");
      break;
    case ADXL345_DATARATE_400_HZ:
      Serial.print  ("400 ");
      break;
    case ADXL345_DATARATE_200_HZ:
      Serial.print  ("200 ");
      break;
    case ADXL345_DATARATE_100_HZ:
      Serial.print  ("100 ");
      break;
    case ADXL345_DATARATE_50_HZ:
      Serial.print  ("50 ");
      break;
    case ADXL345_DATARATE_25_HZ:
      Serial.print  ("25 ");
      break;
    case ADXL345_DATARATE_12_5_HZ:
      Serial.print  ("12.5 ");
      break;
    case ADXL345_DATARATE_6_25HZ:
      Serial.print  ("6.25 ");
```

```
      break;
    case ADXL345_DATARATE_3_13_HZ:
      Serial.print  ("3.13 ");
      break;
    case ADXL345_DATARATE_1_56_HZ:
      Serial.print  ("1.56 ");
      break;
    case ADXL345_DATARATE_0_78_HZ:
      Serial.print  ("0.78 ");
      break;
    case ADXL345_DATARATE_0_39_HZ:
      Serial.print  ("0.39 ");
      break;
    case ADXL345_DATARATE_0_20_HZ:
      Serial.print  ("0.20 ");
      break;
    case ADXL345_DATARATE_0_10_HZ:
      Serial.print  ("0.10 ");
      break;
    default:
      Serial.print  ("???? ");
      break;
  }
  Serial.println(" Hz");
}

void displayRange(void)
{
  Serial.print  ("Range:         +/- ");

  switch(accel.getRange())
  {
    case ADXL345_RANGE_16_G:
      Serial.print  ("16 ");
      break;
    case ADXL345_RANGE_8_G:
      Serial.print  ("8 ");
      break;
    case ADXL345_RANGE_4_G:
      Serial.print  ("4 ");
      break;
    case ADXL345_RANGE_2_G:
      Serial.print  ("2 ");
      break;
    default:
      Serial.print  ("?? ");
      break;
  }
  Serial.println(" g");
}
```

```
// Data wire is plugged into port 2 on the Arduino
#define ONE_WIRE_BUS 2
#define TEMPERATURE_PRECISION 12

// Setup a oneWire instance to communicate with any OneWire devices
OneWire oneWire(ONE_WIRE_BUS);

// Pass our oneWire reference to Dallas Temperature.
DallasTemperature sensors(&oneWire);
int numberOfDevices;                    // Number of temperature devices found
DeviceAddress tempDeviceAddress;       // We'll use this variable to store a found device
address

// function to print the temperature for a device
void printTemperature(DeviceAddress deviceAddress)
{
 float tempC = sensors.getTempC(deviceAddress);
 Serial.print(tempC);
 Serial.print(" C");
 Serial.print("\t");
 Serial.print("\t");
}

// function to print a device address
void printAddress(DeviceAddress deviceAddress)
{
  for (uint8_t i = 0; i < 8; i++)
  {
    if (deviceAddress[i] < 16) Serial.print("0");
    Serial.print(deviceAddress[i], HEX);
  }
}

float sensorValue0;
float sensorValue1;
float sensorValue2;
float sensorValue3;
float sensorValue4;
float sensorValue5;

float voltage0;
float voltage1;
float voltage2;

float current0;
float current1;
float current2;

float power0;
```

```
float power1;
float power2;

boolean ADCread = true;

String content = "";
char floatbuf[32];

const float alpha = 0.5;
double fXg = 0;
double fYg = 0;
double fZg = 0;

void setup(void)
{
 // start serial port
 Serial.begin(9600);
 Serial1.begin(19200);
 Serial.println("Light Sensor Settings");

 if(!tsl.begin())
 {
  /* There was a problem detecting the ADXL345 ... check your connections */
  Serial.print("Ooops, no TSL2561 detected ... Check your wiring or I2C ADDR!");
  while(1);
 }

 /* Display some basic information on this sensor */
 displayLightSensorDetails();

 /* Setup the sensor gain and integration time */
 configureSensor();

 /* Ready to go! */
 Serial.println("Inclination Test"); Serial.println("");

 /* Initialise the sensor */
 if(!accel.begin())
 {
  /* There was a problem detecting the ADXL345 ... check your connections */
  Serial.println("Ooops, no ADXL345 detected ... Check your wiring!");
  while(1);
 }

 /* Set the range to whatever is appropriate for your project */
 accel.setRange(ADXL345_RANGE_2_G);

 /* Display some basic information on this sensor */
 displayAccelSensorDetails();
```

```
/* Display additional settings (outside the scope of sensor_t) */
displayDataRate();
displayRange();
Serial.println("");

/* Ready to go! */

// Start up the temperature library
sensors.begin();

// Grab a count of temperature devices on the wire
numberOfDevices = sensors.getDeviceCount();
Serial.println("");
Serial.println("Temperature Sensor Settings");
Serial.println("------------------------------------");

// locate devices on the bus
Serial.print("Locating temperature devices...");
delay(500);

Serial.print("Found ");
Serial.print(numberOfDevices, DEC);
Serial.println(" devices.");
Serial.println("");
delay(500);

// report parasite power requirements
Serial.print("Parasite power is: ");
if (sensors.isParasitePowerMode()) Serial.println("ON");
else Serial.println("OFF");
delay(500);

// Loop through each device, print out address
for(int i=0;i<numberOfDevices; i++)
{
  // Search the wire for address
  if(sensors.getAddress(tempDeviceAddress, i))
        {
           Serial.println("");
                Serial.print("Found device ");
                Serial.print(i, DEC);
                Serial.print(" with address: ");
                printAddress(tempDeviceAddress);
           Serial.println("");
           delay(500);

                Serial.print("Setting resolution to ");
                Serial.println(TEMPERATURE_PRECISION, DEC);

                // set the resolution to TEMPERATURE_PRECISION bit
```

```
                sensors.setResolution(tempDeviceAddress, TEMPERATURE_PRECISION);

                Serial.print("Resolution actually set to: ");
                Serial.println(sensors.getResolution(tempDeviceAddress), DEC);
            delay(500);
        }else{
                Serial.print("Found ghost device at ");
                Serial.print(i, DEC);
                Serial.println(" but could not detect address. Check power and cabling");
        }
 }
 Serial.println("------------------------------------------------------------");
 Serial.println("------------------------------------------------------------");
}

void loop() {

while(ADCread){

 /* Get a new sensor event */
 sensors_event_t eventLight;
 tsl.getEvent(&eventLight);

 /* Display the results (light is measured in lux) */
 Serial.println();
 Serial.println("Test Conditions");
 Serial.println("------------------");

 if (eventLight.light)
 {
   Serial.print(eventLight.light);
   Serial.print(" lux");
   Serial.print(" ----> for sunlight: ");
   Serial.print(eventLight.light*0.0079);
   Serial.println(" W/m2");
 }
 else
 {
   /* If event.light = 0 the sensor is probably saturated and no reliable data could be
generated! */
   Serial.println("Sensor overload");
 }

  double pitch, roll, Xg, Yg, Zg;

 /* Get a new sensor event */
 sensors_event_t eventAccel;
 accel.getEvent(&eventAccel);

 /* Display the results (acceleration is measured in m/s^2) */
```

```
 Xg = eventAccel.acceleration.x;
 Yg = eventAccel.acceleration.y;
 Zg = eventAccel.acceleration.z;

 //Low Pass Filter
 fXg = Xg * alpha + (fXg * (1.0 - alpha));
 fYg = Yg * alpha + (fYg * (1.0 - alpha));
 fZg = Zg * alpha + (fZg * (1.0 - alpha));

 //Roll & Pitch Equations
 roll  = (atan2(-fYg, fZg)*180.0)/M_PI;
 pitch = (atan2(fXg, sqrt(fYg*fYg + fZg*fZg))*180.0)/M_PI;

 Serial.print("Pitch: ");
 Serial.print(pitch);
 Serial.print("deg");
 Serial.print("\t");
 Serial.print(", Roll: ");
 Serial.print(roll);
 Serial.println("deg");

// call sensors.requestTemperatures() to issue a global temperature
// request to all devices on the bus
sensors.requestTemperatures();              // Send the command to get temperatures

// Loop through each device, print out temperature data
for(int i=0;i<numberOfDevices; i++)
 {
  // Search the wire for address
  if(sensors.getAddress(tempDeviceAddress, i))
        {
           Serial.print("T");
           switch (i)
             {
               case 0:
                 Serial.print("_mono");
                 break;
               case 1:
                 Serial.print("_thin");
                 break;
               case 2:
                 Serial.print("_poly");
                 break;
             }

                Serial.print(": ");
                // It responds almost immediately. Let's print out the data
                printTemperature(tempDeviceAddress);          // Use a simple function to print
out the data
       }
```

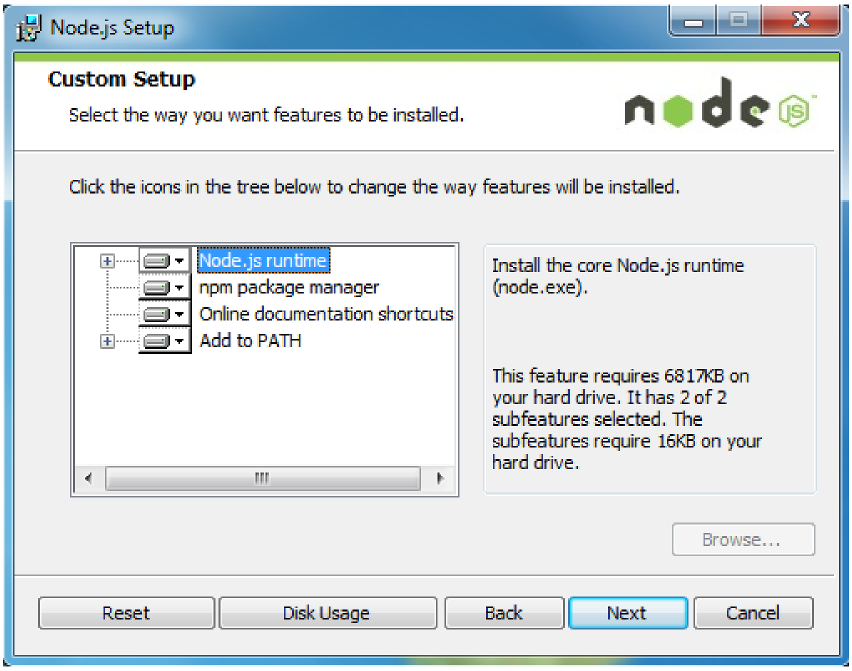
```
 }

sensorValue0 = analogRead(A0);
sensorValue1 = analogRead(A1);
sensorValue2 = analogRead(A2);
sensorValue3 = analogRead(A3);
sensorValue4 = analogRead(A4);
sensorValue5 = analogRead(A5);

// Convert the analog readings (which goes from 0 - 1023) to voltages (0 - 20V) or (0 - 65V)
voltage0 = 4 * sensorValue0 * (5.0 / 1023);
voltage1 = 14 * sensorValue1 * (5.0 / 1023);
voltage2 = 4 * sensorValue2 * (5.0 / 1023);

// Convert the analog readings (which goes from 0 - 1023) to currents (0 - 6A)
current0 = (sensorValue3 / 0.79)  * (5.0 / 1023);
current1 = (sensorValue4 / 0.79) * (5.0 / 1023);
current2 = (sensorValue5 / 0.79) * (5.0 / 1023);

 // Calculate the power
power0 = voltage0 * current0;
power1 = voltage1 * current1;
power2 = voltage2 * current2;

// print out the values you read:
 Serial.println("");
 Serial.println();
 Serial.println("PV Modules");
 Serial.println("----------");
 Serial.print("U_mono: ");
 Serial.print(voltage0, 3);
 Serial.print(" V");
 Serial.print("\t");

 Serial.print("U_thin: ");
 Serial.print(voltage1, 3);
 Serial.print(" V");
 Serial.print("\t");

 Serial.print("U_poly: ");
 Serial.print(voltage2, 3);
 Serial.print(" V");
 Serial.println("\t");

 Serial.print("I_mono: ");
 Serial.print(current0, 3);
 Serial.print(" A");
 Serial.print("\t");
 Serial.print("\t");
```

```
Serial.print("I_thin: ");
Serial.print(current1, 3);
Serial.print(" A");
Serial.print("\t");
Serial.print("\t");

Serial.print("I_poly: ");
Serial.print(current2, 3);
Serial.println(" A");

Serial.print("P_mono: ");
Serial.print(power0);
Serial.print(" W");
Serial.print("\t");
Serial.print("\t");

Serial.print("P_thin: ");
Serial.print(power1);
Serial.print(" W");
Serial.print("\t");
Serial.print("\t");

Serial.print("P_poly: ");
Serial.print(power2);
Serial.println(" W");
Serial.println();

Serial.println("Battery Bank");
Serial.println("------------");
ADCread = false;
}

while(Serial1.available()) {

   content.concat(Serial1.readStringUntil('\n'));

   if (content.indexOf('V') == 0) {
     content.substring(2).toCharArray(floatbuf, sizeof(floatbuf));
     Serial.print(content.substring(0,2));
     float number_0 = atof(floatbuf);
     Serial.print(number_0/1000);
     Serial.println(" V");
     number_0 = 0;
   }

   if (content.indexOf('I') == 0) {
     content.substring(2).toCharArray(floatbuf, sizeof(floatbuf));
     Serial.print(content.substring(0,2));
     float number_0 = atof(floatbuf);
     Serial.print(number_0/1000 - 0.21);
```

```
      Serial.println(" A");
      number_0 = 0;
    }

    if ((content.indexOf('P') == 0) && (content.indexOf('I')) != 1) {
      Serial.print(content);
      Serial.println(" W");
    }

    if ((content.indexOf('C') == 0) && (content.indexOf('h') != 1)) {
      content.substring(3).toCharArray(floatbuf, sizeof(floatbuf));
      Serial.print(content.substring(0,3));
      float number_0 = atof(floatbuf);
      Serial.print(number_0/1000);
      Serial.println(" Ah");
      number_0 = 0;
    }

    if (content.indexOf('S') == 0) {
      content.substring(4).toCharArray(floatbuf, sizeof(floatbuf));
      Serial.print(content.substring(0,4));
      float number_0 = atof(floatbuf);
      Serial.print(number_0/10);
      Serial.println(" %");
      number_0 = 0;
    }

    if (content.indexOf('T') == 0) {
    Serial.print(content);
    Serial.println(" min");
    ADCread = true;
    }

  content = "";
}
}
```

10.4 Appendix: Front-end program documentation

Install the latest version of NodeJS (http://www.nodejs.org/en/download) with the default features.



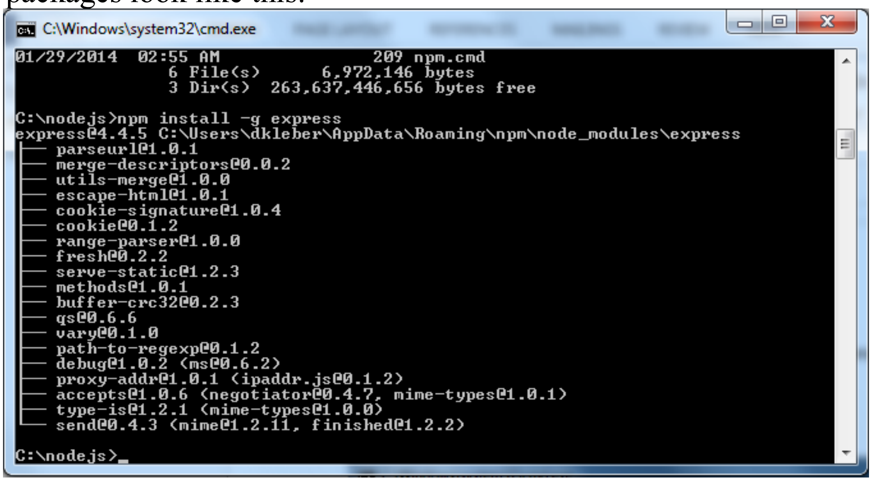
Once finished, install the Express module using the Node Package Manager. Press the Windows Key + R to open an "Execute" window and type

cmd

to open the command prompt. Navigate to the installation path (Program Files by default) and execute

npm install -g express

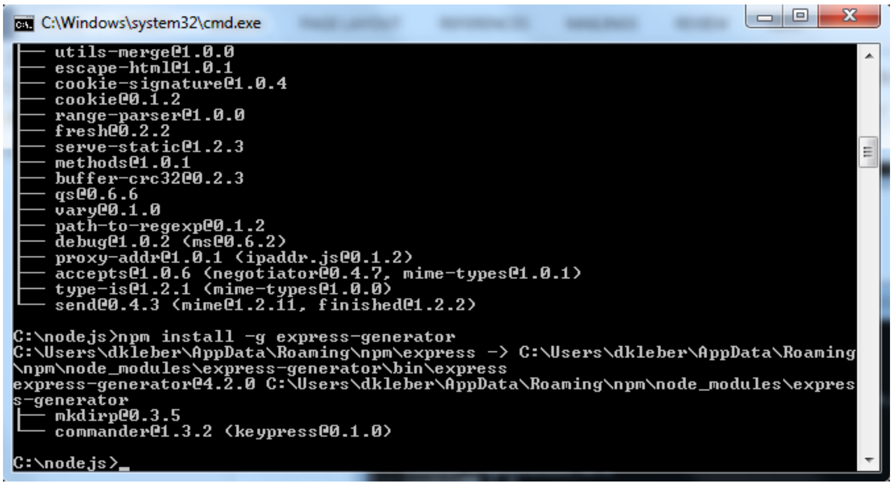
The installed packages look like this:



Afterwards, install the Express Generator by typing

npm install -g express-generator

which generates the following screen:



Finally, navigate to the root directory of the Solar Charging Station and execute

    npm install

to install the NodeJS server on that location.

Configuration:

With the Arduino board connected to the computer, open the Device Manager by pressing Windows Key + R and typing the following in the "Execute" window:

    devmgmt.msc

Note the Port in which the Arduino is connected.

Locate the file "portConfig.json" in the root of the Solar Charging Station folder, right-click it, and open it with Notepad. Edit the port in the "measurement" section so that it is the same port found in the Device Manager. Leave baudrate at 9600.

```
"measurement": {
  "port": "COM4",
  "baudrate": "9600"
},
```

Execution:

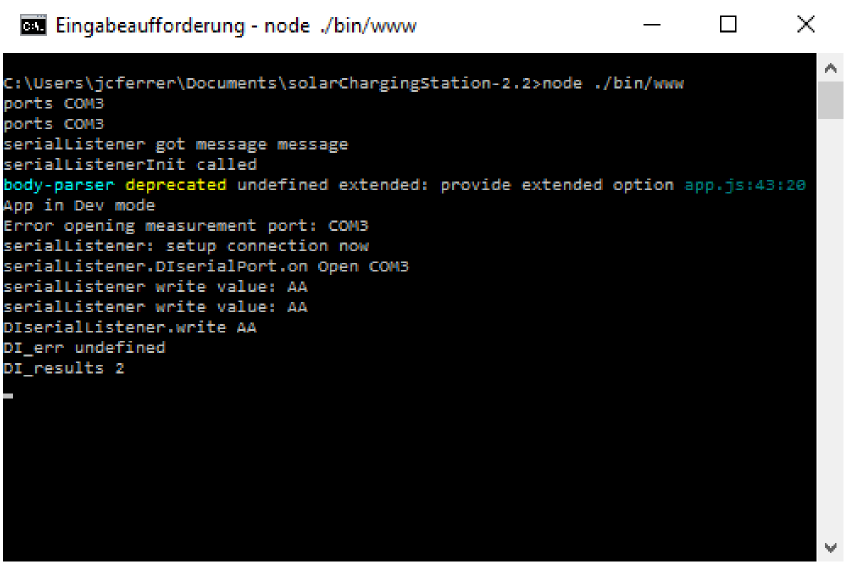
Press the Windows Key + R to open an "Execute" window and open the command prompt by typing

    cmd

Navigate to the Solar Charging Station folder and execute

    node ./bin/www

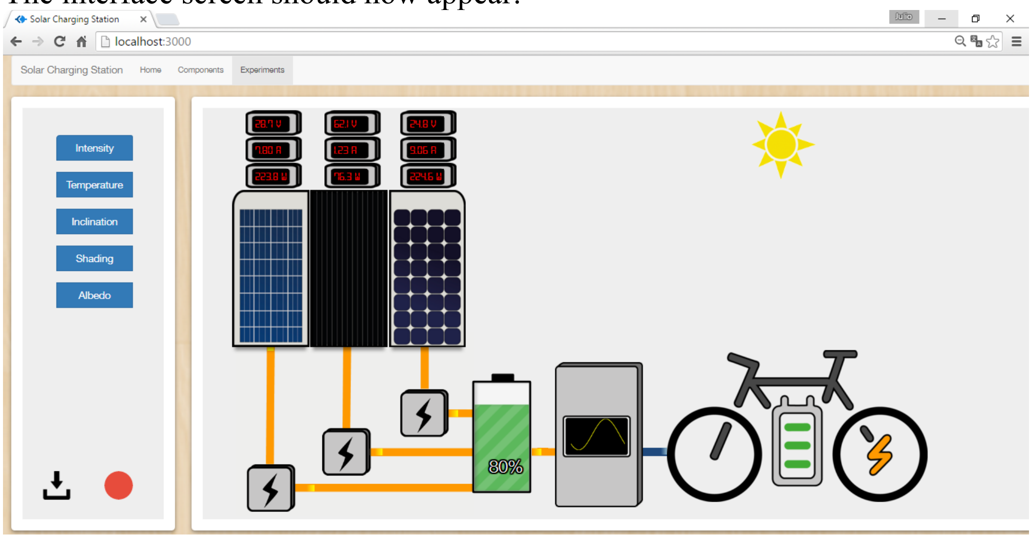
The following commands should appear on the screen. Note that even if some errors are reported while opening the port, a successful communication between PC and board is signaled by the lines "serialListener write value: AA"



Open a Web browser and in the address bar type

localhost:3000

The interface screen should now appear:



To display all components fully, enter full-screen mode by pressing the key F11.

Troubleshooting:

If the interface does not appear on screen:

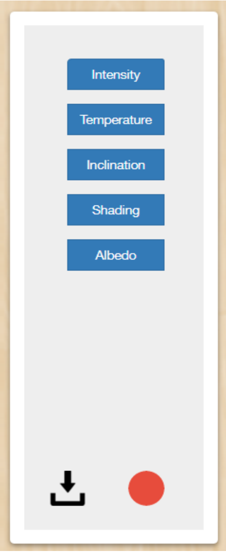
- Make sure NodeJS is correctly installed.
- Check that "node install" was executed from a command line window in the root folder of the Solar Charging Station project.
- Add the NodeJS installation path to the "PATH" section of the System Variables.

If the interface appears, but no data is coming in:

- If the Arduino board is configured in verbose mode, it takes a while to send the data as the initialization process occurs. Wait a few seconds and refresh the page.
- Check that the file "portConfig.json" has the correct port, as seen in the Device Manager.

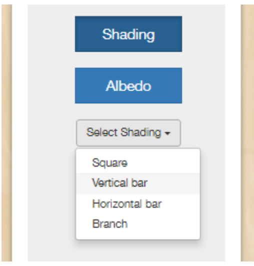
- Open the browser's console for additional debugging options.

Features:

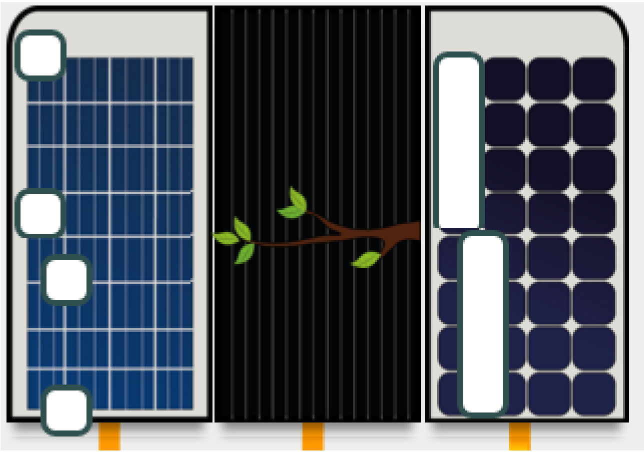


On the left side of the screen, the menu panel contains the buttons that show/hide the different measurement labels.
Each button is clickable and touch-sensitive if running on a touchscreen device; once clicked, the buttons stay in the 'pressed-down' position until clicked again.
"Intensity", "Temperature" and "Inclination" show their respective labels on the first click. "Shading" and "Albedo", when activated, show a dropdown menu where the user selects the specific element to be displayed.
The two downmost buttons are used for the recording and downloading of specific measurement snapshots. Pressing the red "Record" button saves the measurements at that specific time, the latest of which is shown in the table in the lower part of the screen. The "Download" button, located to the left, prompts the user for a download location of a comma separated value (CSV) file, with shows a table with all the measurements saved by the "Record" button.

As mentioned before, both the "Shading" and "Albedo" buttons display dropdown menus where the user selects a specific element to be displayed.
The shading elements appear on the screen only when the "Shading" button is activated, and disappear when inactive, although they retain their last position on the screen.



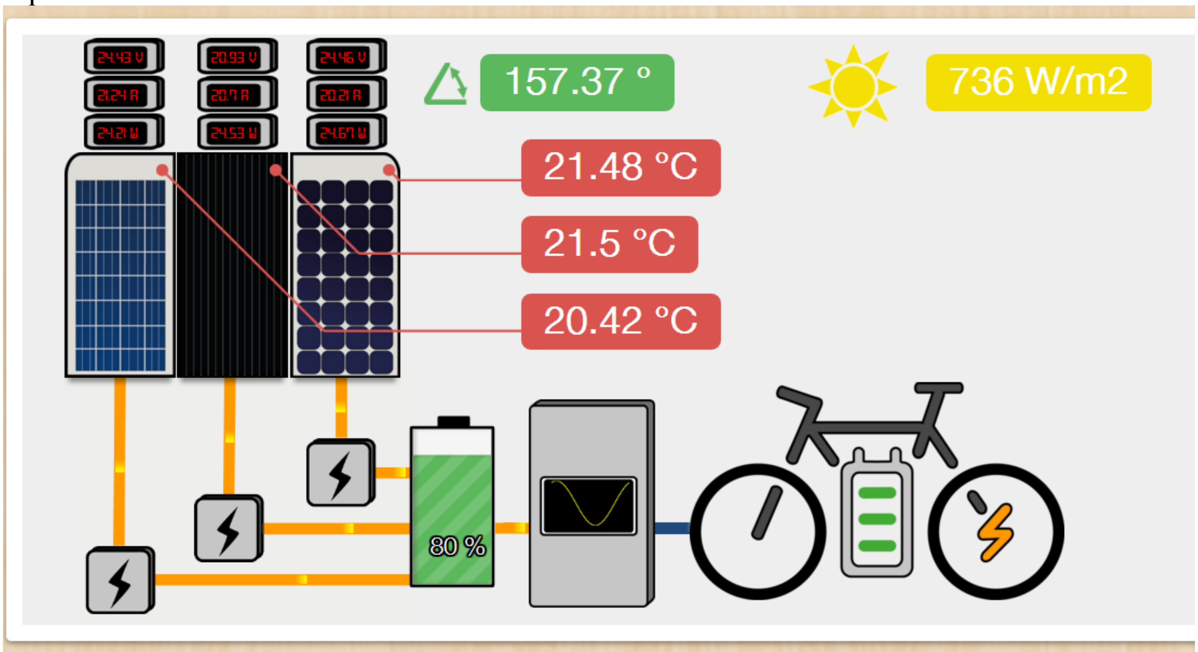
All the elements are draggable with either mouse or touch controls, and can be placed on top of the modules to represent previously defined experimental setups.
When dropping a geometric element on top of either the polycrystalline or the monocrystalline modules, they "snap" into a predefined location that represents specific cases of shading: half a cell shaded, full cell shaded, part of four cells shaded, among others. The geometrical elements have no placement restrictions when placed on top of the thin film module, while the "branch" element has no restriction at all. Only one element can be active at a time, but the figure below shows a superposition of different places to show the possible locations.



The “Albedo” button enables the albedo element selection menu, where the user can choose to display the snow or grass indictators on screen. This elements have no interactive funtionality and serve only to keep track of the experimental conditions at the time of the measurements.

Component panel

The component panel is where all of the measurements and experimental components are represented.



Above each module , three meters that show readings for voltage, current and power.
On the yellow label and next to the sun, the solar irradiance measurement, activated by the “Intensity” button on the Menu Panel.
In the red labels, the temperatures of each of the modules, activated by the “Temperature” button of the Menu Panel.
In the green label, the inclination of the modules, activated by the “Inclination” button of the Menu Panel.
The charge controllers are represented by boxes with an electric bolt icon on them. These graphics are merely informative.
The battery is charged by the charge controllers, and its current state of charge is displayed by the percentage reading inside it and its level shown in green, which changes height proportionally.
Both the inverter and the electric bycicle are merely represented on graphics and have no extra functionality.

Measurement panel

On the lower part of the screen, the measurement panel shows a table that updates itself with the measurements made at the time of the “Record” button push.

Date	T_mono	T_thin	T_poly	U_mono	U_thin	U_poly	I_mono	I_thin
28/4/2016 9:47:23	21.65 °C	20.23 °C	24.08 °C	21.54 V	20.52 V	24.92 V	23.97 A	20.3 A

The table only shows the latest measurement, so as to provide the user with a visual aid of the conditions before or during any experiments. To analyze all mesurements made so far, the "Dowload" button of the Menu Panel should be used.

Interface code

The file "mainScreen.ejs" located under the "Views" in the Solar Charging Station folder contains the HTML code for rendering the interface, a Javascript snippet to receive the information and the CSS style lines that define the position of the graphical elements.

Script files

The first lines of code declare the location of the necessary script files. They provide the serial communications functionality for information transmission, recording and exporting of measured information and the Bootstrap stylesheets for aesthetics.

```
<html lang="en">
   <head>
      <script type="text/javascript"
src="/javascripts/addShadeToData.js"></script>

      <script type="text/javascript" src="/javascripts/JSON2TSV.js"></script>
      <script type="text/javascript" src="/javascripts/dataSocket.js"></script>

      <script type="text/javascript" src="/javascripts/recordScript.js"></script>
      <meta charset="utf-8">
      <meta name="viewport" content="width=device-width, initial-scale=1.0">
      <link href="stylesheets/bootstrap.css" rel="stylesheet" type="text/css"/>
```

CSS

Inside the "Style" tag is the CSS code that determines the position of the graphical elements. A typical example follows:

```
.label-inclination{
position:absolute;
left: 6000px;
top: 45px;
}
```

This defines the position of the label that shows the angle of inclination of the solar modules. As with most graphical elements of the interface, its position is "absolute" as it was designed with the the specific resolution of the Solar Station's tablet in mind. The "left" and "top" values define its location in the screen.

Additional parameters such as "z-index", height, width or shadow properties are also defined in the CSS section for elements that require it.

Body

Following the “Style” section is the “Body” part of the HTML document, where the elements are placed in the screen, starting with a declaration of layout and interface-specific scripts:

```
<scriptsrc="javascripts/jquery/jquery.js" type="text/javascript"></script>
<script src="javascripts/jquery/jquery-ui.js" type="text/javascript"></script>
<script src="javascripts/jquery/sevenSeg.js" type="text/javascript"></script>
<script src="javascripts/bootstrap.js" type="text/javascript"></script>
<script src="javascripts/draggabilly.pkgd.js"></script>
```

They add the jQuery Javascript library, as well as the seven segment displays found for power, voltage and current measurements. Additionally, the Draggabilly package is loaded to allow for drag-and-drop functionality of shading elements.

Navigation Bar

The navigation bar is defined next in the following code:

```
<nav class="navbar navbar-default">
  <div class="container-fluid">
    <div class="navbar-header">
      <a class="navbar-brand" href="#">Solar Charging Station</a>
    </div>
    <div>
      <ul class="nav navbar-nav">
        <li><a href="#">Home</a></li>
        <li><a href="#">Components</a></li>
        <li class="active"><a href="#">Experiments</a></li>
      </ul>
    </div>
  </div>
</nav>
```

The active tab is set as the “Experiments” one. Further development of “Home” and “Components” sections would be added to the bar in this section.

Button menu

Next is a Bootstrap Jumbotron element inside a column of size 2. This contains the buttons visible on the left side of the screen, which allow the display and hiding of measurement labels such as “Intensity”, “Temperature” and “Inclination”. Every button has an identification specified in the form on an “id” tag, as the following example shows:

```
id="btnIntensity"
```

This identification is used later in the Javascript section to map each button to its function. Finally, the “Download” and “Record” buttons are defined as follows:

```
<input type ="image" class="save" src="images/save.png" width="50"
height="50" alt="" onclick="saveDataFunction()" />
<input type="image" class="rec" src="images/rec.png" alt"" id="rec"
onclick="recordFunction()" />
```

These buttons trigger external Javascript functions for downloading and recording measurements through the “onclick” property.

Graphical elements

In a size 10 column is located the second Bootstrap Jumbotron that contains the solar station setup graphics and the labels that display the measurements. All elements are identifiable in-code by a comment line that signals their location.
The solar modules and their respective measurement displays are declared in the following way:

```
<img class="poly" src="images/poly.png" width="137" height="279" alt=""/>

<img class="meter-vPoly" src="images/meter.png" width="100" height="45" alt=""/>
<div id="vPoly" class="reading-vPoly meter">ERR</div>
```

The first line inserts the polycrystalline module image, while the second line inserts the generic meter with its specified width and height.
The third line with ID “vPoly” shows the actual measurement, in this case voltage as evidenced by the suffix ‘v’ in the identification. By default, all measurement labels and meters have the value “ERR” to indicate an error in data transmission and parsing. Under normal circumstances, this “ERR” value is overwritten by the actual measurement coming in from the Arduino, only briefly shown to the user when the interface screen is first loaded.
The battery graphic is composed of a vertical progress bar inside a battery-shaped container. The progress bar’s length changes according to the state of charge of the battery. The length is defined in the “style=’width: ‘” property, while the label itself is displayed in a “p” tag nested inside:

```
<div class="batt-container">
    <div class="progress vertical">
        <div class="progress-bar progress-bar-success progress-bar-striped active bar" role="progressbar" aria-valuenow="90" aria-valuemin="0" aria-valuemax="100" style="width: 80%"><p class="rotate" id="battery">80%</p>
        </div>
    </div>
</div>
```

The last of the graphical components of the interface is a table located in the bottom of the screen, inside a third Bootstrap Jumbotron. Initially empty, the table shows the last recorded measure when the user presses the red “Record” button on the left-side menu. Being a regular HTML table, the headers of each column are defined in a “th” tag, while the contents in the “td” tags are updated when the recorded event is launched.

JavaScript Snippet

The third and final component of the interface is the Javascript functionality. After a “script” tag, the initial variables are declared:

```
var recordDataItem;
shadingStatus = "No shading";
var datasocket = io.connect('http://127.0.0.1:1337');
```

```
var $bar = $('.bar');
```

The first function, declared as

```
$(document).ready(function(){
```

contains the different click-triggered functions tied to the buttons, showing or hiding elements in the case of the label selectors or recording and downloading in the case of the measurement buttons. An example of a function for showing and hiding a label is shown below:

```
$( "#btnIntensity").click(function() {
        $( "#showIntensity" ).toggle();
});
```

The function waits for the element with ID "#btnIntensity", in this case corresponding to the "Intensity" button, to be activated. If clicked, the element with ID "#showIntensity", the label with the measurement, is toggled, meaning it is shown if previously hidden, or viceversa.
The following function populates the measurement table with the last recorded values:

```
$( "#rec").click(function() {
        $( "#showRec" ).toggle(0).delay(600).toggle(0);
        var date = new Date();

        document.getElementById("value-table").rows[1].cells[0].innerHTML =
        date.getDate()+"/"+(date.getMonth()+1)+"/"+date.getFullYear()+"
        "+date.getHours()+":"+date.getMinutes()+":"+date.getSeconds();

        document.getElementById("value-table").rows[1].cells[1].innerHTML =
        recordDataItem.T_mono + ' °C';
        ...
        });
```

It waits for the "Record" button, with ID "#rec", to be clicked, after which it toggles a red "#showRec" label that displays a "Recorded!" message for the user for 600 milliseconds. It then declares a new date variable to be used as timestamp for the value measurements. The "getElementById" function retrieves, as it name implies, an HTML element by its ID. In this case, it points to row 1, cell 0 of the measurement table and modifies its content with the "innerHTML" method, updating the table. In the case of measurements coming from the Arduino board, data is read through the "recordDataItem" method, specifying the variable name to be read.
The drag-and-drop of the shading elements is prepared by declaring "Draggabilly" variables, an external, open source Javascript library for touch applications:

```
var square = new Draggabilly('.square');
```

The position of each of the shading elements is read by the following function showing the case of the Square shader:

```
square.on( 'dragEnd', function() {
        console.log('Square dragEnd', square.position.x, square.position.y);
        shadingStatus = "No Shading";
        //Case 1: half cell is shaded
        // 70 < x <= 200 and 170 < y <= 240
        if(square.position.x > 70 && square.position.x <= 200 && square.position.y > 170
        && square.position.y <= 240){
                squareStyle.left = "92px";
                squareStyle.top = "182px";
```

```
            shadingStatus = "Half Polycrystalline cell shaded by Square";
        } ;
        ...
});
```

The first line waits for the Square shading element to be dropped by checking a "dragEnd" event. Once it happens, it logs the event on the console for debugging purposes and sets the initial "shadingStatus" value as "No Shading". Next, the different shading cases are evaluated. Each case is documented as a comment in the code, with Case 1 corresponding on half a cell being shaded, that is, if the Square element lands between the specified x and y coordinates. An "if" statement checks if the conditions are met and, if they are, the Square's position is "locked" in place by modifying its "left" and "top" properties. Finally, the "shadingStatus" variable is updated.
With this method, each of the shading elements are checked for each of their different cases, locking them in position when needed.

Finally, the data listening function is declared as:

```
        datasocket.on('connect', function (data) {
```

which connects to the selected data socket and starts listening for communications in the serial port. The reading of data and updating of values on the interface occurs in the following code:

```
        datasocket.on('updateData', function (data) {

        recordDataItem = JSON.parse(data);
        document.getElementById("showIntensity").innerHTML = recordDataItem.L_wm2 +
        ' W/m2';

        console.log('record updateData.L_wm2  ' + recordDataItem.L_wm2);
            ...
        });
```

The data socket waits for an "updateData" event signaling new measurements in the serial port. The data is then parsed and stored in the "recordDataItem" JSON variable, which contains all the different values, readable by referencing their names as defined in the Arduino board code. In the case of the example, the solar intensity label is updated by using the "getElementById" method and assigned the value of the "recordDataItem.L_wm2" variable. Finally, the event is logged in the console for debugging purposes.
With the same logic, all values from the Arduino board and read and their respective graphical elements updated in the screen.

10.5 Appendix: Commercially available wind laboratories

Table 24: Comercially available wind laboratories

Company Model	Illustration	Description	Weight	Dimensions [L x W x H mm]	Pros vs. cons
GUNT HM 170	 *http://www.gunt.de*	- Eiffel tunnel with axial fan suitable for aerodynamic study of various small sized models	250 kg.	(Tunnel) 2870 x 890 x1540 (Chamber) 420 x 292 x 292	<u>Advantages</u> - Laminar flow in the measuring chamber - Transparent measuring range <u>Disadvantages</u> - no disassembly for facilitated transport possible - Small measuring chamber
GUNT ET 220	 *http://www.gunt.de*	- Wind tunnel with wind power plant to study the conversion of kinetic energy into electrical power through mini wind turbines	410 kg.	(Tunnel) 2610 x 870 x 1645 (Chamber) 1520 x 790 x 1760	<u>Advantages</u> - Transparent measuring range - Suitable for wind energy experiments - <u>Disadvantages</u> - High weight - No tool-free disassembly possible
GUNT HM 226	 *http://www.gunt.de*	- Eiffel tunnel with radial fan and closed measuring range for visualizing streamlines.	50 kg.	(Tunnel) 1400 x 500 x 490 (Chamber) 252 x 42 x 252	<u>Advantages</u> - Laminar flow - Transparent measuring range; - Light weight - Vmax = 12.7 m/s <u>Disadvantages</u> - Small measuring chamber - Experiments limited to visualization of streamlines
Edibon MINI EEEC	 *http://www.edibon.com/*	- Fundamentals of wind energy by means of a mini wind turbine	15 kg.	(Tunnel) 600 x 400 x 500	<u>Advantages</u> - Light weight - Small size <u>Disadvantages</u> - No measuring chamber - No homogenization flow - No control station - Unsafe due to lack of chamber safeguards
Edibon Wind Tunnel	 *http://www.edibon.com/*	- Axial fan with wind turbine for teaching the fundamentals of wind energy.	140 kg.	(Tunnel) 2300 x 500 x 490 (Chamber) 252 x 630 x 1080	<u>Advantages</u> - Measuring chamber size <u>Disadvantages</u> - High weight - Large dimensions - Poor visibility of the wind turbine
Armfield C15-10	 http://discoverarmfield.com/en/products/view/c15/computer-controlled-subsonic-wind-tunnel	- Undergraduate teaching device to visualize flow over variable objects	220 kg.	(Tunnel) 2250 x 460 x 700 (Chamber) 150 x 150 x 455	<u>Advantages</u> - Wind speed (0-34 m/s); - Steady flow - <u>Disadvantages</u> - Size of measuring chamber - Weight

10.6 Selection process MLS machines and workstations

Machine tools and workstation in the MLF were selected according to the method proposed in 5.1.6.2. In accordance to the method, a set of selection criteria was determined and weighted as a means to evaluate commercially available alternatives. Following MLF elements were appraised:

Table 25: Product comparison. MLF production technologies

Oven – Melting of POM

#	Producer	Model	Weight in kg (30%)	Price in € (30%)	Dimensions (W x D x H) in mm (20%)	Maximum temperature °C (10%)	Source
1	Genlab Limited	MINO/30 General Purpose	20	1700	480*490*500	250	[GEN-15]
2	Raypa Laboratory Equipment	Raypa DO-20 Analogue Drying Oven	27	1423	440*400*610	250	[RAY-15]
3	**Borel Standard Furnaces and Ovens**	**CT 250-19 Conterm Oven**	**21**	**1416**	**600*445*600**	**250**	**[BOREL-15]**
4	Despatch Industries	LBB Convection Benchtop Lab Ovens	63	3600	610*620*660	204	[DEH-15]

CNC milling machine

#	Producer	Model	Weight in kg (40%)	Price in € (40%)	Dimensions (W x D x H) in mm (40%)	Source
1	**BZT**	**PFK 0203**	**60**	**2975**	**340*260*135**	**[BZT-15]**
2	Roland	MDX20	54	3400	203*152.4*60.5	[ROL-15]
3	BZT	PFK 0405	78	3391	520*445*135	[BZT-15]
4	Shopbot	Shopbot Desktop	46.3	5074	610*460*89	[SHO-15]
5	Hass	Al Profil 640	70	4398	600*400*125	[HAA-15]

Drilling Machine

#	Producer	Model	Weight in kg (30%)	Price in € (30%)	Power in W (10%)	Volume in dm3 (20%)	Source
1	**Bosch**	**PBD 40 [BOS-15a]**	**11.2**	**254**	**710**	**75**	**[BOS-15]**
2	Proxxon	TBM 220 [PRX-15]	3.3	190	85	10	[PRX-15]
3	Rotwerk	RB 18 Vario [ROT-15]	29.5	259	600	75	[ROT-15]
4	Flott	TB 10 STW [FLO-15]	20	995	450	64	[FLO-15]

Working stations*

#	Producer	Model	Weight in kg (50%)	Price in € (50%)	Source
1	**Item**	**Diverse**	**323**	**4991**	**Quotation**
2	Rexroth	Diverse	421	5624	Quotation

Once all MLF machine tools were selected, a bidding tender was launched to request quotation of five purpose-specific working stations (assembly, milling, drilling, cutting and soldering).

Offers from tow market leaders (ITEM and Rexroth) were received and considered in the selection process.

The final machine tool selection for the MLF comprised following elements:

Borel CT 250-19 Conterm oven for POM recycling [BOREL-15].

BZT PFK-0203-PX CNC milling machine for lower case milling [BZT-15].

Bosch PBD 40 drilling machine [BOS-15]

Five working stations (assembly, milling, drilling, cutting and soldering)

Two Dremel hand-held sets for cutting and smoothing operations (a), three Toolcraft digital soldering stations ST-100D (b), a Bosch wood chipper for wood downcycling (c), as well as five ITEM handling stations (d) complete the standard equipment of the MLF.

(a) (b) (c) (d)