Aligning cognitive processes with the design process in a University-based digital fabrication laboratory (Ub-Fablab)

Vomaranda Joy Botleng

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Par Vomaranda Joy BOTLENG

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Sous la direction de : Stéphane BRUNEL
et du co-directeur : Philippe GIRARD

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Membres du jury :

M. NOM, Prénom Titre Établissement Président: Mme BRAND-POMMARES Pascale

Mme BRAND-POMMARES Pascale, Professeur, Aix-Marseilles Université, Président

M. EYNARD Benoît, Professeur des Universités, UTC-Laboratoire Roberval, Université de Compiègne, Rapporteur

M. BOUJUT Jean-François, Professeur des Universités, Laboratoire G-Scop Grenoble Alpes University, Rapporteur

M. GIRARD Philippe, Professeur des Universités, École de l'air, Ministère des Armées, Co-Directeur de Thèse, Examinateur

M. BRUNEL Stéphane, Maitre de conférence des Universités, ADT, Laboratoire IMS - UMR 5218 - Université de Bordeaux, Directeur de thèse, Examinateur

M Boulekouran Ben, Invité

Mme Théophile Annette, Invité

Unité de recherche

Laboratoire IMS – UMR 5218

Bâtiment A31, 351 Cours de la Libération, 33400 Talence

Declaration of Originality

I, Vomaranda Joy Botleng, certify that this thesis is my own work except those sections, which have been duly acknowledged. I also certify that this thesis has not been previously submitted to any other university or tertiary education institution.

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Aligning Cognitive processes with the Design process in a University-based Digital Fabrication Laboratory (Ub-Fablab).

Abstract :

The Digital Fabrication Laboratories platform, initially a prototyping platform for local entrepreneurships, is rapidly finding its way into the education arena. This research took a two-fold approach to i) investigate and align cognitive processes with the design process in the fablabs using the Nawita Design Process Model (NDPM) and ii) assesses the capacity of university-based fablabs in preparing citizens for the future design and production industries using the University-Based Fablab Capacity Indicator Scale (Ub-Fablab CIS).
Results for i) showed that materialising the creative ideas incubated in stage 1 of the design process unleashed a stunning peak of cognitive, affective and psychomotor skills in the later stages of the design process.
Results for ii) showed that university-based fablabs have a strong capacity indicator in providing technological infrastructures and a constructionist pedagogical approach.

Keywords :

Digital Fabrication Laboratories, Iterative design processes, Nawita Design Process Model, Cognitive Processes, University-based Digital Fabrication Laboratories, Ub-Fablab Capacity Indicator Scale

Harmoniser les processus cognitifs avec le processus de conception dans un laboratoire de fabrication numérique universitaire (Ub-Fablab).

Résumé :

Les plateformes de type Digital Manufacturing Laboratories, initialement plateformes de prototypage pour les entrepreneurs locaux, trouvent rapidement leur place dans le domaine de l'éducation. Cette recherche a une double finalité pour i) rechercher, capter et analyser les processus cognitifs présents dans les processus de conception dans un environnement fablabs en utilisant le modèle de processus de conception Nawita (NDPM) et ii) évaluer la capacité des fablabs universitaires à préparer les étudiants pour leurs futures conceptions dans les industries de production en utilisant des indicateurs efficients de capacité (Ub-Fablab CIS). Les résultats ont montré deux choses : i) que matérialiser les idées créatives incubées dans la phase initiale de conception d'un produit a entrainé un pic étonnant de compétences cognitives, affectives et psychomotrices. ii) que les fablabs universitaires ont une forte capacité de développement de ces compétences en fournissant une bonne infrastructure technologique et une approche pédagogique constructiviste.

Mots clés :

Laboratoires de fabrication numérique, processus de conception itératifs, modèle de processus de conception Nawita, processus cognitifs, laboratoires universitaires de fabrication numérique, échelle d'indicateurs de capacité Ub-Fablab

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Acronyms

Fab Lab	Fabrication Laboratories
Ub-Fablabs	University-based Fablabs
MIT	Massachusetts Institute of Technology
CBA	Center for Bits and Atoms
SETC	South End Technology Center
CNC	Computer Numerical Controlled
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
NRC	National Research Council
STEM	Science, Technology, Engineering and Mathematics
PCM	Pulse –code Modulation
ABC	Atanasoff-Berry-Computer
ZPD	Zone Proximal Development
MKO	More Knowledgeable Others
STM	Short Term Memory
WM	Working Memory
LTM	Long Term Memory
VSS	Visuo-Spatial Sketchpad
PL	Phonological Loop
LTP	Long Term Potentials
HOTS	Higher Order Thinking Skills
LOTS	Lower Order Thinking Skills
UNESCO	United Nations Educational, Scientific and Cultural Organization

NDPM	Nawita Design Process Model
IoT	Internet of Things
AR	Augmented Reality
AI	Artificial Intelligence
AM	Additive Manufacturing
PFL	Pre-Frontal Cortex
DIY	Do It Yourself
ICT	Information Communication Technology
ABS	Acrylonitrite Butadiene Styrene
PLA	Polylactide
VITE	Vanuatu Institute of Teacher Education
OLB	Observable Learning Behaviour
Bloom’s CPA	Bloom’s Cognitive, Psychomotor, Affective
Ub-Fablab CIS	Ub-Fablab Capacity Indicator Scale
RMM	Rock Milling Machine
PS1	Production Study 1
PS2	Production Study 2

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List of International Conference Participation

Name of International Conference	Date of Conference	Venue	Participation
1. 21st International Conference on Engineering Design (ICED 17)	21 – 25 August 2017	University of British Columbia, Vancouver, Canada	Author & Paper Presenter
2. PATT – 34 International Conference	10 - 14 July 2017	Millersville University, Philadelphia, USA	Author & Paper Presenter
3. PATT-32 International Conference	20-26 August 2016	Delft University of Technology, Utrecht, Netherlands	Author & Paper Presenter
4. World Makers Education Alliance (WMEA)	18-21 November 2016	Nanning, South China	Country Representative & Presenter
5. Upcoming PATT-38 International Conference	3-6 June 2019	University of Malta, Malta	Author of a peer-reviewed and approved paper to be presented in an upcoming conference

General Introduction

Technological revolutions throughout the centuries have impacted the society in many ways, but the changes made were not strongly felt as the changes that are caused by the digital technological revolution. The digital technological revolution has had major changes economically, politically, culturally and in many other ways. The impact of digital technology in the society pushes educationists, scientists, designers, engineers and other professionals to scrutinize ideologies, theories, and philosophies to update skills, knowledge and even attitudes to help the society cope with the changing technologies.

With the current impact of digital technology on education and industries, organizations like the National Research Council (NRC) are calling for reforms in education to prepare citizens to cope with the technological and industrial changes. The NRC Report (NRC, 1999 cited in Blikstein, 2013) reported that, '…technology is too fast for the 'skilled-based' approach to be effective and instead called for a 'fluency approach' (pp.204-205). The report calls for Institutions '…to include the development of adaptive, foundational skills in technology and computation, in particular « [intellectual] capacities [to] empower people to manipulate the medium to their advantage and to handle unintended and unexpected problems when they arise (ibid). The second report from the NRC (2002) also called for a move form 'computer skills' towards 'computational fluency' or 'literacy' and broadening technological literacy to include basic engineering knowledge, and the nature and limitations of the engineering process (ibid).

While there are calls for the education sector to cater for the so-called 21st Century Skills, the industrial sector, on the other hand, is called to rethink design and production practices in order to cater for sustainability (inclusive of eco-design and circular economy) and to embrace the latest technologies in preparation for the Industries 4.0. Platforms like the fablabs therefore could play a vital role as a 'support platform' to augments efforts to equip individuals with the so-called '21st Century skills' and to also prepare citizens for future design and production industries.

The concept of Digital Fabrication Laboratories (commonly known as Fablabs) was founded by Professor Neil Gershenfeld and his team in the Massachusetts Institute of Technology Center for Bits and Atoms (MIT CBA) in Boston in 2003. Fablabs are physical spaces equipped with the latest low-cost technological infrastructures for digital fabrication. It is a space where people meet face-to-face to invent and make (almost) anything together (Gershenfeld, 2005). In less than two decades, the fablab concept spread throughout the United States of America (USA), Europe and other regions of the world like wildfire. Initially targeted at communities as a prototyping platform for local entrepreneurships, the concept is rapidly finding its way into educational institutions and is used as a platform for learning and innovation. Chapter 1 of the thesis has some background information on fablabs.

The fablabs established in universities (the researcher used 'Ub-Fablabs' to refer to these fablabs) could serve both educational and industrial-related purposes. In education, as mentioned, there are calls for education reform to equip citizens with the so-called 21st Century Skills undoubtedly involve high-order thinking skills (cognitive), complex psychomotor skills and complex affective skills (see chapter 2 for details). Since there has been little or no research into the cognitive process embedded in the design process in Ub-Fablabs, the first principal aim of this research is

1 To investigate and align cognitive processes with the design process in a Ub-Fablab

In industries, the unanticipated high output of wastes during the lifecycle of a product puts to question the current practices of design and production. According to Siefried Dais (Tscheiesner & Loffler 2016 Interview), the current manufacturing sectors/companies operate in isolation. The design companies create product solutions and design specifications for customers while manufacturing companies/industries produce for the customers. This approach, not only has it concentrated skills to only the 'experts' in the fields of design and production, but responsive attitudes towards resource conservation and sustainability (inclusive of eco-design and circular economy) may not have been nurtured or incubated within these sectors. Designing in the 21st century therefore calls for an innovative platform that could integrate design and production in an environment where not only skills and knowledge of high-tech production machines are gained but also an environment where collaboration through digital networking, educational and responsive attitudes towards resource conservation and sustainability could be incubated. The Ub-Fablabs are in a vital position to play that role, however, there is little or no research into its capacity to play that role thus the second principal aim of this research is

2 To critically assess the capacity of Ub-Fablabs to prepare citizens for the future design and production industries.

The research questions to guide this research are:

1 What are the types of cognitive processes embedded in the design process in Ub-Fablabs?
2 How efficient are Ub-Fablabs preparing citizens for the future design and production industries?

A blend of quantitative and qualitative approach to research has been utilised in this research to seek answers to the two key research questions. To ensure credibility of the study, a triangulation of methods involving a theoretical framework through document analysis and literature review; empirical analysis (through observations and online content analysis) and data analysis was utilised. Chapter 4 of this thesis has the details of the methodology used in this research.

To answer research questions one and two, this research is divided into two parts, Part one and Part two.

In part 1 of the research, the researcher studied two cases of design and production of two products. The researcher refers to these two studies, Production study 1 (PS1) and Production study 2 (PS2).

1 In PS1, the researcher observed a group of students designing and producing an originally-thought-out product compost of many raw materials (rocks, wood and synthetic materials). The product resembles a Rock Milling Machine (RMM). The group used a variety of traditional and modern production machines/tools to produce to produce the RMM.

2 In PS2, the researcher observed an individual person producing a pre-designed product, a chain, downloaded from data file. The product is made from a single material (PLA filament). The person uses only one production machine, the 3D printer to produce the chain.

Why carry out PS1 and PS2 for part 1 of this research? To carry out PS1 alone would be a one-snap shot of the occurrences of the cognitive processes involved in the design process in Ub-Fablabs. By carrying out PS1 alongside PS2 in part one of this research, the findings not only inform of the types of cognitive process that can be unleashed during a design process, but it also help in the design of projects that will maximise the unleash of cognitive processes during a design process. This research therefore compares PS1 and PS2 to see how the following aspects of design and production can influence the unleashing of cognitive processes during a design process. These are:

1 producing an original thought-out product versus producing a product downloaded from data files
2 producing a product made up of many raw materials versus producing a product made up of only 1 raw material
3 Producing a product using many types of production machines versus producing a product using just one type of production machine
4 producing a product in groups versus one person producing a product

In PS1 and PS2 the researcher used an iterative design process model, the Nawita Design Process Model (NDPM) (see chapter 3 for details) to track the activities during the design process. OLB were recorded using field notes, video-recording and still photography. Data was analysed using an adapted protocol analysis and results were graphed using pie and bubble-chart graphing. Part one of chapter 5 of the thesis has details of the result and discussion.

In part 2 of the research, an adapted online content analysis was used to collect data from 90% of the Ub-Fablabs worldwide. An Ub-Fablab Capacity Indicator Scale (Ub-Fablab CIS) was developed and used to score on four potential aspects of an Ub-Fablab if it were to be qualified to be used as a support platform to incubate proactive minds for the future integration of design and production industries. These components are i) Technological infrastructure; ii) Constructionist pedagogical approach; iii) Collaboration through digital networking and iv) sustainability (inclusive of eco-design and circular economy). Part two of chapter 5 has the details of the results and discussion.

Chapter 6 of this thesis contains an overall conclusion, limitations of this study and recommendations for future research into Ub-Fablabs.

Chapter 1

1 Introduction

The concept of Digital Fabrication Laboratories (commonly known as Fablabs) emerged from Gershenfeld's class '*How to make (almost) anything'* at the Massachusetts Institute of Technology (MIT) in 2001. The first fablab was established at the South End Technology Center (SETC) in Boston by the MIT-CBA team led by Sherry Lassiter, a colleague of Gershenfeld. The second fablab was set up in the town of Sekondi-Takoradi in Ghana. In less than a decade, there is almost an exponential growth of these fablabs (Figure 1.1) globally spanning from countries in Europe to the tiny nation states in Oceania. According to Gershenfeld (Gershenfeld, 2005) the fablabs have doubled in numbers almost every 18 months. By September 2017, we could identify a total of 1,182 fablabs.

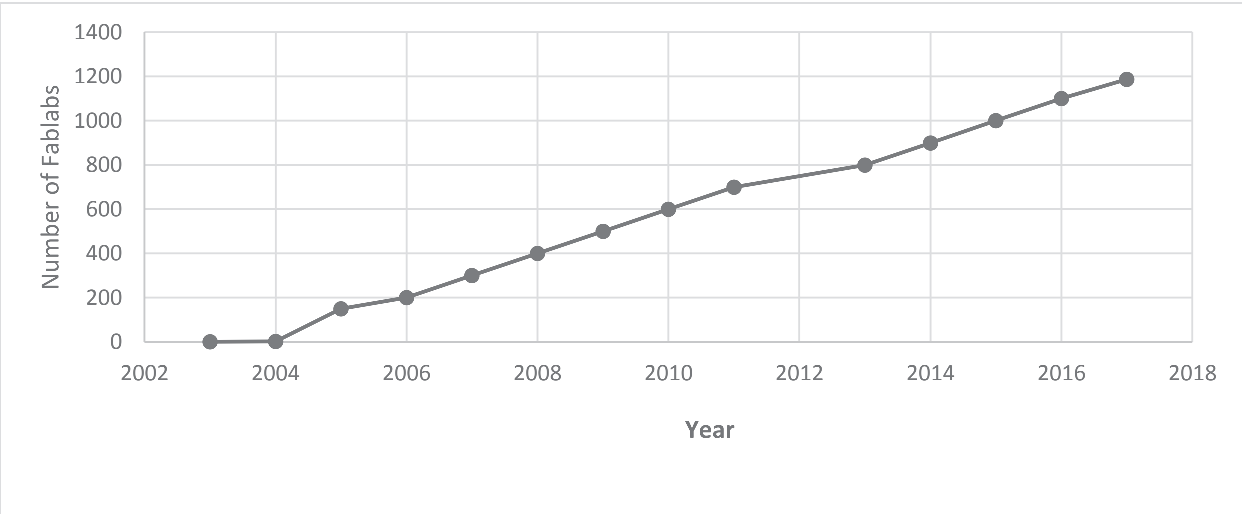


Figure 1.1 Graph showing the growth of fablabs (Source: Data gathered from the Fablab website (Fablab website, n.d), graph drawn by researcher).

It is interesting to note that most of these labs are found in Europe (52%) with France alone leading by over 50% of these, followed by the North American region (15%), Asia (14%), Latin America and the Caribbean (10%), , Africa (4%), The Middle East (4%) and Oceania, particularly in Australia and New Zealand (1%) (Fig 1. 2).

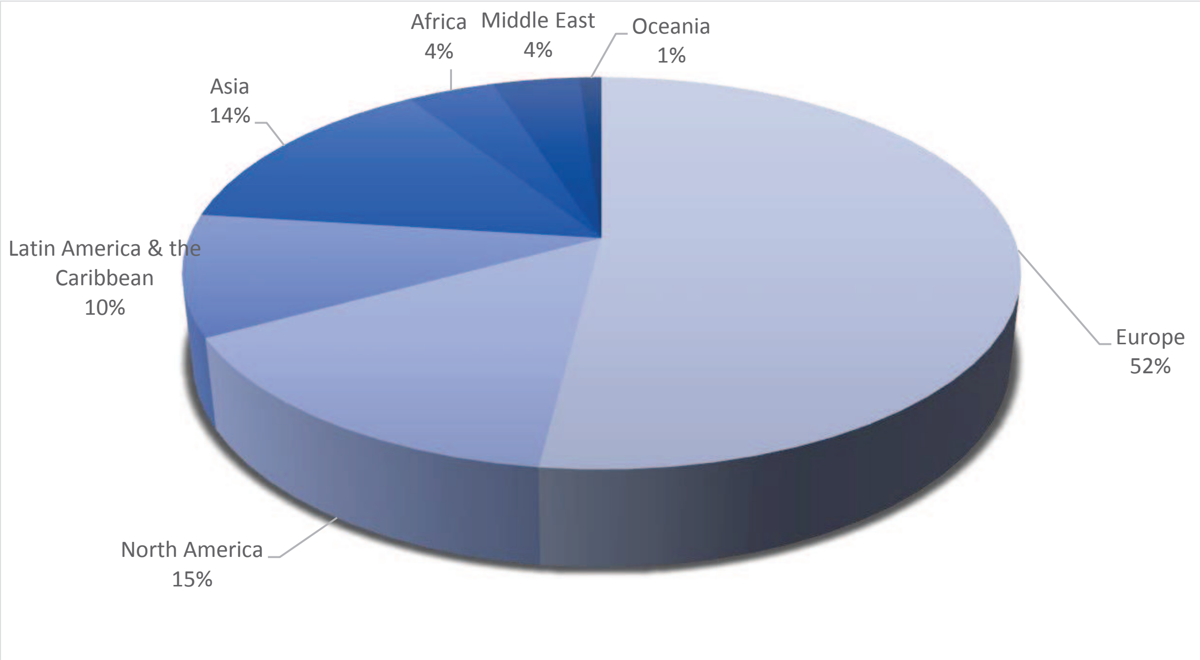


Figure 1.2 Graph showing the distribution of fablabs by major regions (Source: Data gathered from the Fablab website (Fablab website, n.d)

Figure 1.2 reveals a very interesting trend in the spur of these fablabs across the major regions. Although the concept was incubated in the US (North American region), the European countries swiftly adopted the concept, and by early 2017, they are leading by over 52% of the total number of fablabs worldwide, almost half of that are found in France alone. One may wonder why.

The concept of 'people making or creating things themselves' has been a way of life for people down the centuries. These skills, however, have again been brought into the spotlight this century yet in another form, **enhanced by modern technologies** (Gershenfeld, 2005). This new form of 'people creating things' has sprung up in Europe around about the same time the MIT was setting up the first fablab in the United States in 2001, but under the popular names of hacker space, makerspace and techshop. The concept of hacker space started in Europe, particularly in Germany in the late 1990s and had its first independent hacker space called the 'C-base', opened in 1995 followed by other popular hacker spaces like the NYC Resistor in 2007 and the Noise Bridge in 2008. 'Makerspace', was a born-out name for the 'hacker space' in 2005 when the MAKE Magazine was published (it however came into public in early 2011). In the US, the TechShop, on the other hand, is a 'for-profit' space started in 2006 in Menlo Park, California and call themselves 'America's First Nationwide Open-Access Public Workshop' and was offering public access to high-end manufacturing equipment in exchange for membership fees (Cavalcanti, 2013).

These spaces in Europe had similar purposes to what Mr Gershenfeld had in mind about his MIT laboratory. Cavalcanti (Cavalcanti, 2013) spoke of the intentions of hacker space and makerspace in Europe as places where:

anyone should be able to make anything at any time out of (almost) any materials ; the original goal of the space was to democratize the act of making something from scratch as well as you can (whatever it may be) – not repurpose what already exists (p. 3).

That word, '*anything*' gives the person the liberation to think up, devise methods, create the object according to the concept or ideas in one's brain whether the objects be '*…beautiful or practical, complex or simple, 'intelligent' or not* (Walter-Herrman, 2013, p. 2).

The emergence of these makerspaces also generated many novel approaches to augment traditional manufacturing processes and encouraged a series of shifts: from 'centralized' mass production towards 'distributed' mass production; from 'dictated' technology towards 'democratized' technology; from 'specialized engineers' towards 'ordinary people'; and from 'uniformed' products towards more customized or personalized products (Figure 1.3) (Gordon, 2011).

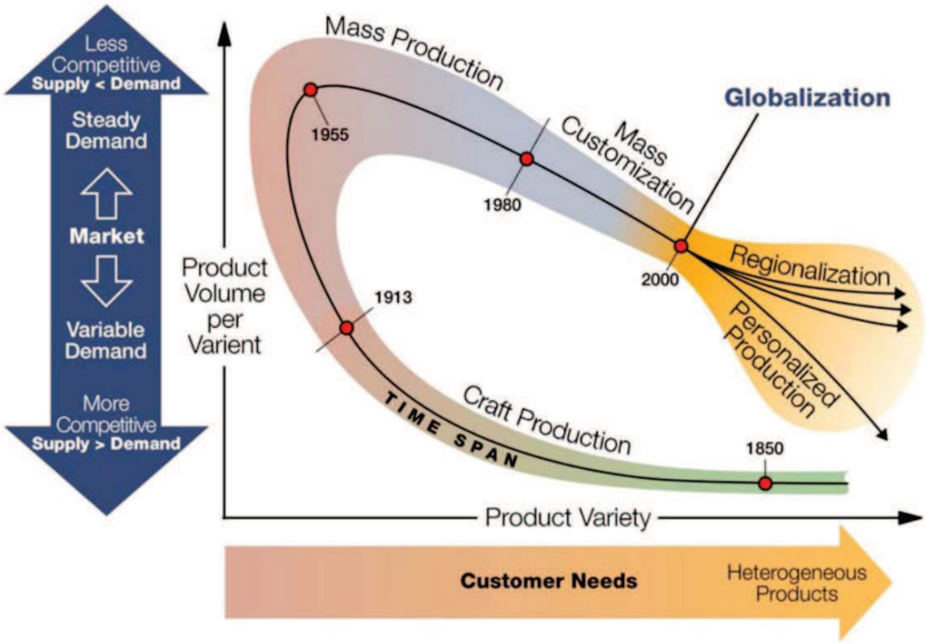


Figure 1.3: Evolution of Paradigm in manufacturing (Koren, 2010)

1.1 What actually are Fablabs?

Fablabs are physical spaces equipped with the latest low-cost technological infrastructures for digital fabrication where people meet face-to-face to invent and make (almost) anything together (Gershenfeld, 2005). Although in many contexts fablabs are referred to as 'digital fabrication laboratories', according to Gershenfeld (Gershenfeld, 2012), digital fabrication refers to the '… processes that use the computer-controlled tools to fabricate or create things. At this stage, however, the 'digital' part of these tools resides in the controlling computer, but the materials themselves are analog. A deeper meaning of 'digital fabrication' is manufacturing processes in which the materials themselves are digital' (p.12).

The distribution of fablabs shows that approximately 87% of the fablabs are based in the communities and used mainly for entrepreneurs while 13% of the fablabs are established in educational settings as learning platforms (Figure 1.4).

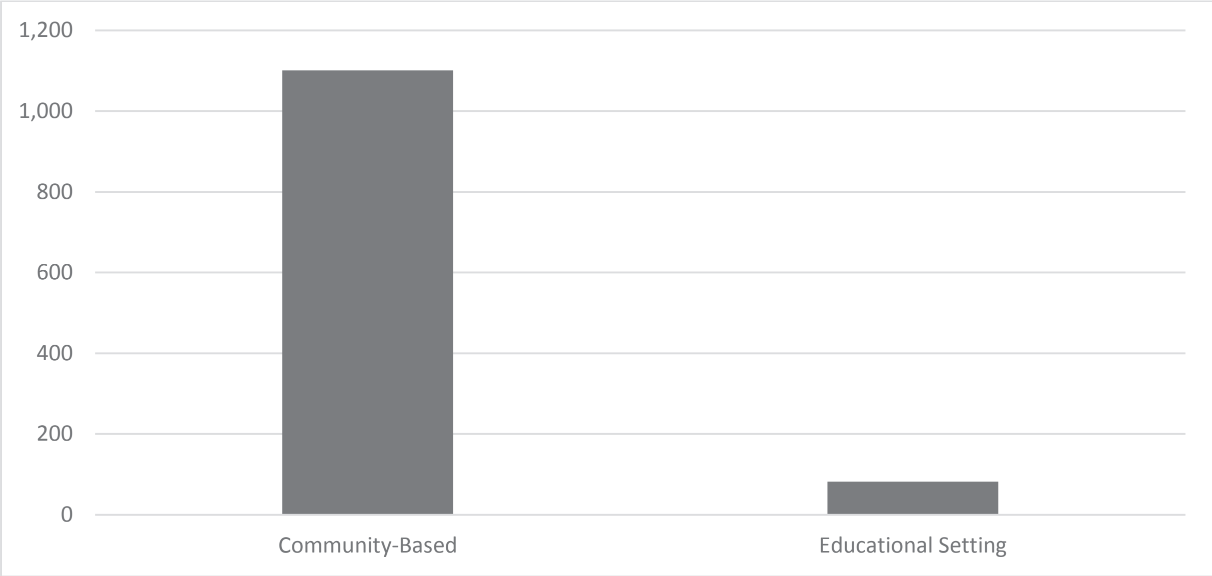


Figure 1.4 Graph showing distribution of Fablabs in Communities and Educational Settings (Data gathered from the Fablab website (Fablab website, n.d)).

An umbrella organization, the Fab Foundation, formed in 2009, facilitates and provides support for the fablab network around the world. Two other organizations that provide educational support programs for the fablab network are the Fab Academy and the Fab Ed. It is, however, important to note that each fablab has yet its sub-organizational structure depending on whether it is a fablab within an educational setting or as an independent business setting.

1.2 The Fablab Charter

The Fablab network is guided by a Fablab Charter (Figure 1.5)

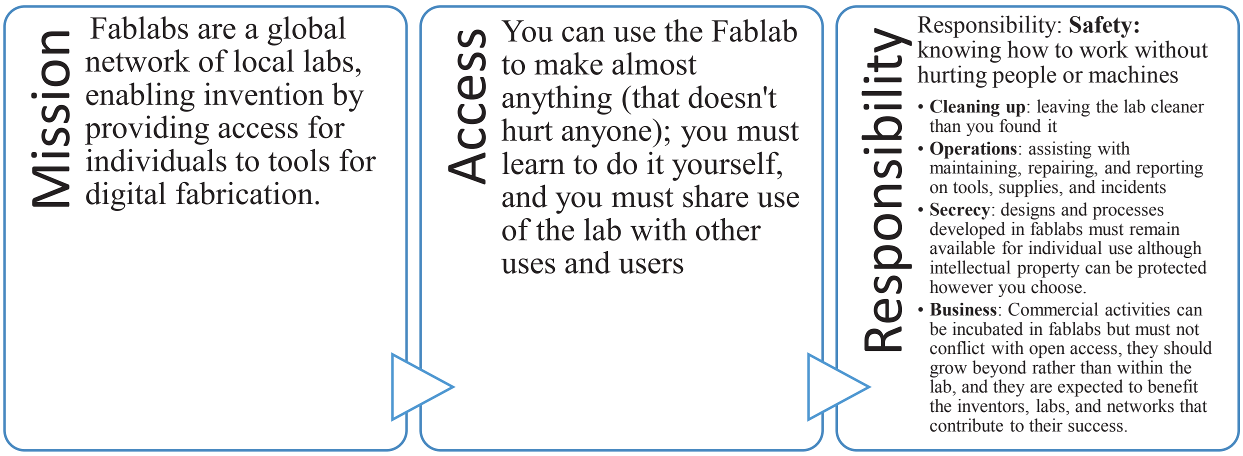


Figure 1.5 The Fablab Charter (Fab Foundation, 2012)

1.2.1 The requirements of a fablab

The processes in a fablab network seem to fall under four areas, which, are interwoven into the requirements outlined below:

1 Design and Production: How the fablab is operated, the production result and how the fablab can take advantage of the production.
2 Collaboration and Communication: How people collaborate and connect in the fablab network
3 Sharing Knowledge: How the knowledge is shared.
4 Education: How people are educated.

Guided by the Fablab Charter, the FabFoundation (FabFoundation, 2012) has outlined at least 4 requirements for spaces to be recognized as fablabs. These requirements neatly blends a technological infrastructure, built-in mechanisms and a collaborative learning environment that can enhance technological and collaborative skills.

1.2.2 Requirement 1: Public access to fablabs

The Open-access status of fablabs offers an inviting and gender-neutral environment where individuals, including novices, can create or construct. It also allows individuals who just want to experiment with and enhance their practical knowledge of electronics and the high-tech prototyping machines to do so without any external pressures (Martinez & Stager, 2013). Grothaug (Grothaug, 2011) identified three possible users of a fablab:

1 *the inventor* – someone who has a well-considered idea with probably a sketch, but needs the assistance of the Fab lab to produce a prototype so he could sell the idea to an interested company or an investor
2 *the designer* – someone who may be creative or technically talented as well as know how to operate the machines in the fablab. This person could be found making his own inventions or helping others in the Fab lab

3 *the customer* – Someone who needs a product, but does not know how or what to do, particularly if the product demands a low level technology and development companies could not do it for him/her (pp 5-7).

To provide professional assistance for the face-to-face users in the fablabs, two important personnel in fablabs include fablab managers and the fablab gurus or fablab technical expert. The role a fablab manager plays include promoting the fablab locally and externally through, for example, fablab festivals/conferences or through the fablab network website; manage fablab finances and as an overseer of the daily operation of a fablab. The fablab gurus or fablab technical experts, on the other hand, are the technical people who have backgrounds in mechanical engineering or design and possibly architecture and off course with electronics and/or computer programming. The gurus work direct with users in the fab lab by teaching users how to use the software, machines, maintain the machines as well as help people design and make things in the fablabs. This person also could help the manager design programs for the community. Some fablabs could also have a third person working in the Fablab on part-time basis to maintain the computers, networking and internet access or any other IT problems that may arise (Fab Foundation, 2012).

For the fablabs that are established in educational settings, the fablab rules and class schedules could restrain people from easily accessing the machines at any time they want.

1.2.3 Requirements 2 & 3: Participate in global fablab network and collaborate with other fablabs

This requirement pushes all fablabs to be connected to the internet to allow access to projects and designs globally via the Fablab website. Gershenfeld (Gershenfeld, 2012) used an example to illustrate the wonder of this requirement.

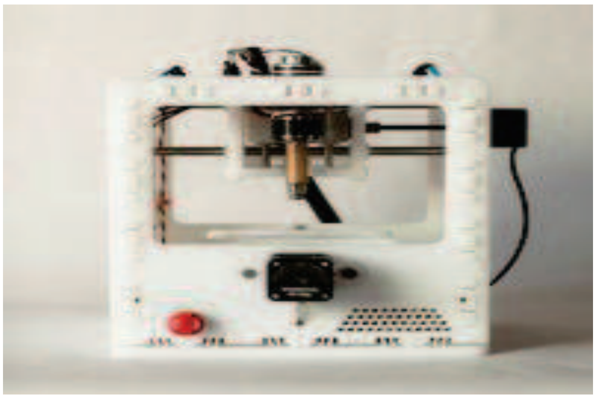
> From the Boston lab, a project was started to make antennas, radios and terminals for wireless networks. The design was refined in a fablab in Norway, was tested at one in South Africa, was deployed from one in Afghanistan, and is now running on a self-sustaining commercial basis in Kenya. None of these

> sites had the critical mass of knowledge to design and produce the networks on its own. But by sharing design files and producing the components locally, they could do so together (p. 11).

Although there are discussions about the difficulties faced (see Troxler et al 2014 for details of these challenges), this requirement has a built-in mechanism for all users to gain computer skills in order to access the designs and projects. This mechanism is supported by courses run by the MIT Fablab and supporting organizations like the Fablab Academy and the Fablab Ed. The courses help users acquire computer skills in order to use online designs and projects. In so doing, users enhance their technological and collaborative skills.

1.2.4 Requirement 4: To share a common set of machines /tools and processes

The production machines in the Fablabs are standardised machines proposed by the MIT CBA. These production machines include Computer Numerical Control (CNC) milling, laser cutters and etchers, vinyl cutters and 3D printers (see Figure 1.6 for examples of these production machines). Such production machines are able to print, cut or mill objects from data files.



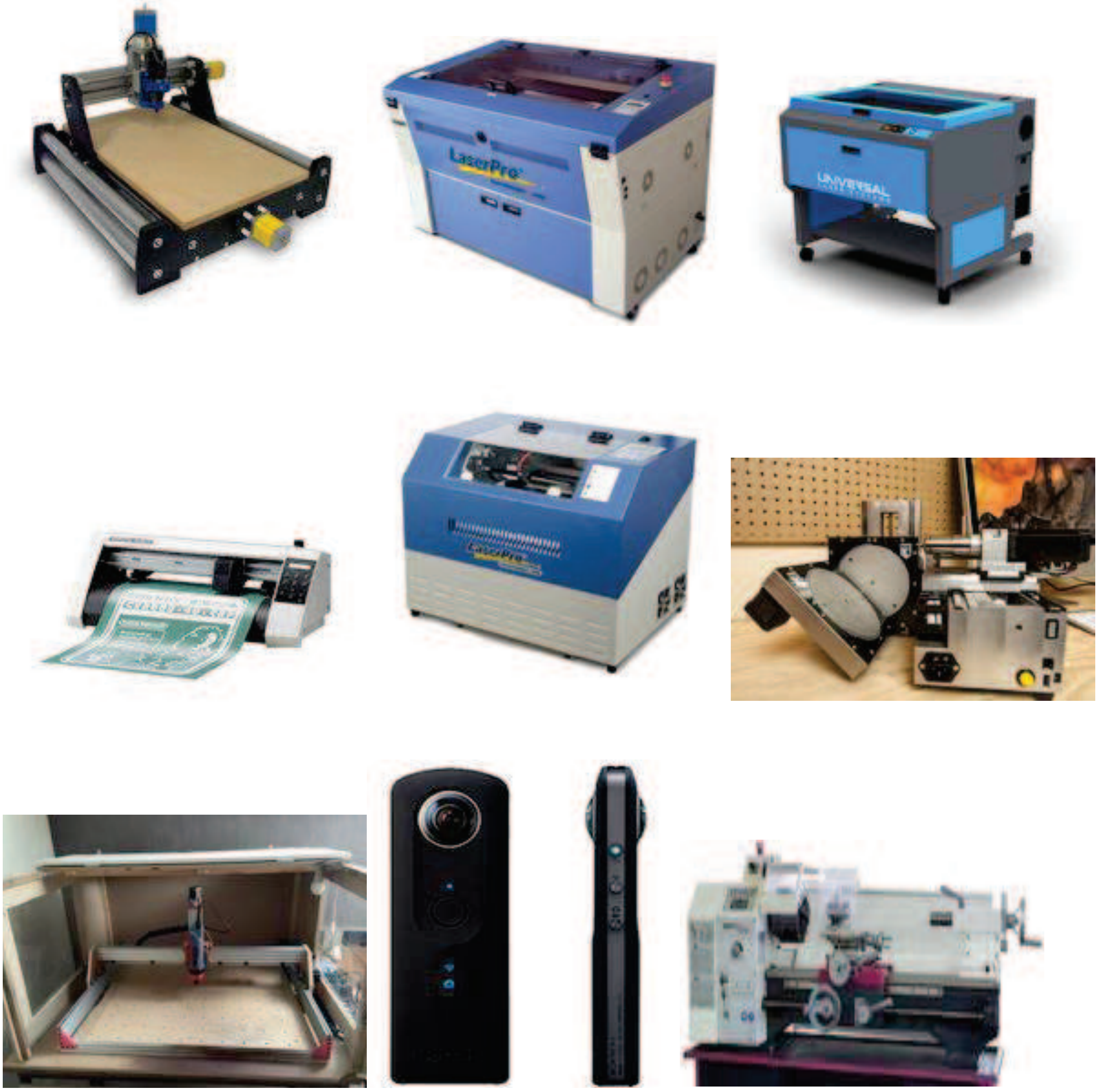


Figure 1.6: The common production machines in a fablab. [Refer to Fablab website (Fablab website, n.d.) for details of these production machines]

These machines can be classified as either ‘additive machines’ or ‘subtractive machines’. The subtractive production machines use mainly the traditional manufacturing methods where the starting materials are removed or ‘taken away’ to create a final product. This type of manufacturing process can produce a lot of waste materials.

The 3D printer, on the other hand, is an additive machine. To come up with a product, the 3D printer adds materials layer by layer with each cross section stacked on top of the one below it to create new and different shapes and products. Because this new manufacturing process can be performed without huge, high-throughput machinery, the 3D machines can be used almost anywhere in the world. By adding materials to create new products the additive manufacturing process leaves a near-zero waste. The presence of 3D printers and the CNC machines in a fablab play an important role in distinguishing the fablabs from the traditional work stations (Martinez & Stager, 2013).

Although 3D printers vary in their design and how they work, the most important parts that one needs to know are:

1 **The Case/structure**: These can be made of metal, wood or plastic. Some are open on all sides to let heat and fumes out and little hands in.
2 **The Print-head**- the mechanism that controls where the molten filament squirts out. Many 3D printers move the printer head back and forth and side to side in an X, Y grid using a granty system. The print bed moves down in the Z direction as the object is created. A few reverse this and move the printer bed in the Y, Y space and the print head up and down in the Z direction.
3 **Print bed or Build Platform**: This is the flat platform on which the printed object is built. Some printers use heated print beds so that the warm molten plastic hitting a cold surface doesn’t wrap the object.

4 **Extruder:** The extruder is the part that grabs the filament and feeds it through the printer to the hot end. It's like the trigger mechanism on a glue gun feeding the glue stick toward the metal nozzle.
5 **Hot-end or print Nozzle**: This is the hottest part of the printer, where the filament is melted into molten plastic and deposited onto the print bed or the partially completed object. (Martinez & Stager 2013, p. 94)

There are two types of plastic filaments that are used in low-cost 3D printers in fablabs in schools

1 ABS (Acrylonitrite butadiene styrene) – ABS is what LEGOS are made of, generally sturdier but more expensive than PLA and melts at a higher temperature.
2 PLA (Polylactide) – PLA is made of cornstarch or sugar, so it is potentially biodegradable. However, it requires a composting process so just throwing it in the trash or recycle bin isn't really saving the planet. Some types of PLA are more flexible than ABS, while others are more rigid.

The standardized computers are the IBM-compatible computers supported by Computer-Aided Engineering (CAE) software such as

1. Computer-Aided Design (CAD), the predecessor of the Ivan Sutherland 1963 Sketchpad software (Sutherland 1963)- to draft and draw products (designing) and
2. Computer-Aided Manufacturing (CAM) – this software transforms the drawings (designs) done by the CAD into physical models. The software used in fablabs are also available under the Open-source (or comparable) licenses therefore are adaptable and developable (Walter-Herrman, 2013, p.2).

These production machines and software being standardised enhance fablab collaborations and avoids the problems of compatibility of machines between the fablabs. These production machines and software allow students in Ub-Fablabs progress from a concept to a prototype that can be tested in the real world.

1.3 Progression of fablabs into education settings

Initially targeted for rapid prototyping for entrepreneurship for local communities the concept of fablabs has made its way into educational settings and is used as a platform for learning and innovation (Figure 1.7). In 2008, as part of the Fablab@Schools Project, Paul Blikstein built the first Fablab in a school of Education in the U.S where graduate courses were conducted to teach students to design projects for K-12 education (Martinez & Stager, 2013).

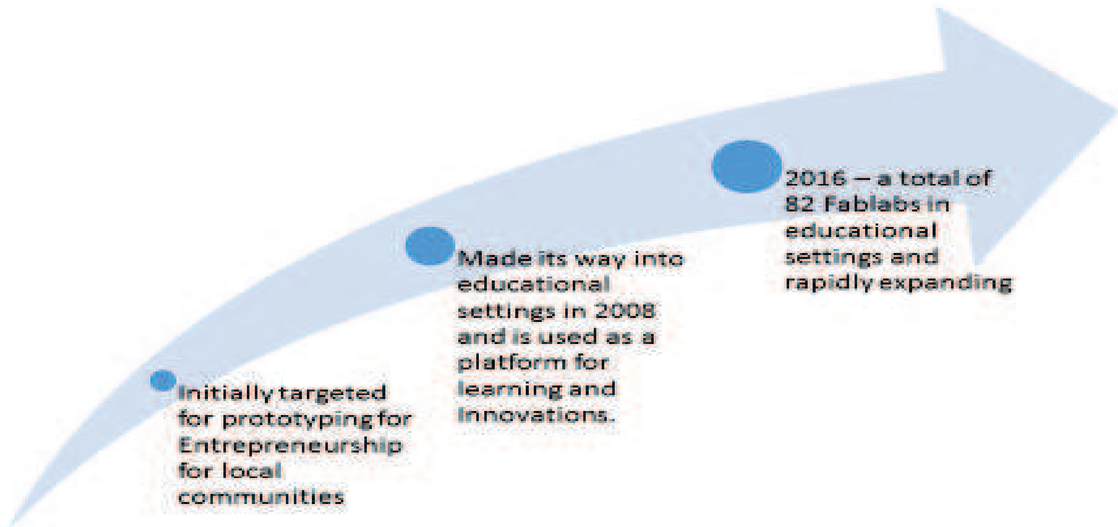


Figure 1.7 Progression of fablabs into Educational settings

To date total of 82 fablabs have been set up in educational settings of which 57% are University-based Fablabs, 40% are High School-based and 3% are Elementary school-based Fablabs (Figure 1.8).

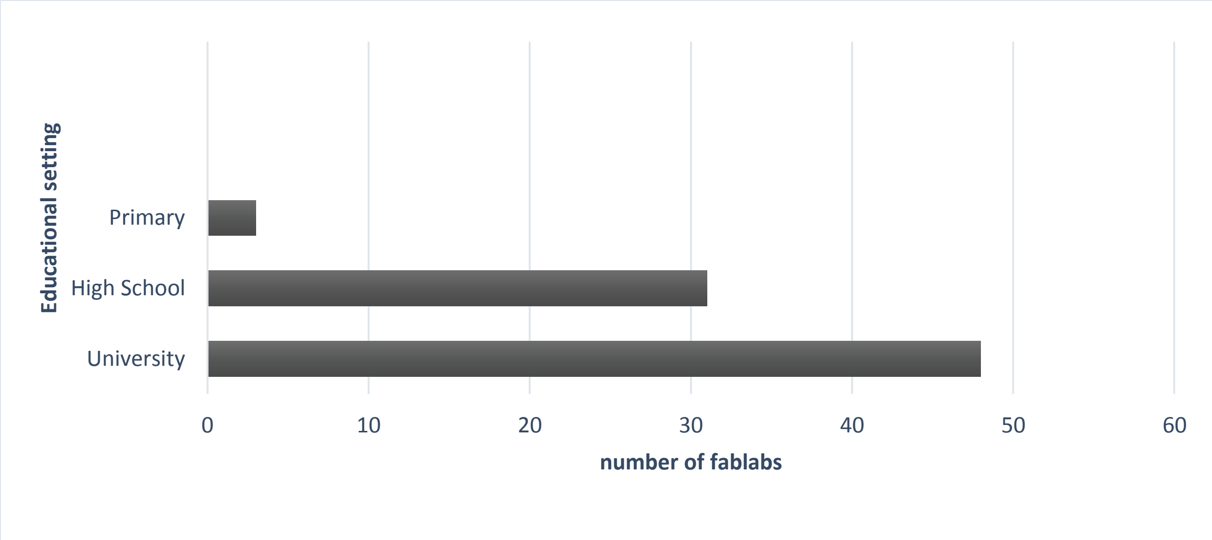


Figure 1.8 Distribution of fablabs in educational settings

The Fab Foundation (Fab Foundation, 2012) describes a Fablab as the '…educational outreach component of MIT's Center for Bits and Atoms (CBA), an extension of its research into digital fabrication and computation (p. 1) where,

Users learn by designing and creating objects of personal interest or import. Empowered by the experience of making something themselves, they both learn and mentor each other, gaining deep knowledge about the machines, the materials, the design process, and the engineering that goes into invention and innovation. In educational settings, rather than relying on a fixed curriculum, learning happens in an authentic, engaging, personal context, one in which students go through a cycle of imagination, design, prototyping, reflection, and iterations as they find solutions to challenge or bring their ideas to life (ibid, p.12).

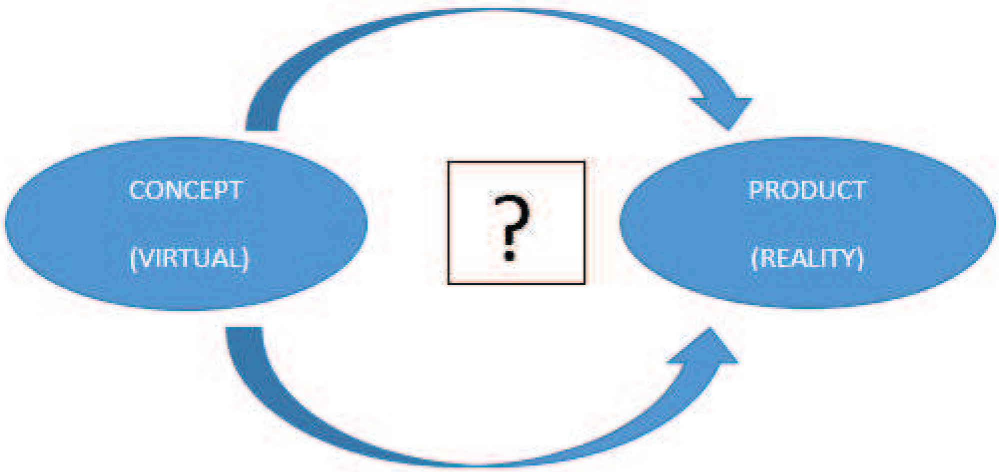
Brunel (Brunel et al, 2008) have emphasised the capacity of a product to generate knowledge during i) design phase ii) production and manufacturing iii) its use by the customers iv) its maintenance and v) during training phase. Blikstein (Blikstein, 2013) further argued that that the fablab platform is one of a promising concept that can be utilised in educational settings to augment the new sets of skills and intellectual activities crucial for work, conviviality and citizenship (cited in Walter-Herrman, 2013).

1.4 Problem Statement

The fablabs, however, are often loosely referred to as just, '*a place where people have access to low-cost digital production tools and meet face-to-face to create anything'*

(Gershenfeld, 2005; Grothaug, 2011; Fab Foundation, 2012; Fablab website, to quote a few). This loose definition of fablabs often leads people to focus mainly on the social aspects of fablabs and the final prototype or product. There are, however, two critical aspects of fablabs that may have been undermined or overlooked thus warrants a research as such. The two aspects are discussed in the following paragraphs.

1. The cognitive processes (inclusive of cognitive, affective and psychomotor domains) that are embedded and generated during the design process itself need to be realised.



The design process that fablab users iterate through to finally come up with their finished prototype/product can be viewed as a type of **problem-solving activity** (Eastman, 1968). Reiman (Reiman, 1963; cited in Eastman, 1968) described the problem solving activity in places like the fablab as a 'transformational problem-solving activity'. The activity begins with an initial information state and requires the task to transform into an acceptable solution state. The problem solving tasks alone require high-order thinking skills and rigorous psychomotor skills (mechanical, electrical, and embedded software operation skills) to transform the ideas into the desired prototype/product. This therefore involves a lot of retrieval of declarative and procedural information from the brain's Long Term Memory (LTM) to the Working Memory (MW) for processing. In the WM, a lot of Prefrontal Cortex (PFC) high-order cognitive processes such as rehearsal, coding, planning, making judgements, decision-making, critical and creative thinking, retrieval and encoding of new memory to be sent back to LTM takes place. The PFC of primates, believed to be the most developed part of a mammalian brain (Barbas, 1988; Jones & Powel, 1970; Kawamura & Naito, 1984; Nauta, 1972; Panda, Dye, & Butters, 1971; Panda & Selzer, 1982 cited in Nishijo, Ono & Yamatani 1990, p. 503) is highly activated during activities, in particular the cerebellum, putamen, caudate nucleus and the motor cortex where procedural information encoded and stored in LTM is retrieved. According to a study done in 1986 on non-human primates, the ventral putamen showed neuron responses to task-dependant activities and the number of PFL neuron responses increased as the learning of tasks progresses (Nishijo, Ono, Nakamura, Kawabata, & Yamatani, 1986; Nishijo, Ono, Namakura, Tamura & Muramoto, 1987; Kubota & Funahashi, 1982; Kubota & Komatsu, 1985 cited in Yamatani, Nishijo & Ono 1990, p. 528). Various other lesion studies suggest PFC neurons involvement in volition or attention, reward-related functions, orientation, and movement initiation or suppression (see reviews by Rosenkilde, 1983 cited in Yamatani, Nishijo & Ono, 1990).

Literature in neuroscience have also shown that intense activities cause the neurons to fire more frequently making the experiences more intense thus increases the likelihood for the event to be encoded as a memory in the LTM (see chapter 2 for details). These neurons 'communicate' with each other through the synapses and whenever something is learnt, neural networks are created, altered or strengthened (Mastin, 2010). Hebb's postulate in 1973, which influences a lot of the modern day studies in neuroscience, stated:

« When an axon of cell A… excite [s] cell B and repeatedly or persistently takes part in firing it, some growth processes or metabolic change takes place in one or both cells so that A's efficiency as one of the cells firing B is increased' (ibid).

This process involves the creation of new proteins within the body of the neutrons. The creation of new protein in the neutrons strengthens the electrochemical transfer of neurotransmitters across synapse gaps to receptors and also reinforces the communication strengths of certain circuits of neutrons in the brain. With repeated use, the efficacy of a synapse can change as a result of experience, providing both memory and learning. For example, an enduring (>1 hour) increase in synaptic efficacy that results from high frequency stimulation of an afferent (input) pathway (Mastin, 2010).

There has been very little or no prior research study into the cognitive processes and its alignment with the design process in fablabs. Prior researches which are somewhat close to this research include the mobile ICT documentation of problem-solving activities. The term documentation has been used to describe both the end-product and the process itself (Hrastinski & Lindell, 2016; Williams, Iglesias & Barak, 2008). Hargrove (Hargrove, 2013) cited in Hrastinski & Lindell (Hrastinski & Lindell, 2016) claimed that students put much more work into the documentation of their products than the documentation of their processes. Students have fixed representations of the end-product thus the explanation of the processes they took to arrive at the product is flawed. Several researches, for example the Israeli research by Williams, Iglesias & Barak (William, Iglesias & Barak, 2008); the British research project e-scape (Kimbell, 2012) and the Swedish research (Hartell & Skogh, 2015) confirmed Hargrove's statements. Two reasons given were that

1 students feel that documentation of their end-products should be at its best and
2 ii) technology teachers do not see documentation as a means for learning and reflection
(Hrastinski & Lindell, 2016).

This research therefore plans to take a different stance to bring to light these important cognitive processes, which, will be discussed in subsequent chapters.

This research will investigate these activities in the university-based fablab to identify the different cognitive processes that are involved. The product of this research will therefore lend a support for fablabs (whether university-based or community-based) to be viewed as 'not just a place to meet and create things' but a critical place where high-order cognitive processes take place thus offers a suitable platform to be used in educational settings for learning, innovations, and enhancing collaboration skills.

2. The capacity of fablabs established in educational settings as potential support platforms to 'incubate proactive minds' for the future design and production industries are often overlooked or undermined.

The establishment of fablabs in universities need not be ‘just spaces for students to carry out design courses’, but they can serve as ‘support platforms’ to equip citizens with the 21st century skills and also incubate proactive minds for the future design and production industries. Several authors have argued that students in the 21st century need to look beyond the core subjects in schools. They need to know how to use their knowledge and skills by applying different thinking processes, applying knowledge to new situations, analysing information, comprehending new ideas, communicating, collaborating, solving problems and making decisions. These thinking processes are not new (Rotherham & Willingham, 2010). Design processes in places like the fablabs involve these thinking processes, which, have often been either overlooked or undermined. Aided by modern technology (Gershenfeld, 2005) the fablab platform can be one of a promising platform to equip citizens with the 21st century skills. Blikstein (Blikstein, in Walter-Herrman 2013) listed three advantages of integrating fablabs into schools being that fab labs

1 enhance existing practices and expertise
2 accelerate invention and design cycles and
3 enhance long-term projects and deep collaboration

Posch (Posch, 2013 cited in Walter-Herrman 2013, p. 66) supported Blikstein’s claim by stating that fablabs play an important role in science and engineering education as they ‘*seem to be ‘very promising for hands-on learning approaches in STEM-related disciplines as well as for design and artistically motivated creations’.* These claims warrant a research as such as this one to help identify the capacities of the fablabs established in universities.

1.5 Aims and focus of this study

1.5.1 Focus of study

For the purpose of this research, the researcher will focus only on the fablabs being established in universities. The term University-based Fablabs or Ub-Fablabs for short, coined by the researcher, will be used throughout this thesis to distinguish it from industry or entrepreneurship oriented fablabs in communities.

1.5.2 Aims of study

This research is divided into two parts, part one and part two. The main principal aim of part one is

1 To investigate and align cognitive processes with the design process in an Ub-Fablab.

The key questions that guide part one of the research are:

1 What are the types of cognitive processes embedded in the design process in Ub-Fablabs?

The principal aim of part two is

2 To critically assess the capacity of Ub-Fablabs to prepare citizens for the future design and production industries

The key question that guide part two of the research is:

How efficient are Ub-Fablabs in contributing to 'incubating proactive minds' for the future design and production industries?

1.6 Organization of the thesis

This thesis consists of six chapters. Chapter 1 gives a brief background of fablabs in general and stated the problems, focus and aims of this research.

Chapter 2 specifically deals with a review of relevant literature on concepts related to this research and previous research done by other researchers on fablabs. This wealth of information led to the development of a conceptual framework outlined in chapter 3.

Chapter 4 describes the research methods and techniques used in this research and why they are preferred over the others.

Chapter 5 presents the results and analysis of data drawn from secondary and primary sources of data collected.

To conclude, Chapter 6 summarizes the findings of the study, draws an alignment between the cognitive processes (cognitive, psychomotor and affective) with the NDPM. Limitations of this study and recommendations for future researches are also stated in chapter 6.

1.7 Summary of chapter One

The fablabs, initially targeted for local entrepreneurships in local communities, have entered the educational arena and are used as a platform for learning and innovations. There is, however, a gap in research into its capacities to tease out cognitive processes and its capacity to be used as a support platform to promote the so-called 21st Century Skills and to incubate proactive minds for the future design and production industries. Therefore, the first aim of this research is to investigate and bring to surface the cognitive processes involved during the design process and to align them with Bloom's revised Taxonomy. The second aim is to investigate the capacities of Ub-Fablabs to incubate proactive minds for the future design and production industries.

The next chapter (Chapter 2) is the literature review of the main concepts that hold this research in place.

Chapter 2

2 Literature Review

2.1 Background

In the previous chapter, chapter1, the background and rationale of this research, the statement of the problem, the aims and the research questions that guide this research were discussed. In the discussions, the researcher highlighted a gap in research into the cognitive processes that occur during the design process in the fablabs and also the need for research into the capacities of Ub-Fablabs in equipping citizens with the so-called 21st century skills and incubating minds for the future design and production industries. The two key research questions formulated in chapter one that will guide this research to help fill the gap are

1 What are the cognitive processes embedded in the design process in Ub-Fablab?
2 How efficient are fablabs in 'incubating proactive minds' for the future design and production industries?

This chapter, chapter two, therefore contains literature review on the principal concepts pertaining this research. To start paving a pathway to adequately find answers to the two research questions raised in chapter 1, this chapter and subsequent chapters are divided into Parts 1 and 2.

Part 1 of this chapter discusses these principal concepts to be investigated in question one of the research: **cognitive processes** (the concept of cognitive, psychomotor and affective domains, cognitive and procedural knowledge, and thinking processes in problem solving activities); the brain (how information is processed and retrieved and how those processes are important in learning in Ub-Fablabs); design process (definitions, iterative design processes).

Part 2 of this chapter goes on to discuss the current status of design and production industries and the gap that Ub-Fablabs can fill. The main principal concepts are: 21st century skills, emerging new technologies and aspects of sustainable learning that Ub-Fablabs can promote needed to incubate proactive minds for the future design and production industries. Concepts of sustainability (inclusive of eco-design and circular economy concepts) are discussed.

However, before we define and discuss the main concepts that guide this research, it is important that one takes a historic tour back in time to see what triggered the spurs of fablabs and other DIY spaces. The rise of fablabs and other DIY spaces did not happen in isolation. Evolving technology and educational philosophies have brewed such spurs of maker movements this century. With the impact of technology on the society, researches in the last decade has showed how new social practices evolved due to increased use of new digital technologies, especially among young people (Binkley, Erstad, Herman, Raizen, Ripley, Miller-Ricci, & Rumble, 2012). This thus requires educators to rethink key skills needed to equip citizens to face these challenges. The challenges brought about by the digital technologies thus warrants research as such. In the beginning of parts one and two, the researcher starts off by making a link between fablabs and i) education and ii) industries.

Part One

2.2 The relationship between Fablabs and Education

Creating and making things have been a part of life throughout history, but has often been regarded as an 'art' thus the capacity to generate knowledge and learning during the act of creating and making has not been given much attention. A tour back in the history of pedagogy could shed some light on the reasons why this important part of learning has not been given much attention in the past.

2.2.1 The pedagogical trend: From Traditional way of learning to learning by 'doing and constructing' aided by Technology

Radical pedagogic reformists and educational philosophical movements started in around the 17th century, a period referred to as the 'Age of Enlightenment'. That period saw enlightenment thinkers like John Locke who was well known for his postulation about the brain as a 'tabula rasa', which, was later challenged by Rousseau and Freire. It was, however, a postulate that has sent educationists and philosophers rethinking pedagogy. One of the major events that spur his postulation was the rendition of the human brain (Figure 2.1) by Leonardo da Vinci (1452-1519) (Martinez & Stager, 2013).

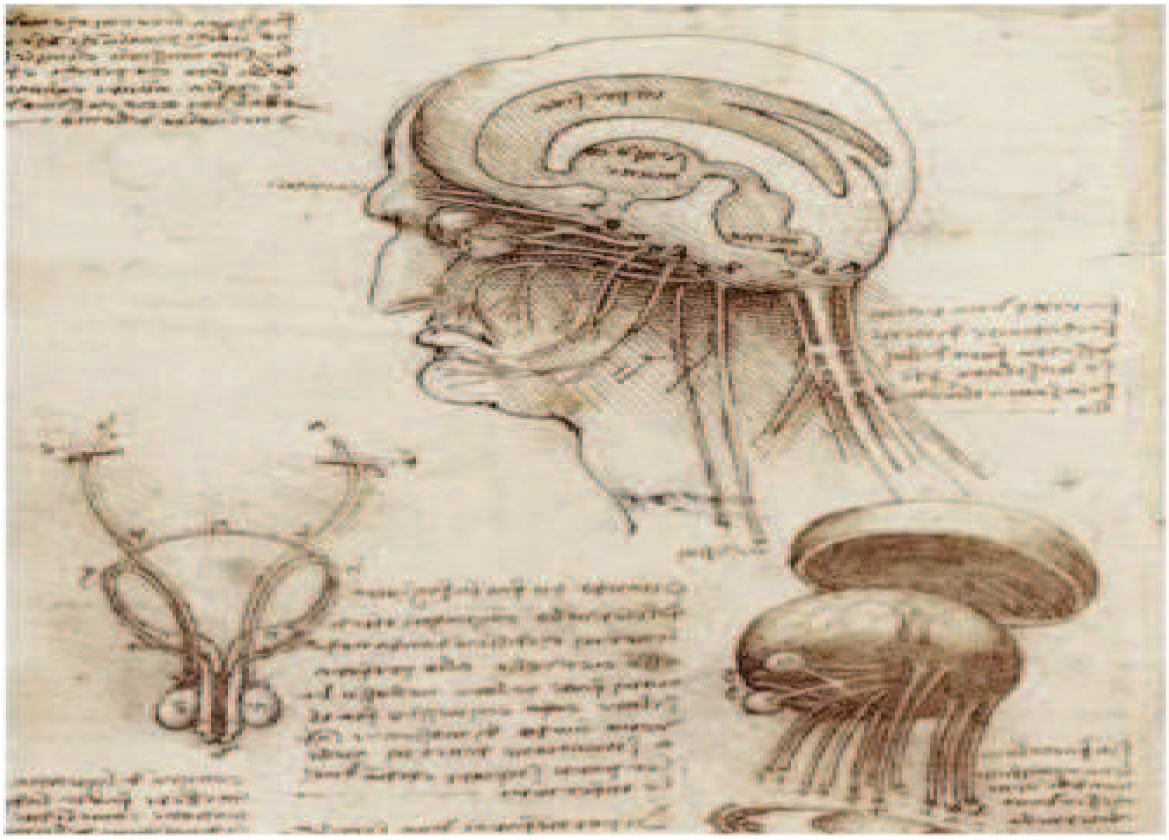


Figure 2.1 Leonardo da Vinci's rendition of the human brain, 1508. *Source:* http://www.drawingsofleonardo.org

What is the significance of this rendition? In ancient Egypt and Greek (around 3000BC) and even in Europe before the turn of the 17th century, the heart, not the brain, was thought to be the '*seat of the mind and the center of intellectual activity'* (Adelman, 1987) and thus was thought of as the most important organ of the body. This was reflected in many rituals and ancient practices (e.g. mummification process in ancient Egypt involved the total removal of the brain while the heart preserved). Aristotle, the great Greek philosopher, even thought that the brain was the cooling mechanism of the blood. He once stated that humans were more rational than other animals because they had a larger brain to cool their hot-bloodedness (Bear et al, 2001). These theories undoubtedly gave rise to such varying colloquial like 'memorizing something by heart' or 'learning by heart' or 'to know by heart' which were reflected in classroom pedagogy of that time.

Pythagorean Alcmaeon of Croton was thought to be the first to consider that it was the brain to be the '*seat of the mind and the center of intellectual activity'* and contains the governing faculty. He believed that, '*all the senses are connected in some way with the brain; consequently, they are incapable of action if the brain is disturbed…the power of the brain to synthesize sensations makes it also the seat of thought: the storing up of perceptions gives memory and belief and when these are stabilized you get knowledge* (Adelman, 1987 p. 843). These views were supported by other important figures in clinical medical science like Galen (129-199); Alhazen (965-1039); Nicholas Copernicus; Andreas Vesalius; Rene Descartes (1596-1650); Thomas Willis (1621-1675), to name a few (Adelman, 1987).

Leonardo da Vinci's rendition of the brain triggered people like John Loche to rethink how people learn. This challenged him to make this educational call to encourage deeper self-regulation of metacognition and learning in 1693. He suggested that a key to good teaching is to help students reflect more about their thinking processes. By articulating their own mental steps in solving a problem, the students would become better thinkers. This reflective process is a modern cornerstone of critical thinking in which certain habits of the mind help students rehearse such reflective processes are basics of modern quality education (Mercola, 2015).

Among the many philosophers, psychologists and educationists of this 18^{th} and 19^{th} century, these are some of the outstanding ones who have contributed to the idea of 'learning by doing or making', a hallmark of the approach to learning in a fablab. Their works are briefly summarised in the following paragraphs.

Maria Montessori, an Italian, in 1897 used an educational approach where she referred to as a 'scientific pedagogy' based on a human development model. Her model has two basic principles i) children and developing adults engage in psychological self-construction by means of interaction with their environments; ii) children, especially under the age of six, have an innate path of psychological development. *Play materials* were central to *materialising* her philosophy of learning and that they be designed in a way that can stimulate nature and to challenge the child to challenge his/her own intellectual development (Montessori, 2001, pp. 112-113 cited in Schelhowe, 2013 pp. 94-95).

While Montessori was busy with advocating her theories, the Swiss pedagogue Johann Heinrich Pestalozzi, building on from his earlier work with Jean-Jacques Rousseau, worked on the idea of ‘self-determined learning’ (to be able to do oneself). He proposed that learning materials are supposed to support learning with the brain, heart and hand, concept building and activity (Pestalozzi 1927-1996) cited in (Schelhowe in Walter-Herrman 2013, p. 94).

Around about the same time in Germany, the educationist Friedrich Wilhelm August Fröbel in a school that run along Pestalozzian lines, made that significant contribution by coining the term ‘Kindergarten’ literally meaning ‘children’s garden’. His emphasis is on play and its use of ‘gifts’ (play materials) and ‘occupations’ (activities). He believed that through play, the inner reality is presented (Schelhowe, 2013).

Although these philosophers (Montesorri, Dewey, Pestalozzi, Froebel, and Freire) were researching independently, their theories all point to one common idea that a child constructs knowledge by him/herself through physically manipulating his/her environment. They also stress that the body and mind play an important role in the construction of knowledge. In Dewey’s words: ‘*The question of the integration of mind-body in action is the most practical of all questions we can ask of our civilisation’* (Dewey 1984, p.29, cited in Schelhowe in Walter-Herrman, 2013, p. 95).

The ideas of John Dewey, Montessori, Froebel and Pestalozzi were magnified, formalized and confirmed (Martinez & Stager 2013) by the Constructivism Theory of the Swiss cognitive psychologist and epistemologist, Jean Piaget (1896-1952). This theory is also the ‘spring board’ for Papert’s Constructionism Theory.

Philip (Philip, 1995 cited in Bhattachrya & Han, 2001) defined constructivism as the knowledge created by people influenced by their values and culture. This knowledge is constructed based also on their intellectual development as one experiences reality during social and physical activities. Martinez and Stager (Martinez & Stager, 2013) further elaborated that the *'knowledge does not result from receipt of information transmitted by someone else without the learner undergoing an internal process of sense making'* (p.13).

Students learn when they construct this knowledge. Learning is simply the process of adjusting our mental processes to accommodate new experiences and this is done through a process called adaptation which is the ability to adjust one's environment (The theories of Piaget, 2011). The four main concepts postulated by Jean Piaget that drive this construction of knowledge are Assimilation, Accommodation, Equilibration and Schemas. Assimilation and accommodation are both part of the adaptation process. Piaget believed that human beings possess mental structures that assimilate external events and convert them to fit their mental structures. These mental structures accommodate themselves to new, unusual and constantly changing aspects of the external environment. In order to organize and accommodate this assimilated information from the environment, a state of equilibrium between the external world and the internal mental structures, called the Schema or Schemes has to be achieved. To achieve this, students have to interpret, make alterations or change their belief systems (Bhattacharya & Han, 2001, p.1). These four processes (explained in this chapter and applied to NDPM in chapter 3) are important in this research as they will be used to explain the processes that take place while makers are busy making things in fablabs.

The social view of constructivism by Lev Vygotsky reinforces Dewey's ideas by saying that knowledge is constructed through social and cultural contexts during physical and social activities. Vygotsky called this process *Internalization* process. For example, for an individual to learn how to build a house, this learning could be achieved through participation in the activity of building a house within a society. Another term associated with internalization process is *appropriation*. (Vygostky, 1978). This is applied where a person uses the tools used and skills learnt in a way unique to himself/herself. For example, internalizing the use of a tape measure (a tool he/she uses and skills learnt from building the house) could be applied to measure other things. In order for internalization process to be achieved, two main principles (Zone of Proximal Development (ZPD) & More Knowledgeable Others, (MKO) play important roles here. These two principles are also relevant to the learning in a fablab.

Paulo Reglus Neves Freire, a Brazilian educator and philosopher and a leading advocator for critical pedagogy and best known for his influential work, the ‘Pedagogy of the Oppressed’ considered to be one of the critical foundation text of the critical pedagogy movement He proposed a pedagogy with a new relationship between the teacher, the student and the society. He likened the traditional pedagogy to a ‘*banking model’* in which a student was viewed as a ‘tabula rasa’ (a concept that was previously criticised by Rousseau) to be filled by the teacher (Darder, 2002)

Papert’s present day proposed Constructionist approach to learning evident in fablabs shared Piagert’s constructivism’s connotation of learning as building structures irrespective of the circumstances of the learning (Papert 1991). Constructionism, a theory developed by Seymour Papert of MIT based on Piaget’s Constructivism theory. Papert, having worked with Piaget in Geneva in the 1950’s and early 1960’s (Akermann n.d.) had this to distinguish the two theories:

Constructionism—the N word as opposed to the V word— shares constructivism’s view of learning as “building knowledge structures” through progressive internalization of actions… It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it’s a sand castle on the beach or a theory of the universe (Papert, 1991 cited in Ackermann, n.d, p. 4)

Ackerman (Ackerman, n.d.) went on to state that Papert’s approach is focused on learning through making rather than cognitive potentials. Constructionism approach helps, ‘…*understand how ideas are formed and transformed when expressed through different media, when actualized in particular contexts, when worked out by individual minds. The emphasis shifts from universals to individual learners’ conversation with* *their own favourite representations, artefacts, or objects-to-think with. To Papert, projecting out our inner feelings and ideas is a key to learning* (p.4).

Papert, like the previous pedagogical reformers believes that '*learning results from experience and that understanding is constructed inside the head of a student, often in a social context*' (Martinez & Stager 2013, p. 72) and defined Constructionist as:

Form constructivist theories of psychology we take a view of learning as a reconstruction rather than a transmission of knowledge. Then we extend the idea of manipulative materials to the idea of learning is most effective when part of an activity the learner experiences as constructing a meaningful product (Papert, 1986 cited in Martinez & Stager, 2013, p. 32).

The dynamitic approach to constructing in a fablab aided by technology could therefore lend a strong standing for the fablab platform to be used to meet that critical need of today's society. Authoritative opinions from by psychologists, scientists and philosophers like Piaget, Dewey, Montessori, Papert, Froebel, Pestalozzi and Freire, to name a few (Fig 2.2), over the years, as discussed in previous paragraphs, have also pointed towards a learning environment categorised by the learning environments offered by Fablabs.

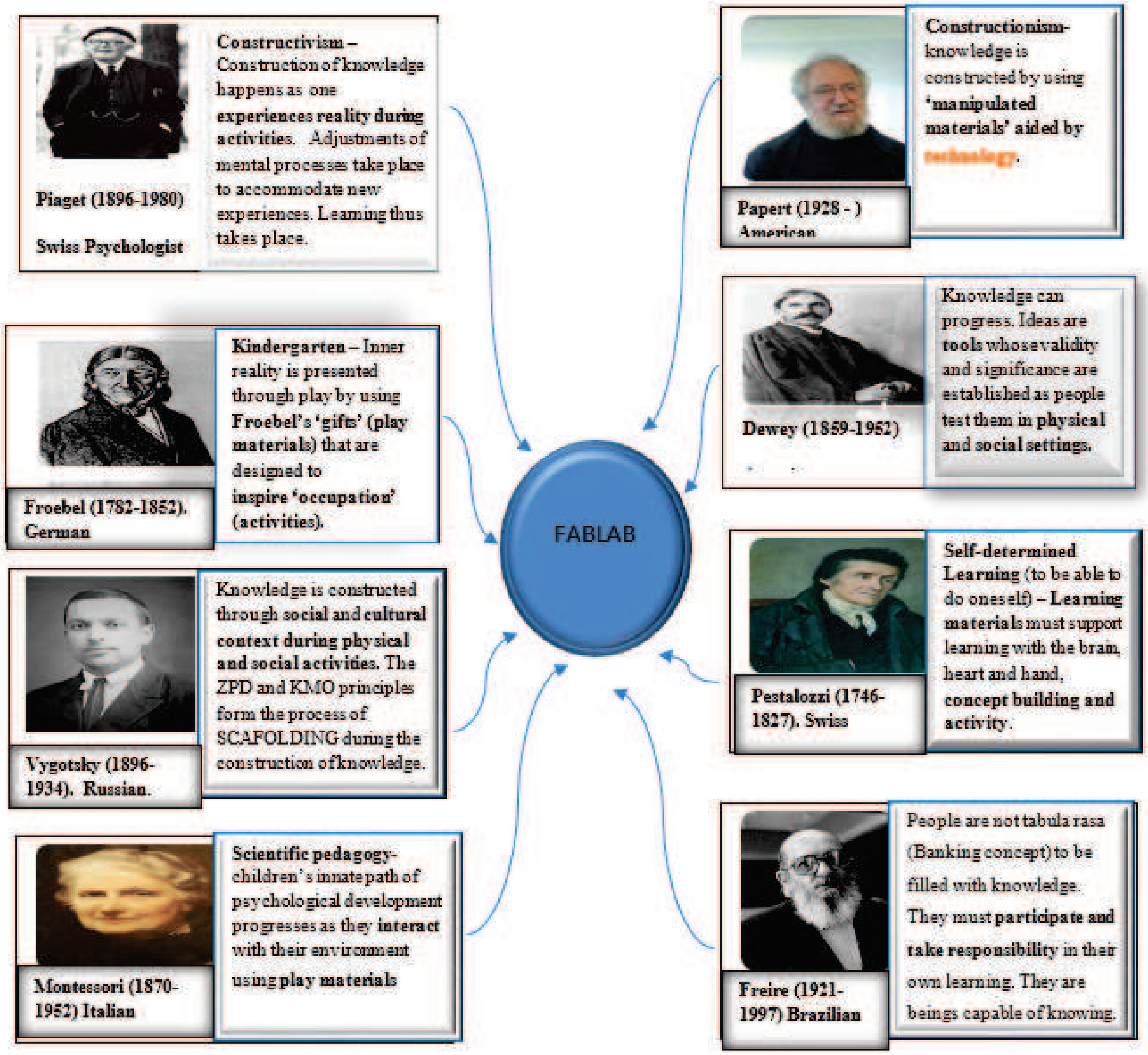


Figure 2.2 Eight of the Pedagogical Reformists. (Photo Credit: Individual biographies in Wikipedia)

2.3 The definition and concepts of Cognition, Knowledge and Cognitive processes in design.

Cognition refers to a set of mental abilities and processes related to knowledge. To sum up a single definition of knowledge would be a snapshot of the concept. Compton (Compton, 2014) agrees that the concept of knowledge being a "…*social construct, the epistemological basis of which is usually located in a pragmatic theory of truth whereby knowledge in any domain is validated by agreement within that domain"* (p.2). These are therefore some classifications of the concept of knowledge.

Anderson and Krathwohl (Anderson & Krathwohl, 2001 cited in Armstrong, n.d.) created a taxonomy of the different types of knowledge in cognition that can exist (Figure 2.3).

Factual Knowledge

- Knowledge of terminology
- Knowledge of specific details and elements

Conceptual Knowledge

- Knowledge of classifications and categories
- Knowledge of principles and generalizations
- Knowledge of theories, models, and structures

Procedural Knowledge

- Knowledge of subject-specific skills and algorithms
- Knowledge of subject-specific techniques and methods
- Knowledge of criteria for determining when to use appropriate procedures

Metacognitive Knowledge

- Strategic Knowledge
- Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge
- Self-knowledge

Figure 2.3 The Types of Knowledge (Compiled from source: https://cft.vanderbilt.edu/guides-sub-pages/blooms-taxonomy/)

The conceptual knowledge (*knowing that* knowledge) and Procedural knowledge (k*nowing how* knowledge) used in technological fields are often termed as 'technological' conceptual knowledge or technological procedural knowledge. Although there is a distinction between them, the two cannot be separated (McCormick, 1997; Ankiewicz, 2013 cited in Engelbrecht, 2016). Technological procedural knowledge differs from technological conceptual knowledge in that it is tacit and embedded in the subconscious (Compton, 2014) sections of the brain thus it *cannot be taught but only gained through thorough practice* (Ankiewicz, 2013 cited in Engelbrecht 2016, p.2).

According to Ankiewicz (Ankiewicz, 2015 cited in Engelbrech, 2016), technological procedural knowledge can be divided into two dimensions: i) a thinking ('minds-on') dimension and ii) an activity ('hands-on') dimension. The 'thinking ('minds-on') dimension' includes complex thinking like critical thinking, creative thinking, decision-making, problem solving and design. The relationship between these thinking processes can be summarised in the concept mapping of the ideas (Figure 2.4).

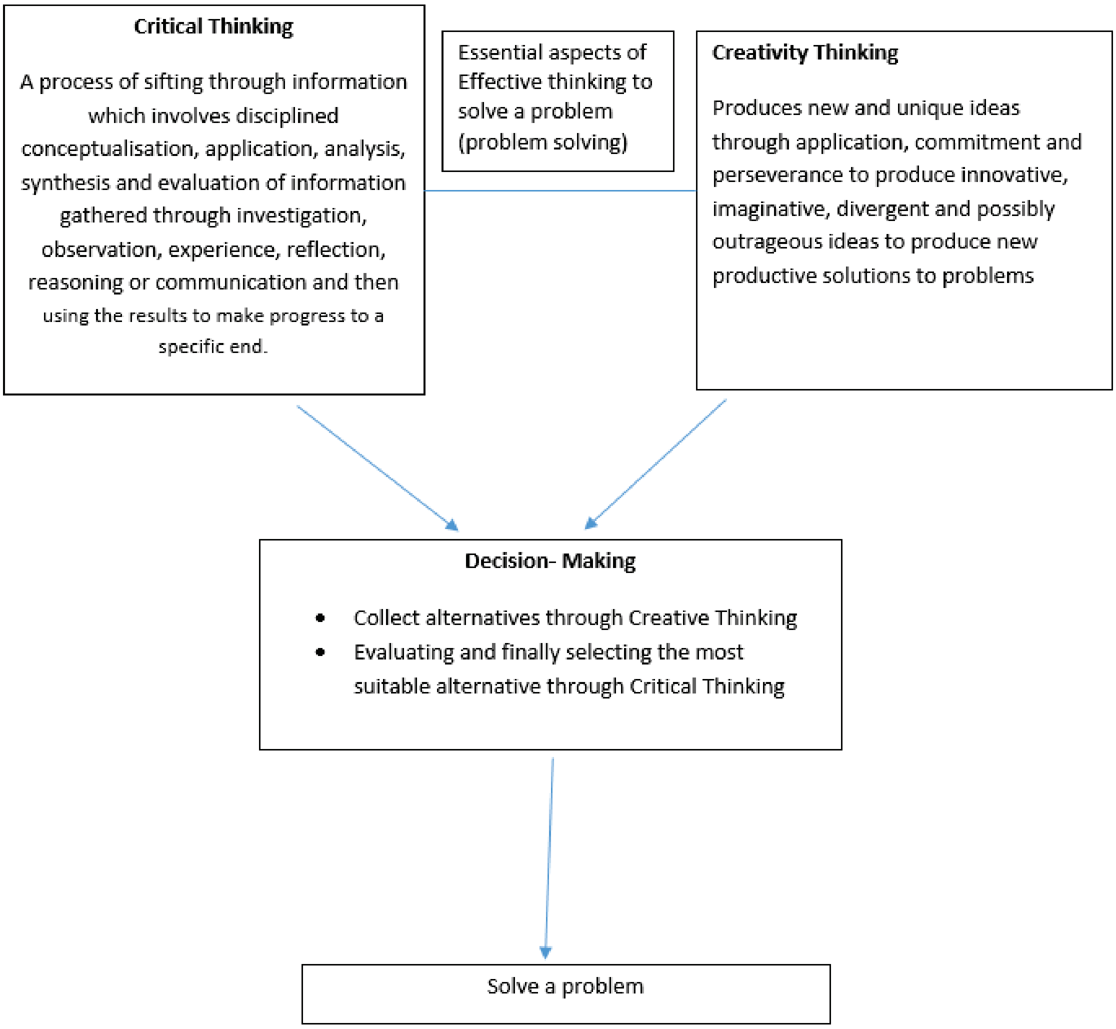


Figure 2.4: Thinking Processes to solve a problem (Source: Ankiewicz (2015) cited in Engelbrecht, 2016. Concepts mindmapped by the researcher).

Critical thinking and creativity thinking are central to design process in a fablab. These types of knowledge are classified under Bloom's Cognitive domain of learning and will be explored in this research study. With a perspective of tacit and explicit knowledge being at opposite ends of a continuum instead of being separate knowledge categories, several authors have tried to categorise these types of knowledge into sub-categories by shifting the notion of knowledge being the 'justified true belief 'to the notion of 'function' (see for example classification framework of Vincenti 1990; Ropohl

1997 and Vries 2002 in Compton, 2014). This research utilises Vries (Vries, 2002) sub-categories of

1 physical nature knowledge;
2 functional nature knowledge;
3 means ends knowledge and
4 action knowledge.

While technological processes classified the activity dimension ('hands-on') dimension as the procedural stages of the technological process (Ankiewicz 2013 cited in Engelbretcht, 2016), a number of procedural stages follow a linear fashion, where one stage is completed before the next one. The 'activity' dimension refers to Bloom's psychomotor domain of learning where students/fablab users physically apply their fine and gross motor skills to do or create things in the fablab.

An early research on design in general by Hall (Hall, 1962 cited in Eastman, 1968) identified the sequence of activities as '*problem identification, data gathering, analysis, synthesis, and evaluation'*. Other authors further divided the initial design activities into, '*determination of a need, identification of the relevant parameters and criteria, generation of initial concepts for plausible solutions, and preliminary evaluation of them in terms of physical realizability and financial feasibility* (Eastman 1968, p. 1). Eastman (Eastman, 1968) in his study therefore referred to design as an 'intuitive process' since, '*little is known about the sequence of activities that produce a creative design and since its procedures are implicit and self-taught'* (p.1). He went to argue that

Lacking for design education is knowledge about how basic design concepts are normally generated and how different activities are integrated to produce an original product. Before significant improvements in the intellectual powers of designers and in design methods are possible, its first seems necessary to determine what comprises self-taught and intuitive design processes (p.2).

These intuitive design processes are what this research aims to investigate. Being intuitive alone is a challenge for anyone doing research into these processes. This research therefore uses a classification of learning behaviours that is widely known as the Bloom's Taxonomy to assess Observable Learning Behaviour (OLB) that take place during design in a fablab.

2.3.1 Bloom's Taxonomy

In order to promote higher forms of thinking in education, In 1956, Dr Benjamin Bloom and his collaborators (Max Englehart, Edward Furst, Walter Hill and David Krathwohl) developed the first version of Bloom's Taxonomy' in 1956. This taxonomy has arisen from Bloom's initial research into OLB under the three domains of learning: Cognitive, Psychomotor and Affective. This research refers to the three domains of learning as CPA for short (see Figure 2.5) (Anderson & Krathwohl, 2001). Other terms that are used by other authors are Knowledge (for cognitive), Skills (for psychomotor) and Attitudes (for Affective). The CPA may be thought of as goals of the learning process. In this research the OLB associated with CPA will be closely observed and monitored to give answers to the research questions that this research intends to seek.

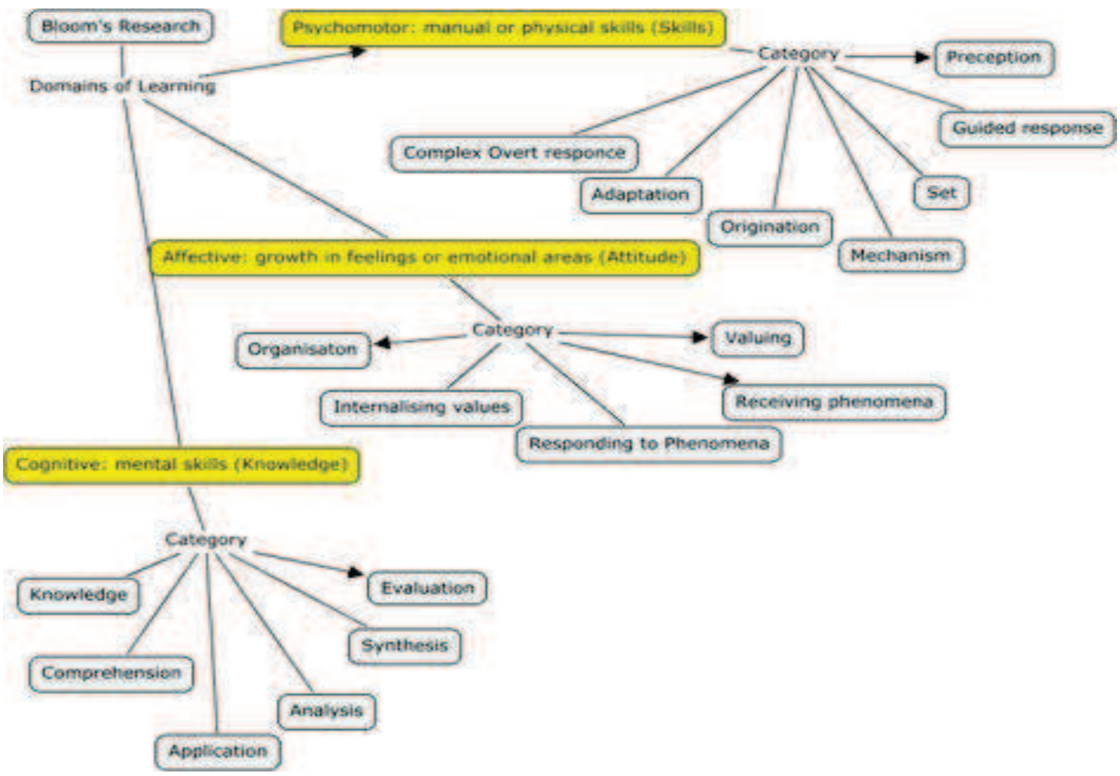


Figure 2.5: Bloom's Domains of Learning

[Source: http://edorigami.wikispaces.com/Bloom's+Digital+Taxonomy]

2.3.2 The Cognitive domain of learning

In 2001, a revised version of the Cognitive Learning domain of Bloom's Taxonomy was published by Anderson and Krathwohl and a group of cognitive psychologists, curriculum theorists and Instructional researchers and assessment specialists. The impact of digital technology on pedagogies has also been reflected in the development of a new Bloom's Taxonomy to include Digital technology. The 2001 version of Bloom's Taxonomy includes the Digital Taxonomy and Collaboration elements, which, are the 21st century essential skills in a fablab and elsewhere (Figure 2.6).

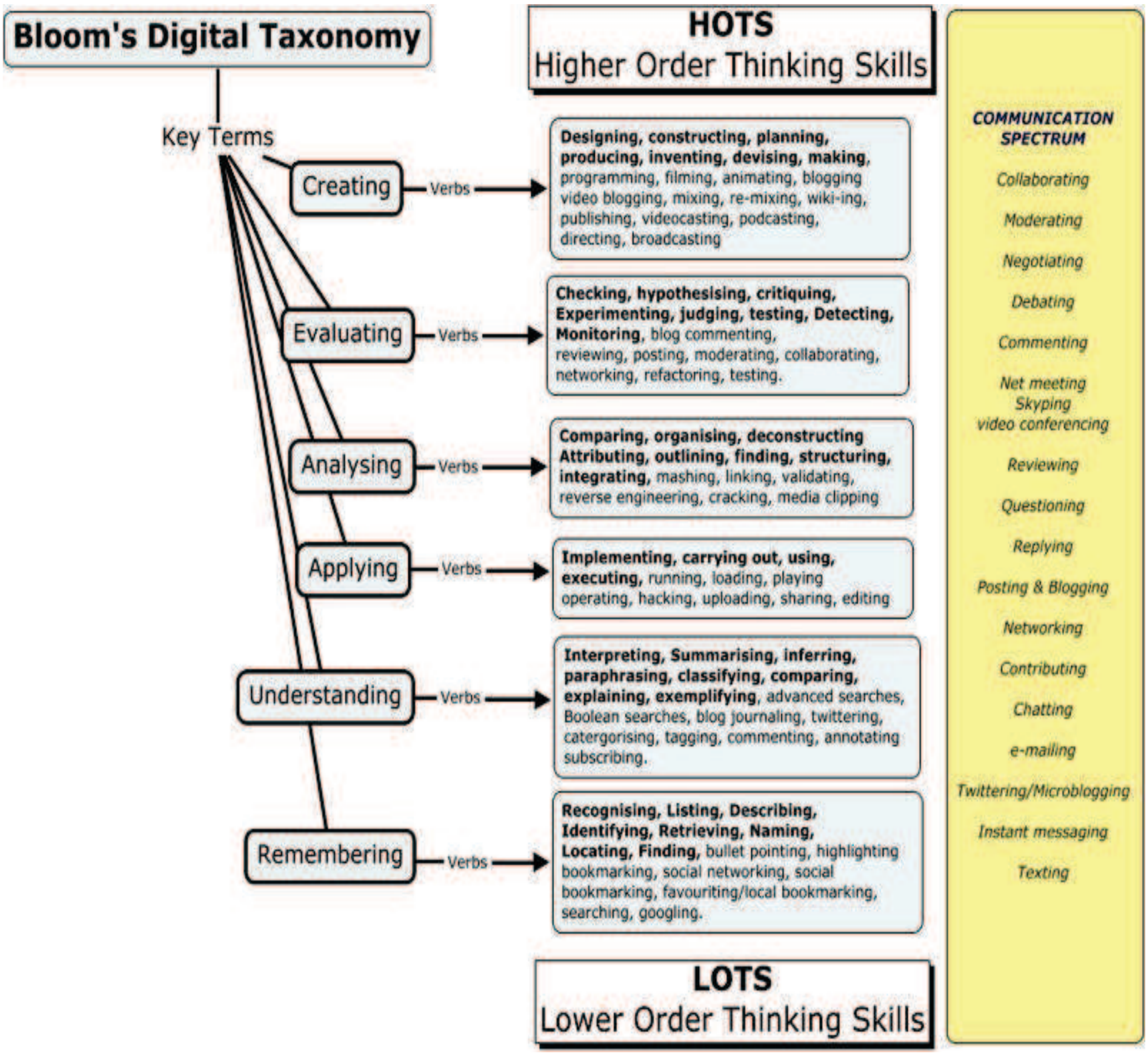


Figure 2.6 Bloom's Revised Taxonomy in 2001 by Anderson & Krathwohl; Bloom's Digital Taxonomy Concept map.

[Source: http: //edorigami.wikispaces.com/Bloom's+Digital+Taxonomy]

2.3.3 The Psychomotor domain of learning

Although a lot of work has been done on the cognitive domain of learning, the psychomotor and affective domains of learning remained untouched in the current educational context (McLain, 2016). Simpson (Simpson, 1972) quoted Bloom (Bloom, 1956:7-8 cited in McLain, 2016) as having found '…*so little done about [the psychomotor domain]*', and *'[did] not believe the development of a classification of these objectives would be very useful*. This research would be one of a few researches which will bring into life and apply the psychomotor and the affective domain of learning to design process in an Ub-Fablab.

A few development of studies into the psychomotor and affective domains of learning include the work of Simpson (Simpson, 1972) who expanded on Bloom's domain of psychomotor. Two other popular versions of the psychomotor and affective domains of learning are found in the work of Dave (Dave, 1970) and Harrow (Harrow, 1972). The Psychomotor Domain consists of seven major categories from most complex to the simplest OLB (see Table 2.1).

Table 2.1: Blooms' taxonomy of psychomotor skills (from complex to simplest OLB)

Blooms Levels of Psychomotor complex to simplest)	**Description (Simpson 1972)**	**Examples**	**Key Words**
Origination	*Creating new movement patterns to fit a particular situation or specific problem. Learning outcomes emphasize creativity based upon highly developed skills.*	***Examples**: Constructs a new theory. Develops a new and comprehensive training programming. Creates a new gymnastic routine*	***Key Words**: arranges, builds, combines, composes, constructs, creates, designs, initiate, makes, originates.*
Adaptation	*Skills are well developed and the individual can modify movement patterns to fit special requirements.*	***Examples**: Responds effectively to unexpected experiences. Modifies instruction to meet the needs of the learners. Perform a task with a machine that it was not originally intended to do (machine is not damaged and there is no danger in performing the new task).*	**Key Words**: adapts, alters, changes, rearranges, reorganizes, revises, and varies.

Complex Overt Response (Expert)	*The skilful performance of motor acts that involve complex movement patterns. Proficiency is indicated by a quick, accurate, and highly coordinated performance, requiring a minimum of energy. This category includes performing without hesitation, and automatic performance. For example, players are often utter sounds of satisfaction or expletives as soon as they hit a tennis ball or throw a football, because they can tell by the feel of the act what the result will produce.*	*Manoeuvres a car into a tight parallel parking spot. Operates a computer quickly and accurately. Displays competence while playing the piano.*	*Assembles, builds, calibrates, constructs, dismantles, displays, fastens, fixes, grinds, heats, manipulates, measures, mends, mixes, and organizes, sketches.* *NOTE: The Key Words are the same as Mechanism, but will have adverbs or adjectives that indicate that the performance is quicker, better, more accurate, etc.*
Mechanism (basic proficiency)	*This is the intermediate stage in learning a complex skill. Learned responses have become habitual and the movements can be performed with some confidence and proficiency.*	*Use a personal computer. Repair a leaking faucet. Drive a car.*	*Assembles, calibrates, constructs, dismantles, displays, fastens, fixes, grinds, heats, manipulates, measures, mends, mixes, and organizes, sketches.*
Guided Response	*The early stages in learning a complex skill that includes imitation and trial and error. Adequacy of performance is achieved by practicing.*	*Performs a mathematical equation as demonstrated. Follows instructions to build a model. Responds hand-signals of instructor while learning to operate a forklift.*	*copies, traces, follows, react, reproduce, responds*
Set	*Readiness to act. It includes mental, physical, and emotional sets. These three sets are dispositions that*	*Knows and acts upon a sequence of steps in a manufacturing process. Recognize one's abilities and limitations. Shows desire to learn a new*	*begins, displays, explains, moves, proceeds, reacts, shows, states, volunteers.*

	predetermine a person's response to different situations (sometimes called mind-sets).	*process (motivation). NOTE: This subdivision of Psychomotor is closely related with the "Responding to phenomena" subdivision of the Affective domain.*	
Perception (awareness):	*The ability to use sensory cues to guide motor activity. This ranges from sensory stimulation, through cue selection, to translation.*	*Detects non-verbal communication cues. Estimate where a ball will land after it is thrown and then moving to the correct location to catch the ball. Adjusts heat of stove to correct temperature by smell and taste of food. Adjusts the height of the forks on a forklift by comparing where the forks are in relation to the pallet.*	*chooses, describes, detects, differentiates, distinguishes, identifies, isolates, relates, selects.*

Source: Simpson (Simpson, 1972).

2.3.4 The Affective domain of learning

Table 2.2: Bloom's taxonomy of Affective Domain (from simplest to complex)

Category of Affective behaviour
Internalising Values: *the ability to internalize values and let them control the person`s behaviour.* *Example: A man marries a woman not for her looks but for what she is.*
Organizing Values: ability to prioritize a value over another and create a unique value system. *Example: A teenager spends more time in her studies than with her boyfriend.*
Valuing: the ability to see the worth of something and express it. *Example: An activist shares his ideas on the increase in salary of labourers.*
Responding to Phenomena: active participation of the learner. *Example: Participating in a group discussion.*
Receiving Phenomena: the awareness of feelings and emotions as well as the ability to utilize selected attention. *Example: Listening attentively to a friend.*

Source: https://explorable.com/domains-of-learning

2.4 The relationship between the brain and the cognitive processes

2.4.1 The function of the brain

Let us not forget that the brain is involved in all the cognitive processes discussed above. The principal areas of the brain that is involved in eliciting cognitive processes involved in learning, which this research will be referring to, are mainly the processes involved in the Frontal lobe, Parietal lobe, Temporal lobe and the Cerebellum (Figure 2.7).

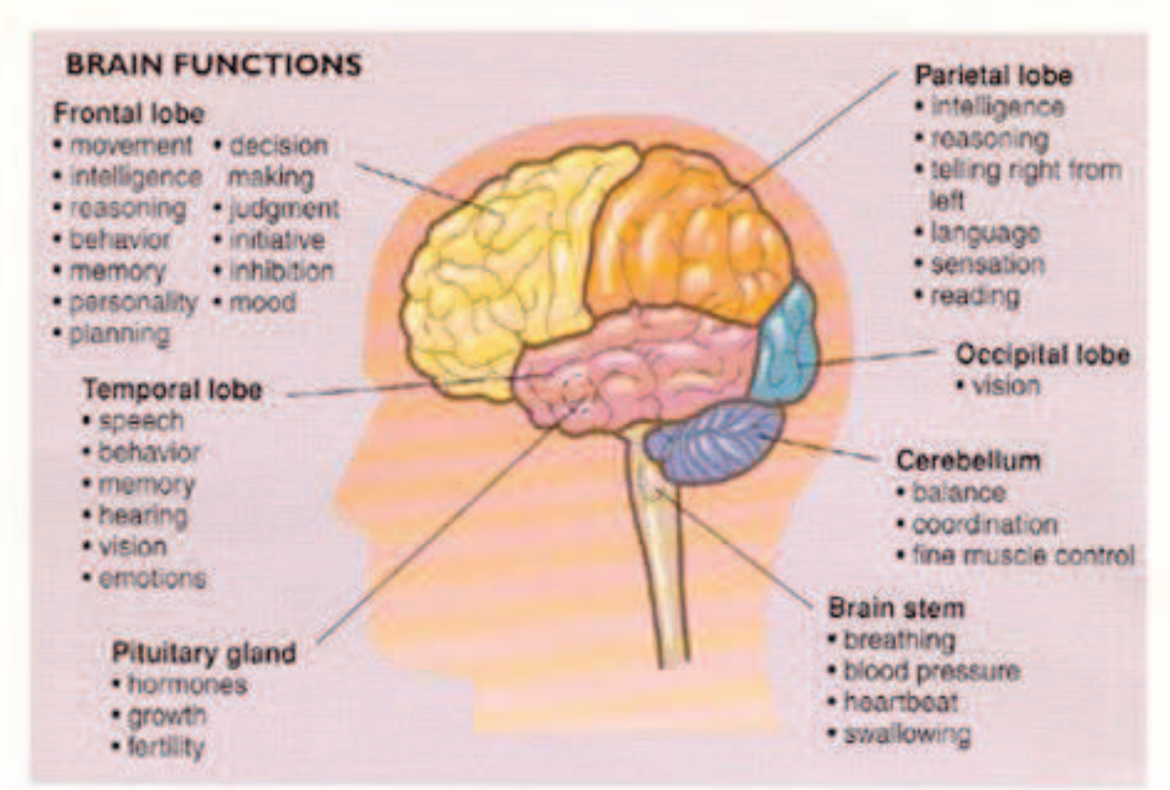


Figure 2.7 The principal areas of the brain that is involved in eliciting Cognitive processes involved in Learning [Source: http://easytimegallery.com/b/brain-parts-and-functions.html]

How information is ***acquired*** by the brain, how this stored information in the brain (in the Long Term Memory, LTM) is ***retrieved*** for use and the reconstruction in the sketchpad of the Short Term Memory (STM) of Working Memory (WM) before ***consolidating*** and ***storing*** it in the LTM for future use is very important if one is to learn to master a skill from activities like those of the fablabs.

Long (Long, n.d. cited in Boettcher, 2008) referred to the acquisition, storage and retrieval of information as **Memory.** There are many definitions and questions about memory and ongoing studies about how the memory contributes to learning. A useful definition of memory is '…*allowing temporally independent recall of various information inputs'* (Eastman, 1968, p.3). The storage and retrieval of information in the brain has been a subject of interest for psychologists, neuroscientists and research for thousands of years. The most widely accepted theory of Memory is the 'Stage Theory' by Atkinson & Shriffin (Atkinson & Shriffin, 1968). The model proposed that information is processed and stored in 3 stages (Figure 2.8) and is processed in a serial, discontinuous manner as it moves from one stage to another. Three other theories that exist are Craik & Lockhart's 'levels-of-processing' (Craik & Lockhart, 1972 cited in Boettcher, 2008) and Rumelhart & McClelland's parallel-distributed processing and connectionist (Rumelhart & McClelland, 1986 cited in Boettcher, 2008).

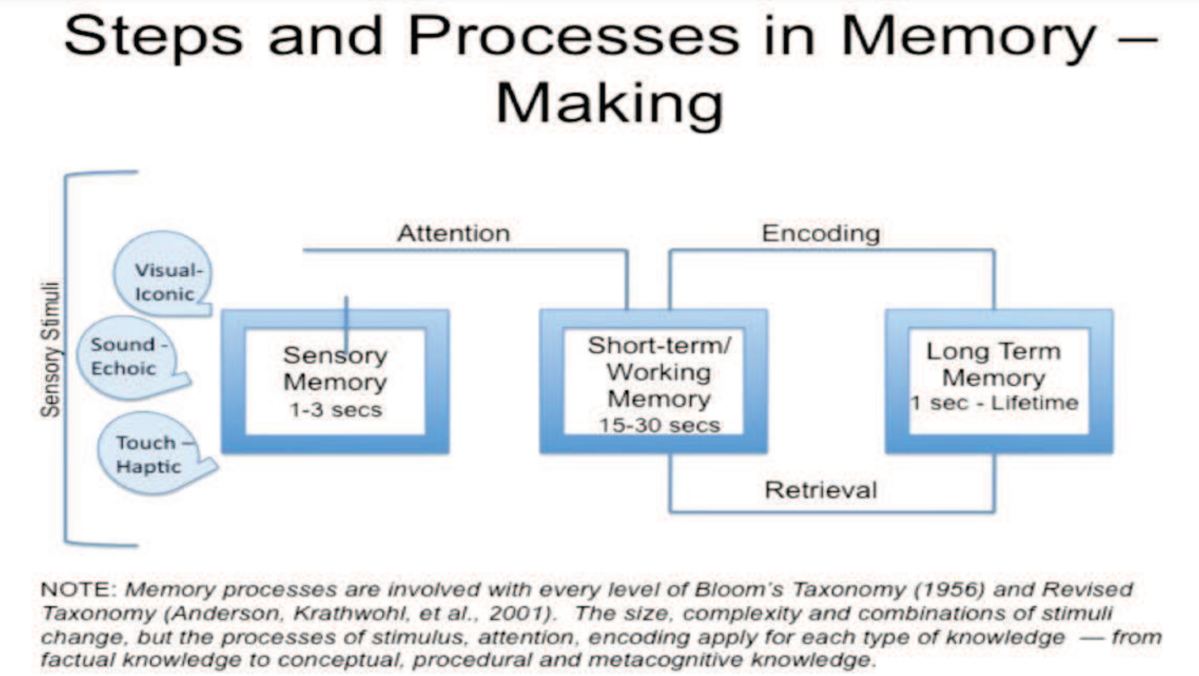


Figure 2.8: Boettcher's Steps and processes in memory making

2.4.2 The Sensory Memory and the Stimulus Input

Acquisition of Knowledge, whether it be declarative or procedural knowledge, it always starts with a stimulus which results in sensory registration or memory. Attention is required to move the sensory data into short term memory for further processing. The sensory memory is the shortest-term element of memory from the original stimuli lasting for 200-500 milliseconds (1/5-1/2 seconds). It can also act as a buffer for the stimuli received by the senses. The stimuli detected can either be ignored or perceived and stored in the sensory memory to be further processed by the brain if useful information. The sensory memory for images is sometimes known as the iconic memory, the memory for aural stimuli is known as the echoic memory and that of touch as the haptic memory (Boettcher, 2008).

Philosopher Immanuel Kant proposed in the 1760's that our knowledge of the outside world depends on our modes of perception. This proposal still holds today, some centuries later (ibid). Cherry (n.d, p. 1) defined Perception as:

…. our sensory experience of the world around us and involves both the recognition of environmental stimuli and actions in response to these stimuli. Through the perceptual process, we gain information about properties and elements of the environment that are critical to our survival. Perception not only creates our experience of the world around us; it allows us to act within our environment.

Responding to external stimuli depend very much on how the brain perceives the information that is passed on to it. It also involves the cognitive processes required to process information, such as recognizing the face of a friend or detecting a familiar scent.

One of the first processes in creating a new memory is called Encoding. Encoding in psychology is the process of getting information into the memory system for storage and later retrieval. This process of encoding begins with attention regulated by the thalamus and the frontal lobe. In this area of the brain, where a memorable event occurs, it causes the neurons to fire more frequently, making the experience more intense and increases the likelihood for the event to be encoded as a memory. The four types of encoding are:

1 Acoustic encoding: encoding of sounds, words and other auditory input aided by the phonological loop, which allows input in the echoic memory to be sub-vocally rehearsed in order to facilitate remembering

2 Visual Encoding: encoding of images and visual sensory information, temporary stored in the iconic memory in the short term memory before encoded for long term memory. This takes place in the amygdala (within the medial temporal lobe of the brain)
3 Tactile Encoding: encoding of how something feels, normally through the sense of touch. Neurons in the somatosensory cortex react to the vibrotactile stimuli caused by the feel of an object
4 Semantic Encoding: Process of encoding sensory input that has particular meaning or can be applied to a particular context
(Mastin, 2010)

2.4.3 The Working Memory (WM)

At a quick glance at the Figures 2.16 & 2.17, the Short-term memory (STM) could be narrowly viewed as a merely a storing component. Well the STM is not that simple. Mastin (Mastin, 2010) described the STM as a 'sketch-pad' for temporary recall of information. It can be thought of as having the ability to remember and process information at the same time. It only holds a small amount of information, (typically around 7 items or even less) in mind in an active, **readily available** state for a short period of time (typically from 10 to 15 seconds or sometimes up to 1 minute) (ibid). The limited capacity of the STM also protects itself from acquiring too much irrelevant information, which would otherwise impede learning.

What then is the Working Memory? Although STM is used interchangeably with WM, several writers have indicated some distinctions between the two terms. For example, Mastin (Mastin, 2010) refers to WM as *'a whole lot more of the theoretical framework of structures and processes used for the temporary storage and manipulation of information'* (p. 1) stored in the STM, in other words, STM is a component of the WM. Atchinson and Shiffrin (Atchinson & Shiffrin, 1968), on the other hand, labelled the STM as the WM since it contains control processes such as rehearsal, coding, decisions and retrieval strategies which are optional-not automatic. Holyoake (Holyoake, 2008) further defines WM as the '*capability we have allowing us to co-ordinate mental operations with temporary stored information during cognition* (p.1). Working memory therefore goes beyond the concept of a short term store and includes the ability to perform mental operations-classic example being a complex arithmetic operations.

Like Atchinson and Shiffrin (Atchinson & Shiffrin, 1968), Baddeley & Hitch (Baddeley & Hitch, 1974) labelled the STM as the WM. They argued that the Multi-Store Model depicting the STM as a unitary system where it only holds limited amount of information in short periods of time with very relatively little processing is not a true representation of the amount of processing that is done in the STM. In 1974, Braddeley & Hitch had come up with a model outlining the other components of the STM: the Central Executive, the Visuo-Spatial Sketchpad (VSS) and the Phonological Loop (PL). This model is later updated in 2000 to include the Episodic Buffer (Figure 2.9).

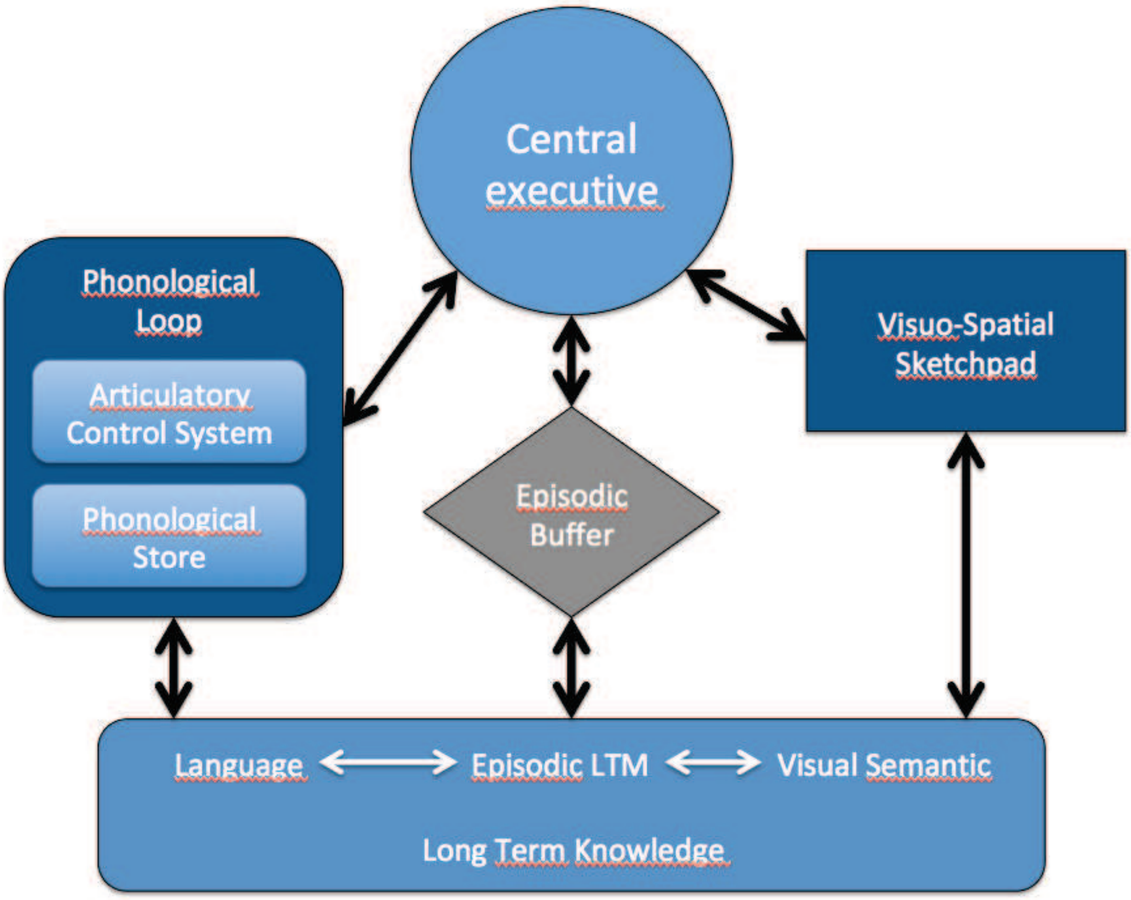


Figure 2.9 Baddeley (Baddeley, 2000) Model of the Working Memory

[Source: http://alevelpsychology.co.uk/?q=working-memory-baddeley-hitch-1974]

The Function of the Central Executive includes

1 monitoring and coordinating the operation of the VSS and the PL;
2 deciding on which information the WM should pay attention to and which should be sent to the Long-Term Memory (LTM);
3 allocating data to the VSS and PL
4 dealing with cognitive tasks as mental arithmetic and problem-solving.

The VSS (inner eye) stores and process information in a visual or spatial form. Visual information refers to what things look like. Baddeley (Baddeley, 2000) believes that it is the VSS that plays the important role in helping us navigate through our environment. The VSS also displays and manipulates visual and spatial information stored in the LTM. He used the illustration of giving information about the number of windows you have at the front of your house. You would yourself picturing the front of your house and counting the windows. What has actually happened was that an image of your house has been retrieved from your LTM and is pictured on your sketchpad.

The PL deals with spoken and written material. It consists of two parts:

1 **Phonological Store** (Inner ear) – Linked to speech perception. Hold information in speech-based form (i.e. spoken words) for 1-2 seconds. Spoken words enter the phonological store directly while written words have to firstly be converted to an articulatory (spoken) code before entering the store.
2 **Articulatory Control Process** (inner voice) is linked to speech production. In addition to its function to convert written materials into an articulatory code for storage as mentioned above, McLeod (McLeod, 2012) described the other function of the Articulatory Control Process as acting '…*like an inner voice rehearsing information from the phonological store. It circulates round and round like a tape loop. This is how we remember a telephone number we have just heard. As long as we keep repeating it, we can retain the information in the WM* (p.4)

The **Episodic Buffer** acts as a ‘backup’ store which communicates with the LTM and the other components of the WM. It binds together all the information and combines them with the information about time and order and prepares for storage in the Episodic LTM.

2.4.4 The Long Term Memory (LTM)

The LTM has

1 **Declarative Memory**, which, can also be called the Explicit Memory. The Declarative Memory is further divided into two types of memory
the episodic memory
the sematic memory

2 **Procedural memory**, which, can also be called the implicit memory. (see Figure 2.10).

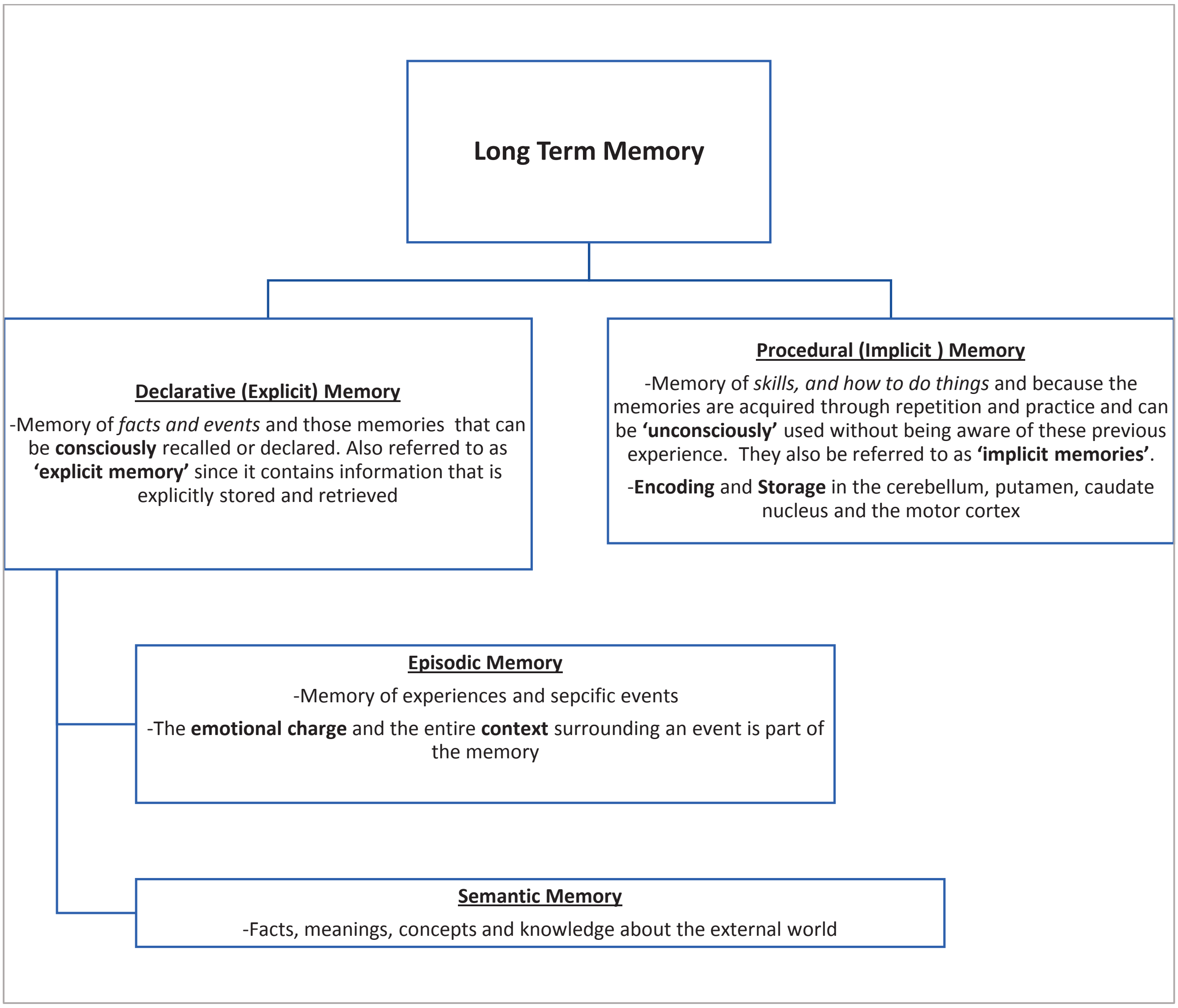


Figure 2.10 The Long Term Memory

A very important cognitive process called ***Memory consolidation*** takes place to stabilize the acquired information after its initial acquisition (Mastin 2010). The Consolidation of memory is believed to be consisted of two other processes called the *'synaptic consolidation'* (happens within the first few hours after learning or encoding) and the '*systemic consolidation'* (where hippocampus-dependent memories become independent of the hippocampus over a period of weeks to years) (Mastin, 2010). This process paves way for the establishment of the LTM.

2.4.5 Retrieving the stored information from the LTM for use

We have thoroughly look at the function of the brain, the different types of memory and the function that the neurons play in learning, we are ready to look at how this information can be made useful to us. It would not be of any good if the information is just stored in the brain without further processing.

The two main methods of accessing memory are **recognition** and **recall.**

According to Mastin (Mastin, 2010**) recall** or **retrieval** of memory refers to the subsequent re-accessing of previous encoded and stored information in the brain. Simply you could think of it as ‘remembering’. During recall, the brain ‘replays’ a pattern of neural activity that was originally generated in response to a particular event, echoing the brain’s perception of the real event. In fact, there is no real solid distinction between the act of remembering and the act of thinking.

This recalling process involves re-visiting the nerve pathway the brain formed when encoding the memory and the strengths of those pathways determines how quickly the memory can be recalled. Recall effectively returns a memory from long-term storage to STM or WM, where it can be assessed. It is then re-stored back in the LTM, thus consolidating and strengthening it (Mastin, 2010).

2.4.6 Brain Plasticity: Maximising the brain capacity during activities

Studies have shown that, the constant retrieval of information, reconstructing, consolidating and storing of information in LTM involves a process of physical changes in the structure of neurons (or nerve cells) in the brain, a process known as **Long-Term Potentials** (LTP). These are some points to note about LTP:

1 Synapses become more or less important over time (plasticity)
2 LTP is based on experience
3 LTP is based only on local information (Hebb’s postulate)

(Bear et al, 2001)

Neurons are cells that transmit electro-chemical signals (nerve signals) to and from the brain and the nervous system at up to 200mph. There are about 100billion neurons in the brain (see Figure 2.11).

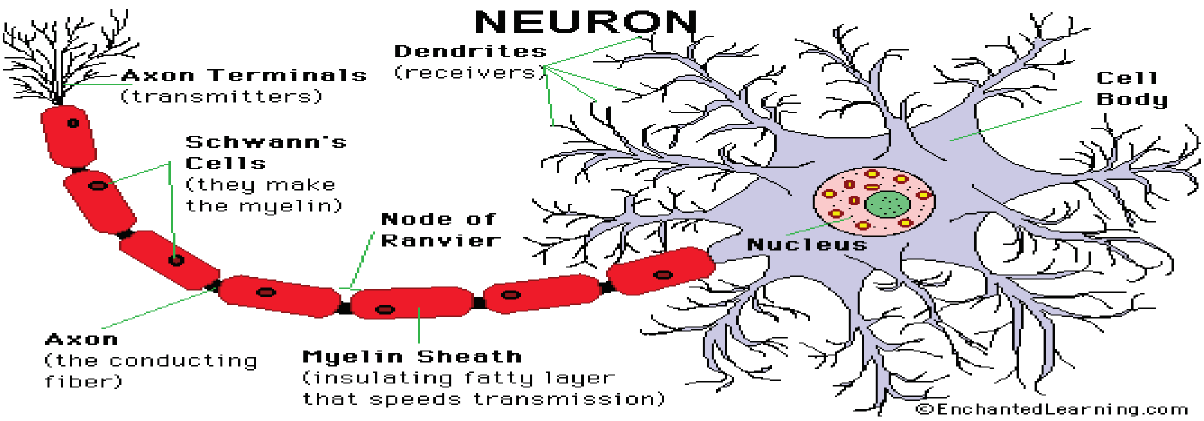


Figure 2.11 The parts of a neuron [Source:http://www.enchantedlearning.com]

Neuron cells play the important role in transmitting and transforming the electrical signals at the synapses (Figure 2.12).

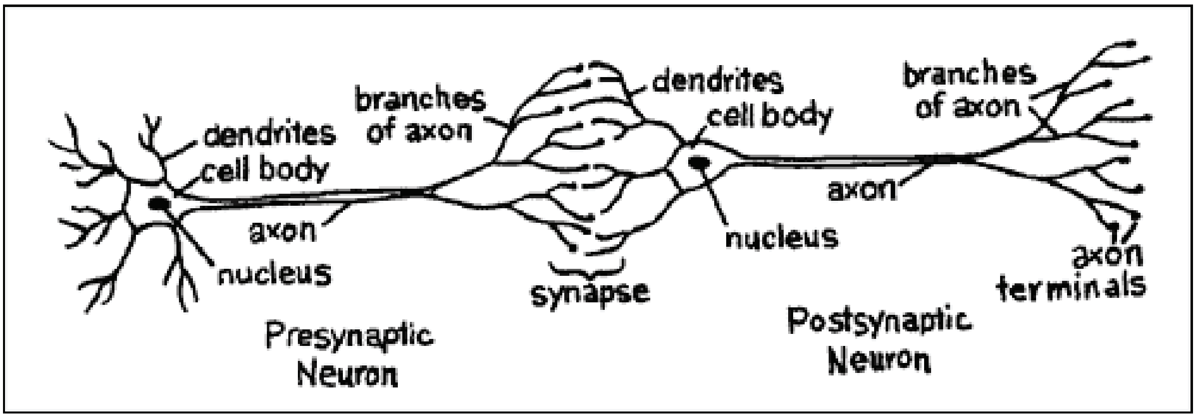


Fig 2.12 Presynaptic and postsynaptic neuron in position for transmission

[Source:https://science.education.nih.gov/supplements/nih2/addiction/guide/lesson2-1.html]

What is this got to do with the learning and mastering of skills in a fablab? From what we know of neuron structures and how they 'communicate' with each other through the synapses is that whenever something is learned, circuits of neurons in the brain known as neural networks, are created, altered or strengthened. The efficacy of a synapse can change as a **result of experience**, providing both memory and learning. With repeated use, the efficiency of these synapse connections increases, facilitating the passage of nerve impulses along particular neural circuits, which may involve many connections to the visual cortex, the auditory cortex, the associative regions of the cortex, etc. (Mastin, 2010).

This research therefore will explore the activities in a fablab that can contribute to the strengthening of these neural circuits in the brain.

The activities that this research intends to explore are activities embedded in the design process in an Ub-Fablab. It is therefore appropriate at this point to explore the concepts in design.

2.5 The design process in a Ub-Falab

2.5.1 The definitions and concepts of design

The term **'design'** has varying definitions. According to Ralph and Wand (2009, p. 109), design can either be classified as

1 noun - as 'a specification of an object, manifested by an agent, intended to accomplish goals, in a particular environment, using a set of primitive components, satisfying a set of requirements, subject to constraints or as a

2 verb- being, 'to create a design, in an environment where the designer operates'

Kumaragamage (2011) gave an alternative definition of design as, '…a roadmap or a strategy approach for someone to achieve a unique expectation. It defines the specifications, plan, parameters, costs, activities, processes and how and what to do within legal, political, social, environmental, safety and economic constraints in achieving that object '(Design Manual volume 1, p.1).

This research uses Kumaragamage's definition of design as a process. Viewing design as a process in an Ub-Fablab, it would entail activities occurring at different stages and involving cognitive processes discussed earlier in this chapter.

Despite extensive research into the models, theories and methods of design since 1950's (for example: The Blessing model of Stage-based & activity-based design process model; the solution vs problem-oriented model; March's PDI model of reasoning in design; Jones model of the design; Evan's design spiral; the Engineering design process (Blessing, 1994; Lawson, 1980; Birmington et al, 1997; cited in Bahrami & Dagli, 1993), there is not a single model that is agreed to provide a satisfactory description of the design process.

While the definition and concept of design process cannot be pinned down, what is important to note is that, according to Eastman (Eastman, 1968), design can be viewed as a type of **problem-solving activity**. The approach taken by the design process resembles the approach taken by other fields such as the field of chess (Newell, Shaw, Simon, 1958; de Groot, 1965); for geometry proofs (Gelernter et al, 1960); puzzle solving (Newell, 1968); and musical composition (Reitman, 1964) where predictions and relocation processes are evident (cited in Eastman 1968, p. 2).

This research uses an iterative design process to track the OLB during activities in a Ub-Fablab therefore it is important to look at what an iterative design process looks like and how this particular design process model is appropriate for use in a Ub-Fablab.

2.5.2 The Iterative Design Process models

The theory of 'iterative designs' could be traced back to 1962 when Hall (Hall, 1962) developed the 'two-dimensional perspective of project development'. The first one being the serial stage and second the cyclic problem-solving activities in each of the stages. Asimow (Asimow, 1962) further transferred Hall's ideas to that of design stating that the stage could be the morphological dimension of the design process while the cyclic process be applied to the designers' day-to-day activities as problem-solving dimensions. Blessing (Blessing, 1994) referred to Asimow's theory as stage- and activity-based design process. Other models deriving from Hall's initial theory emphasise iterative activities within each stage and a convergence on the design solution by progressively using more concrete activities at each stage.

The descendant of the design process model that is used by the Maker movements, which the fablab is part of, is believed to have taken from Winston Joyce in 1970, who undoubtedly, has built on from Hall's serial stage theory in development. This model was later termed the 'Waterfall Model' (though this is not the exact name that Joyce used back then) (see Figure 2.13).

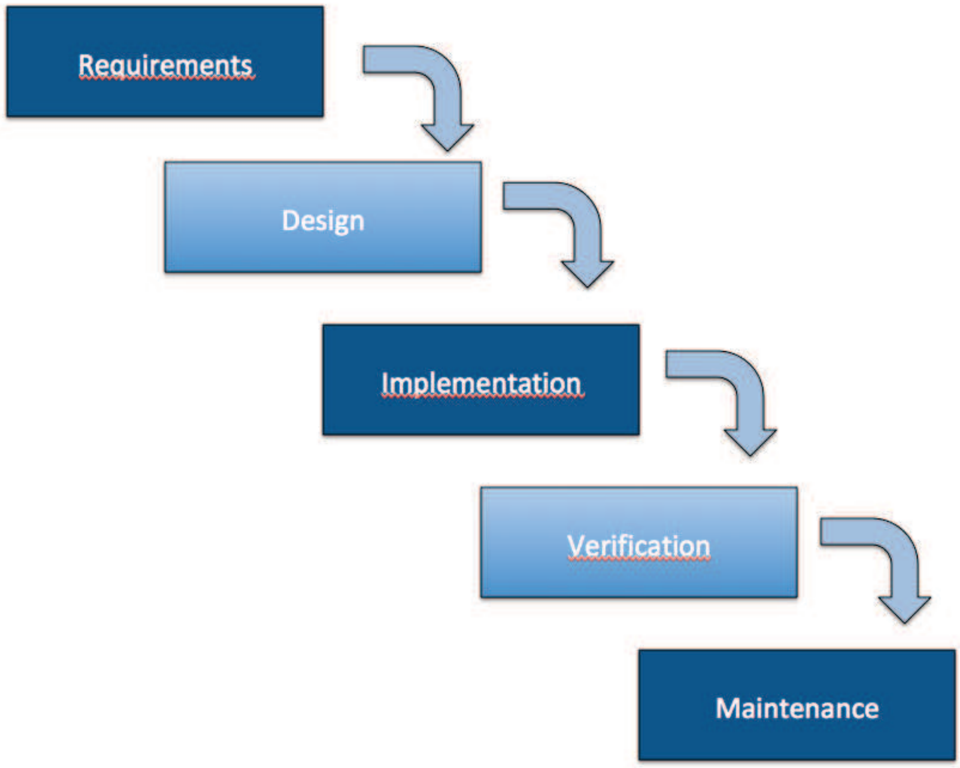


Figure 2.13 The Waterfall Model. [Source: http://www.waterfall-model.com/]

The Waterfall Model was used by computer scientists to develop computer software, where each stage is planned, build tested and completed before progressing on to the next stage without any iterative processes between each stage. This model was extensively used before the introduction of computer software programs such as the Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). It would have been costly if, for example, after building the 22nd floor of a skyscraper and you realise that essential things needed for the ground floor, for example, the proper fire escapes, were not included in your initial plan. Off course, iterative process between the stages in this phase of the construction would be costly as no one will tear the skyscraper down to re-plan and rebuild another one (Martinez & Stager, 2013).

With the present day use of CAD and CAM software programs, the risks associated with the waterfall design model have been reduced and products are becoming more customized to individual needs as one can, '…even *tinker even as you build, spiralling though a series of stages as you make progress* (Martinez & Stager 2013, p. 48). The two examples of design process models used in this new era of computers and the CAD and CAM software programs are the 'Spiral Design Model' (Boehm, 1988 cited in Martinez & Stager, 2013) and the 'Iterative Development Model' see Fig 2.14). The iterative development model is used by the maker movement (Martinez & Stager 2013) and would therefore be appropriate to apply in Ub-Fablabs.

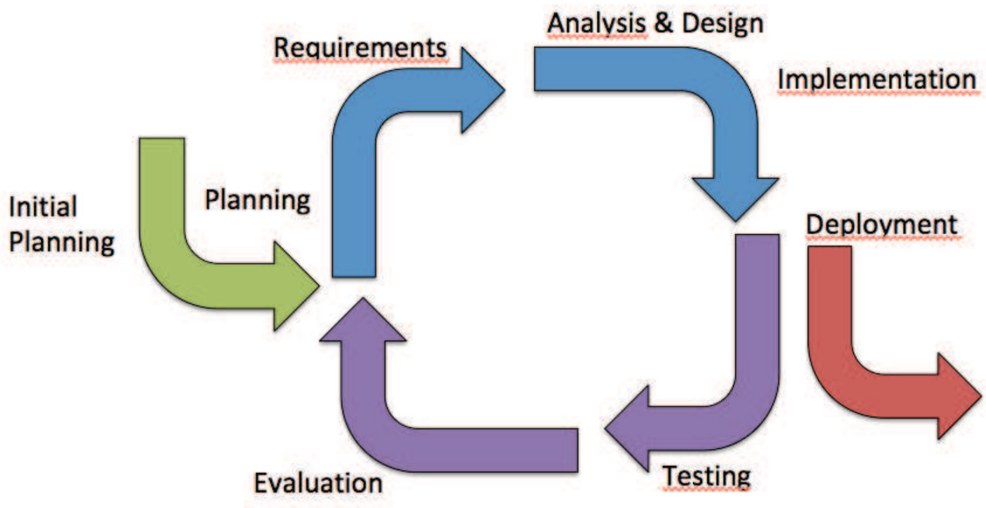


Figure 2.14 Iterative Development Model

[Source: http://www.waterfall-model.com/iterative-software-development/]

Iterative design processes models can now be successfully applied in Fab labs for the following reasons:

1 With CAD and CAM programming and simulations that are available in fablabs allows one to build and iterate between each stage
2 The low-cost machines and tools used in the fablabs allows one to progress from a concept to the prototype that can be tested in the real world
3 The open-access status of a fablab allows one to build his/her own prototype/product while iterating at his/her own pace without any external pressures.

Building on from the concept of iterative design process models discussed in this chapter, this research proposes an iterative design process model in chapter 3 to align the cognitive processes with the stages of the iterative design process. The proposed iterative design process model in chapter 3 does not intend, in any way, to undermine the current design process models.

2.6 Defining a more robust approach to learning

2.6.1 The definitions and concepts of Life-long learning, life-wide learning, sustainable learning and a sustainable learning environment.

Due to the ever-changing environment in this century, a more robust approach to learning needed be considered if citizens are to keep up with the changes. The concepts such as that of Life-long learning, life-wide learning, sustainable learning and sustainable learning environment need attention.

Some scholars have tried to define Papert's constructionist approach to learning adopted by the fablabs as simply, 'Learning-by-making'. However, Papert and Idit Harel stated that 'constructionism should be considered, '*much richer and more multi-faceted, and very much deeper in its implications than could be conveyed by such formula'* (Papert, 1991).

To achieve the calibre of this 'rich and multi-faceted and deeper implications of constructionism', a lot of thought has to be put into the approach that is used in Ub-Fablabs. Papert and his successor Mitchel Resnick from MIT Lab used the term **'Lifelong Kindergarten'** to refer to the activities in makerspaces. The activities in makerspaces are likened to activities done by kids in a kindergarten. While Piaget proposed that children need to handle concrete objects in order to learn, while adults can think in abstraction, Papert and other researchers had this to challenge Piaget's proposal. They think that there was an overemphasis' of abstract thinking against concrete acting that plays an important role in the development of all humans, also for adults…We are inspired by the ways children learn in Kindergarten: when they create pictures with finger paint, they learn how colours mix together; when they create castles with wooden blocks, they learn about structures and stability. We want to extend this kindergarten style of learning, so that learners of all ages continue to learn through a process of designing, creating, experimenting, and exploring'

(Resnick 2012 quoted by Shelhowe 2013 in Walter-Herrmann, 2013, p. 95).

Another concept that has a similar intention of learning to the concept of lifelong kindergarten is the concept of **Lifelong learning.** This concept appeared in literatures some 30 years ago by Edgar Faure in his seminal work, *learning to be* which was later adopted by the UNESCO as, *'a blueprint for universal education'* and an essential workplace component. Its definition, however, are often imprecise and occasionally inconsistent ((Knapper 2006; Kirby, J.R., Knapper, C.K., Lamon, P., & Egnatoff, W.J (2010)). Knapper and his colleague Arthur Cropley have described the characteristics of a lifelong learner as, '*Someone who is strongly aware of the relationship between learning and real life, recognizes the need for lifelong learning and is highly motivated to engage in the process, and has the necessary confidence and learning skills'* (Knapper 2006, p. 2)

Dobson (Dobson, 1982 cited in Kirby et al, (2010)) also argued that not only learning has to be lifelong. It should also be '*life-wide'* meaning that learning cannot be "…*confined to formal education institutions, but rather is seen to take place in a wide variety of settings- including the workplace and in the social and recreational contexts* (p.4).

From a cognitive perspective, Schelhowe (Shelhowe, 2013 cited in Walter-Herrman & Buching (eds), 2013) used the term 'Complex or deep learning' and also closely associated it with sustainable learning. He defines the two terms as:

complex or deep learning means that not only skills for repeatedly acting according to fixed rules are concerned, but that (in the sense of Piaget's understanding of learning) the alteration of mental models as a change of oneself in interaction with the environment takes place. Sustainable Learning means that, according to a (new) mental model, different situations can continuously be handled where the abstract model is applied appropriately (ibid, p.93)

Knapper (Knapper, 2006) believes that lifelong learning is not just for universities and schools but that the '…responsibility of learning *throughout life* and *from life* lies with individuals' (p.2) therefore it has to be learning that is a *'self-directed individual* *initiatives rather than handing down of knowledge from experts or a central authority'*. *In this sense, lifelong learning and life-wide learning are **Sustainable Learning**'* (ibid)

For sustainable learning to occur in an Ub-Fablab, having a **sustainable learning environment** is also important to consider. Blyth (2014) considers a sustainable learning environment as an environment that, *'can produce conditions and mediate relationships that can improve student cognitive, physical and mental wellbeing outcomes'*. In order for this to happen, the physical learning environment is very important to consider. While often people tend to think of the physical learning environment as just a building, in this case, a makerspace filled with machines, Blyth (2014) insisted that the learning environment constitutes "... *interactions between the physical resources (including the building, technology and external spaces), learners, educators, content, society and policy. Indeed, learning itself is complex. Health and wellbeing, affective, social, cognitive and behavioural characteristics of individuals can all impede or enhance learning" (p.1).*

The Australian Teaching and Learning Council outlined what a physical learning environment should look like if it were to offer sustainable learning (cited in Blyth, 2014) (Figure 2.15).

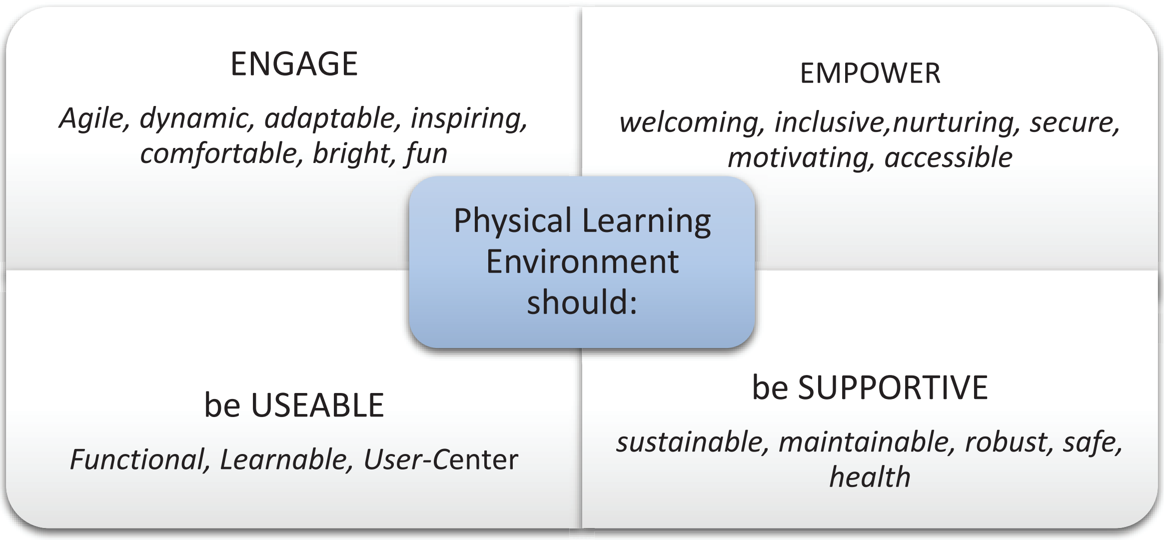


Figure 2.15 The requirements of a sustainable learning environment

The Fab Foundation (Fab Foundation, 2012) has recommended a blueprint for the physical layout of a fablab (Figure 2.16). Whether existing fablabs use this blueprint in their setting up or not, this layout is suitable for Ub-Fablabs. Setting up Ub-fablabs using this plan would not only allow one to venture into the fablab to create things, but it provides for an environment where one enhances CPA skills as well.

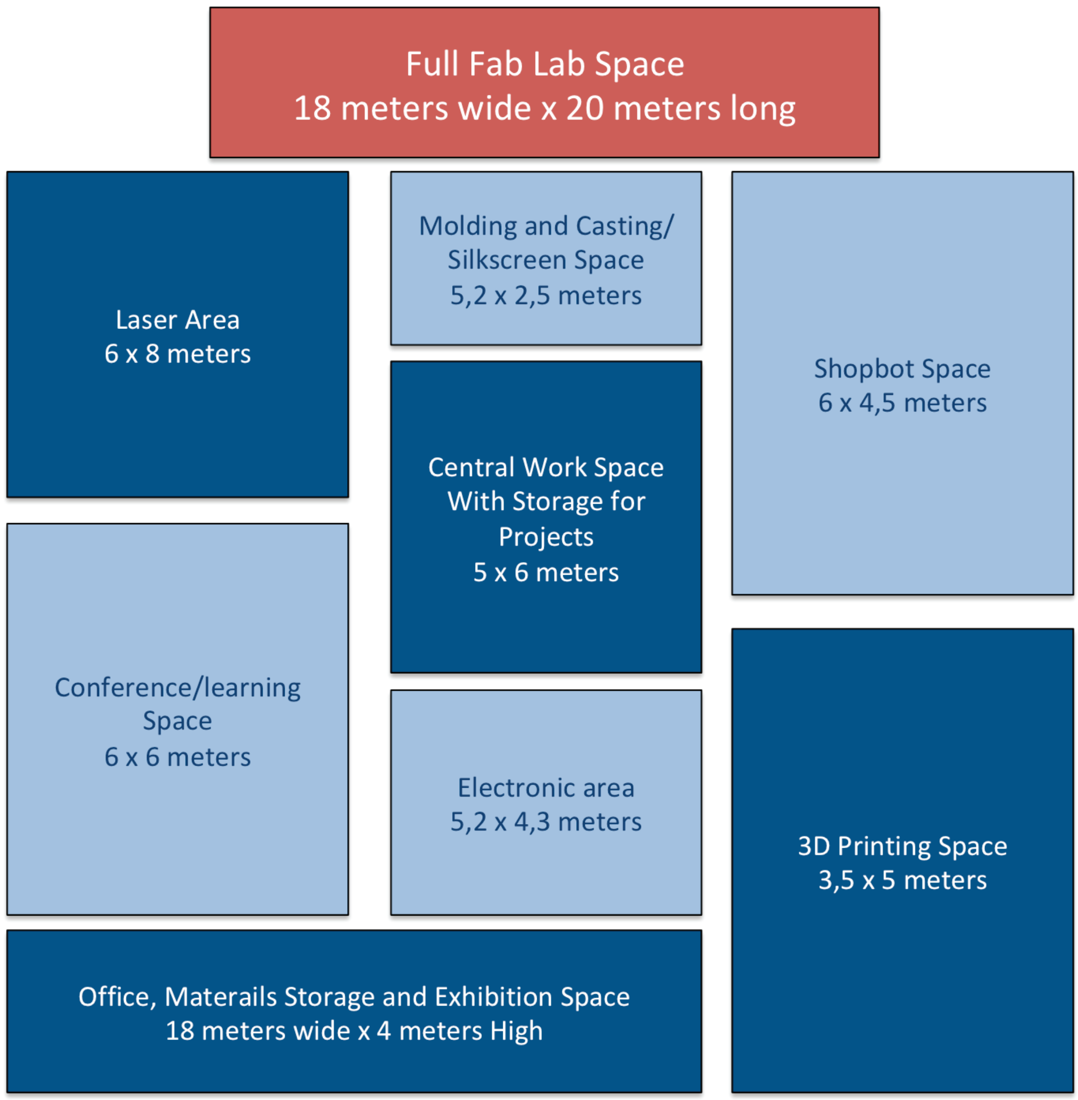


Figure 2.16 : Typical layout of a fablab *(Source : Fab Foundation 2012)*

As part of this research, learning environments in an Ub-Fablab will also be investigated.

Part Two

2.7 The relationship between fablabs and the industry / Technology

2.7.1 Technological/industrial trend: From analog, mechanical and electronic technology to digital technology

The history of technology could be traced back to the Neolithic or Agricultural Revolution. This was the transition period from a lifestyle of hunting and gathering to one of agriculture where domestication of various types of plants and animals evolved. Technologies in that period included mainly agricultural tools while energy was derived from water, coal and oil to transform materials into desirable objects. People lived in harmony with each other in communities, shared every little thing they had and learnt to pass on information by story-telling and passed on knowledge and skills through actual involvement in doing or creating things (Jean Pierre-Bocquet-Appel, 2011).

The medieval period (roughly spanning 10th -13th century) and the Renaissance period (roughly spanning 14th – 16th century) in Europe saw great advancement in technologies. These include the invention of windmills, spectacles, mechanical clocks and greatly improved water mills and building techniques. The medieval universities established between the 11th and 13th century led to a rise of literacy and learning. This played a key role in the Scientific Revolution. A great technological achievement in the Renaissance period was the invention of the printing press by the German goldsmith Johannes Gutenberg. This has allowed the mass production of printed books on a proto-industrial scale and allowed a free flow of information. Another landmark discovery in this century (late 1600s) that contributed to the digital revolution, some 200 years later, was the development of a binary system of numbers by Leibniz. Binary numbers are now utilized by calculating machines combined with digital technology (Todd (1995); Williams (1997); Pierce (n.d.); Grant (n.d.) cited in Wagner 2002).

The technological advancement contributed to the industrial revolutions beginning in the 17th century onwards. A spinning mill, named the spinning Jenny, being invented by James Hargreaves in 1764 was one of the first innovations that marked the start of the Technological Industrial revolution, also named the First Industrial revolution. The descendant machine /tools of the ones currently found in fablabs are the milling machines, e.g. the Maudslay's screw-cutting lathes and James Nasmyth's milling machine which was then used to mill the six sides of a hexagon nut. The paper machine was also invented in this period. This technological industrial revolution centred on textiles, iron and steam engine technologies.

An interesting bit of history worth taking note of is that while the countries in Europe (particularly Great Britain where the technological revolution started which then spread to other parts of Western Europe), there was civil war in the U.S. This civil war has pushed the American inventor Eli Whitney to start the manufacturing process of '**mass production**' of weapons. On the other hand, that civil war also pushed the founder of the Massachusetts Institute of Technology (MIT), William Barton Rogers, to push for a 'Scientific University' that would be *'…grounded in practice and hands-on learning. It would not be an ivory tower but a laboratory for brilliant minds geared to tackling real-world problems'* (Angulo, Dec 21, 2010). This saw the establishment of MIT in 1861 and opened in 1865, adopting a European poly-technical university model. MIT, a century later, established the concept of Digital Fabrication Laboratories (Fab lab), which, this study aims to explore.

The Second Industrial Revolution (around 1867-1914) also known as the Technological Revolution revolved around steel, railroads, petroleum, chemicals and finally electricity. Vaclav Smi named this period the 'Age of Synergy'. It was a time when great engineering science-based innovations and inventions were developed (Vaclav, 2005). One of the landmark inventions of this time was the invention of the telephone by Alexander Graham Bell in 1875. The first successful bi-direction transmission of speech made on the 10th March 1876 between Bell and his colleague, Watson, was this famous message, "*Watson, come here, I want to see you*". To this message, Watson answered (Hochfelder, n.d.). This simple message alone marked a great advancement of electronic technology into utilisation of sound waves to transmit messages. Although the World War I, which took place between 1914- 1918 saw a halt in new inventions, a kick-start of electronic technology after WWI saw another landmark invention. Alec H. Reeves, a worker in the International and Telegraphic Co.

in France, invented pulse-code modulation (PCM) in 1937. This invention, a few years later was used to convert sound waves into digital series of numbers. In terms of manufacturing processes, Henry Ford is claimed to have been the first to invent the manufacturing process of 'assembly lines' in 1903.

The invention of computers had paved way for the onset of digital technology revolution. The invention of computers in this period evolved from Alan Turing's concept of calculability, a mathematical and purely semiotic concept. He postulated that *'mental processes could be seen as just mechanical processes to be stimulated and finally replaced by a machine, revolutionized labour as well as private life and the ways of thinking about mental processes* (Schelhowe (2013) in Hubermann (2013), p.97). Turing's 'abstract machine' came into existent with the first electronic computer in the years leading up to the World War II (1936 - 1940s) by the German, Konrad Zuse, who himself declared that his computation machine was just an 'incarnation of mathematics'. Zuse built the first electro-mechanical binary programmable computer, the Z1, in his parents' living room (see figure 2.17). Replicas of the Z1, the Z2 and Z3 were upgraded and built after the destruction of the Z1 during the war (ibid).

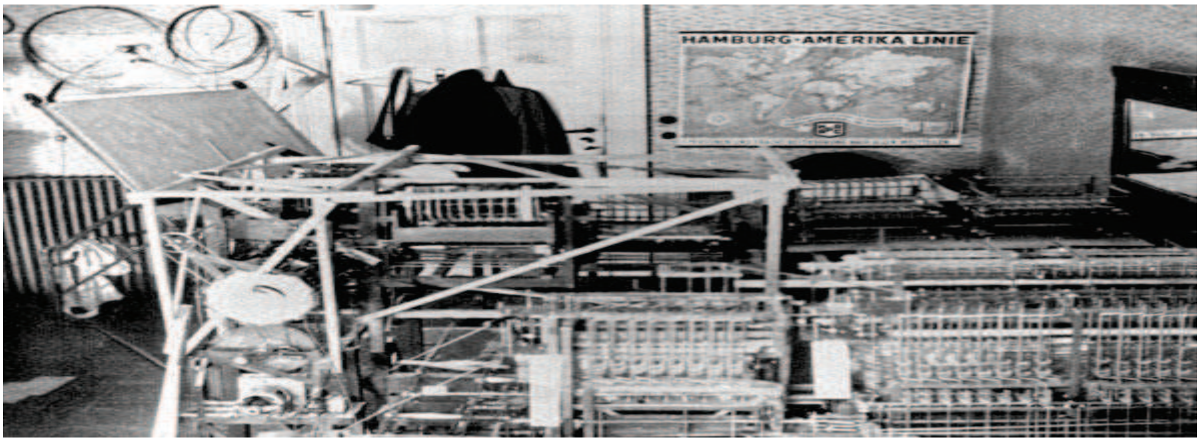


Figure 2.17 The first electro-magnetic binary programmable computer, Z1.

[Photo credit: http://www.computerhope.com/issues/ch000984.htm]

The WWII had then pushed Tommy Flowers from England to invent the first electrical programmable computer, the Colossus, in 1943 mainly to help the British code breakers to read encrypted German messages. These encrypted codes were presumably being facilitated by the Zuse's Z1 electronic programmable computer. Around about the same time Konrad Zuse was inventing the Z1 computer in Germany, John V. Atanasoff and Clifford Berry were inventing the first electronic digital programmable computer, called the Atanasoff-Berry-Computer (ABC). The ABC computer was the first computer to use vacuum tubes as well as the first to incorporate binary arithmetic, regenerative electron memory and logic circuits. The ABC computers are the descendants of the present day Personal computers (Todd (1995); Williams (1997); Pierce (n.d.); Grant (n.d.) cited in Wagner 2002). The invention of the computers and the telephone confirmed and marked an important landmark of this period where light and sound waves were utilised to get messages across devices and thus the onset of Digital Revolution.

2.7.2 The Digital Revolutions

Professor Neil Gershenfeld summed up the Digital Revolutions as follows:

1. Analog to digital communication -1945
2. Analog to digital computation – 1955
3. Analog to digital fabrication - 2005

i) Gershenfeld's 1st and 2nd Classification of digital technology (from analog to digital communications and computation)

The periods 1945 – 1955 and even into the late 1970s saw the technological change from analog, mechanical and electronic technology to digital technology with the adoption and proliferation of digital computers and digital record keeping that continues to the present. According to O'Reilly (O'Reilly, 2014), Professor Neil Gershenfeld, in his keynote address during the Solid conference, stated that "…analog telephone calls degraded with distance'…thus '…digitizing communications allowed errors to be detected and corrected, leading to the internet. Analog computations degraded with time…' thus, '...digitizing computing again allowed errors to be detected and corrected, leading to microprocessors and PCs" (p.1). This period was also known as the Information Age because it was a time when there was a great revolution of communications and the spread of information (Wagner, 2001).

ii) Gershenfeld's third classification of digital revolution: from analog to digital fabrication came as a result in the advancement of technology in science, mathematics, engineering and computing. Coupled with the emergence of free-software and open-source movements (Ehn et al, 2014), these have prepared grounds for the makerspaces like the fablab (Blikstein, 2013). Professor Neil Gershenfeld presented the following about the current status of digital fabrication during the Solid Keynote address, "...manufacturing today remains analog; although the designs are digital, the processes are not" (O'Reilly, 2014). There is emerging research on digitizing fabrications by coding the construction of functional materials and exploring the implications for programming the physical world.

Research Question 2 in this research intends to investigate the capacities of Ub-Fablabs as a support platform to help citizens achieve 21st century skills and integrate sustainable design and production. The following paragraphs discuss literature reviews from secondary sources on some benchmarks of platforms that could qualify it to be used as a support platform.

2.8 The 21ST Century Skills

The impact of digital technology this century on the society has caused organizations like the National Research Council (NRC) and other educational bodies worldwide to call for educational reforms. The urgent call is for citizens to be equipped with the skills and knowledge to cope with the technological changes. The NRC Report (The NRC Report, 1999 ; 2000 cited in Blikstein, 2013) called for education to, '… *include the development of adaptive, foundational skills in technology and computation, in particular « [intellectual] capacities [to] empower people to manipulate the medium to their advantage and to handle unintended and unexpected problems when they arise… to move away* from '*computer skills' towards 'computational fluency' or 'literacy'* and '*broadening the technological literacy to include basic engineering knowledge, and the nature and limitations of engineering process"* (pp. 204-205).

Another new concept appearing now in literatures in the concept of 'T-shaped skills or people'. Believed to be originated from the London newspaper in 1991, the concept refers to the need to have professionals who has a depth of knowledge in one discipline and a breadth of knowledge across multiple disciplines that allows for collaboration (Smathers, 2014). According to IBM, one of the companies along with others like Nike, Apple, IDEO and McKinsey, who claim to be recruiting employees with T-shaped skills has this to say about T-shaped professionals:

T-shaped professionals are valuable because they are empathetic, making them great at teamwork and collaboration, and creative problem-solvers. T-shaped employees are analytic thinkers with the ability to connect ideas across disciplines. Their combination of deep discipline expertise and collaborative ability makes them ‘adaptive innovators’. (Ibid, p.2).

These calls for educational reforms have seen proposals for changes to the way schools deliver their content and the knowledge, skills and attitudes. The Metiri Group (Bevins & Ritz, 2016) believed that the skills needed to maximise educational and economical skills and knowledge can be drawn from studies by several groups including the *Framework for the 21st Century Skills* by the Partnership for 21st Century Skills; *Four Keys to College and Career Readiness* by Conley & The Educational Policy Improvement Center 2011; *Seven Survival Skills* by Wagner & The Change Leadership Group at the Harvard Graduate School of Education and *Technically Speaking: Why All Americans Need to Know More About Technology* by the National Academy of Engineering and NRC. These skills include analytic and problem-solving skills, communications skills, interpersonal and collaborative skills, global awareness, and financial, technological and civic literacy (Cunningham, 2009).

Binkley et al (Binkley et al, 2012) classification of these knowledge and skills falls into four categories namely

1 ways of thinking,
2 ways of working,
3 tools for working,
4 living in the world.

The Metiri Group further categorised these skills into four categories (see Figure 2.18) (Bevins & Ritz, 2016).

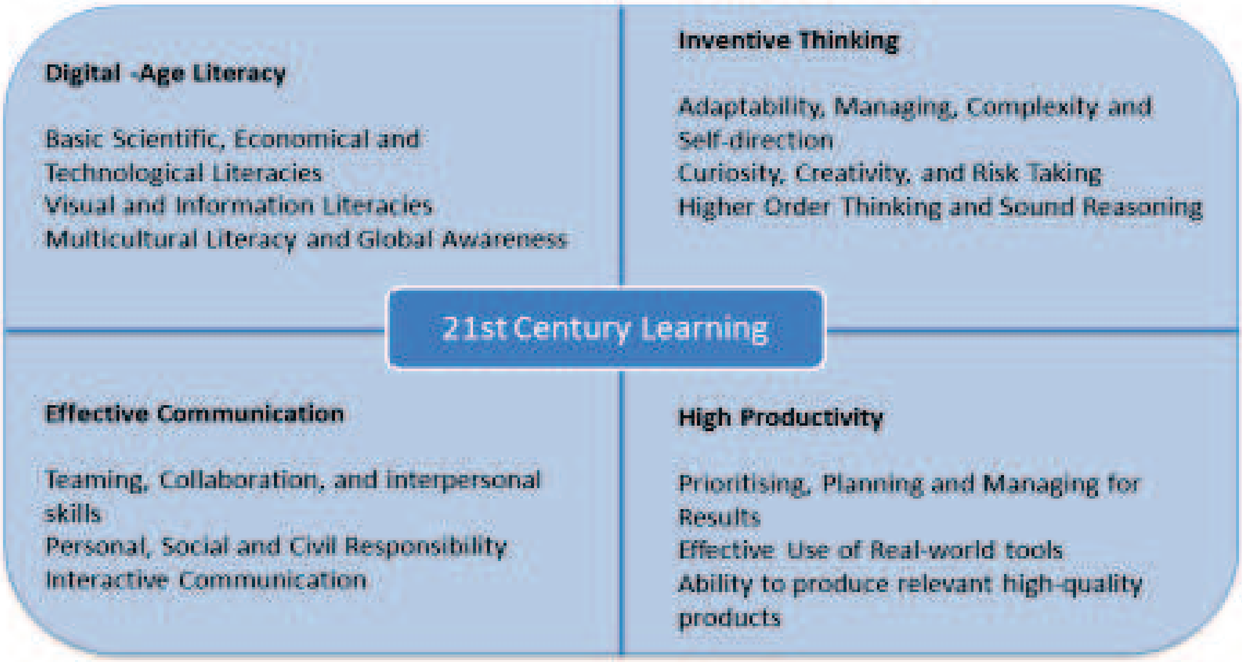


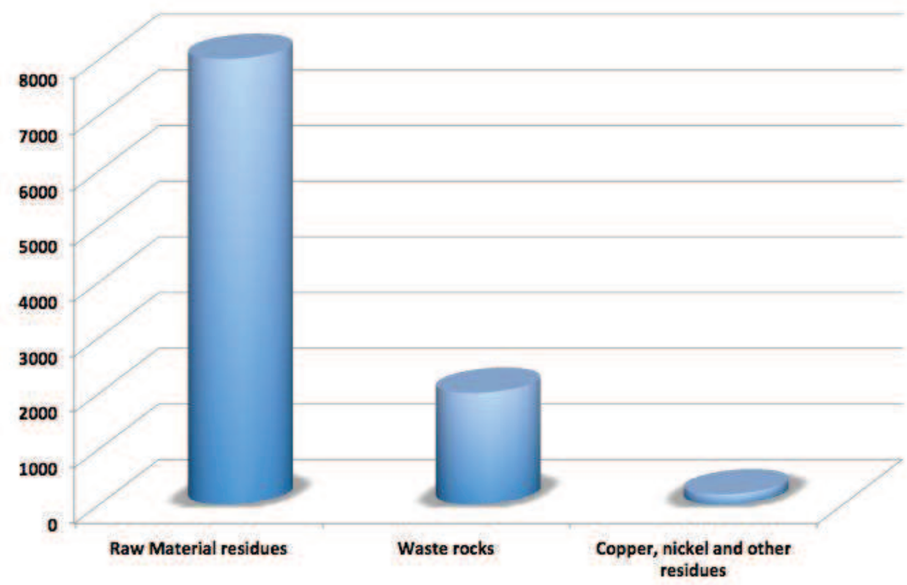
Figure 2.18 Metiri Group Skills for the 21st Century (Ritz & Bevin, 2016).

All the knowledge and skills categorised by the Metiri Group are very relevant to the design process in an Ub-Fablab, which, this research aims to study. The four categories are also closely linked to Papert's Constructionist approach to learning in an Ub-Fablab.

2.9 The Current practices of Design and Production industries: A role for Ub-Falab to incubate proactive minds for the integration of design and production in the future?

Design has played a critical and important role in economic growth in the western world and elsewhere through history, however, the unanticipated high output of wastes during the lifecycle of a product and unexpected market crashes of 2001 and 2008 (Bono & Pillsbury, 2016) puts to question the current practices of design and production. According to Siefried Dais (Tscheiesner & Loffler 2016 Interview), the current manufacturing sectors/companies operate in isolation. The design companies create product solutions and design specifications for customers while manufacturing companies/industries produce for the customers by the mass production processes. This approach, not only has it concentrated skills to only the ‘experts’ in the fields of design and production but responsive attitudes towards resource conservation and sustainability may not have been incubated or nurtured within the sectors.

Waste as a result of car production



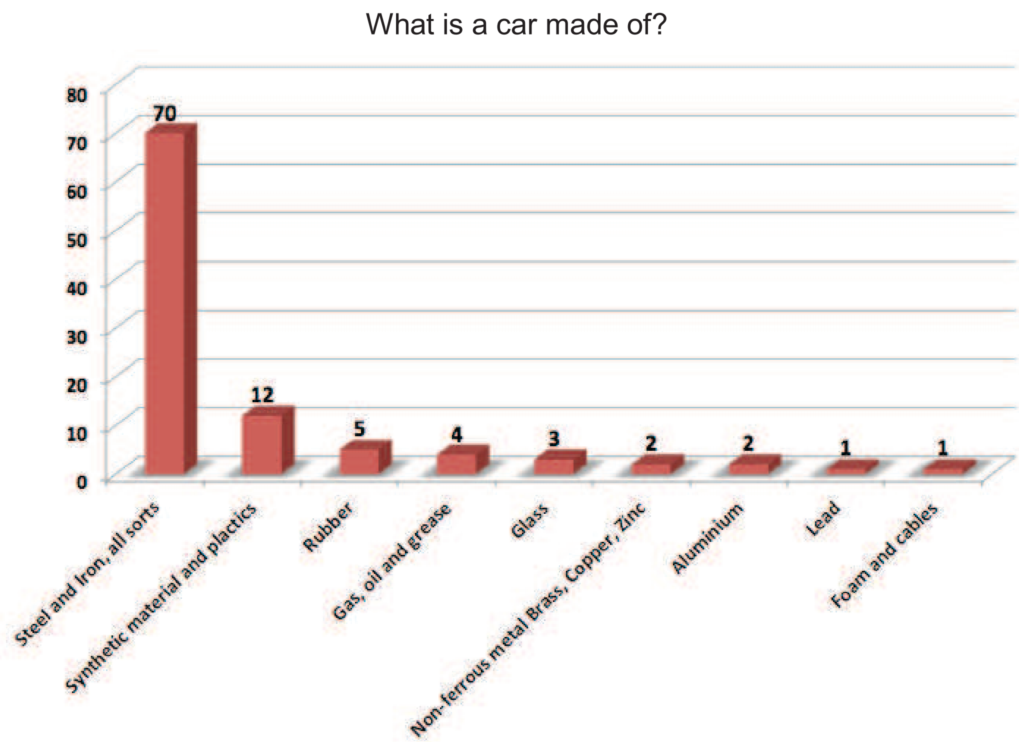


Figure 2.19 Graphs showing the amount of wastes generated during the production of a car. [Source: UNEP: http://www.grid.unep.ch/waste]

In the current practice, the amount of waste produced during the lifecycle of a product can be alarming. Producing a car, for example, according to UNEP (UNEP, n.d.), waste is produced at each stage starting from the production to the disposal of the car (see Figure 2.20).

In summary, from production to disposal of the car, these wastes are produced:

Energy produced and used	
For the extraction of raw material	6%
For the production of the car	4%
For the running	90%
Air Emissions	
Carbon dioxide	36,000kg
Carbon Monoxide	413kg
Volatile organic compounds (VOC)	192kg
Sulfur dioxide	34kg

Nitrogen oxide	28kg

To help cut down on the amount of waste being produced, innovative ways or ideas are to be considered. Three of the concepts appearing in literature that are aiming at reducing waste and at the same time improve inputs will be discussed in the following paragraphs. This research will investigate the capacities of the Ub-Fablabs to cater for these concepts.

2.9.1 Sustainability, Eco-design and Circular Economy

The terms 'sustainable' and 'sustainability' have no universally accepted definitions. Different people have differing views on these terms. It has often been used in the past in ecology to refer to the biological systems and how they endure and remain diverse and productive. However, after the World's first Earth Summit in Rio in 1992, the term was extended to refer to 'sustainable development' (HEC Learning, n.d.). Applying this term to design and production, it refers to eco-design approaches in manufacturing industries that utilise renewable energy sources and eco-design materials thus contributing to a circular economy (Ellen MacArthur Foundation, n.d).

The concepts of circular economy and eco-design are closely related in the sense that to gain a truly circular economy, products have to be eco-designed. The concept of circular economy was first touted by environmentalists John T Lyle and Walter Stahel in the 1970s and re-emerged in 2010 by the Ellen MacArthur Foundation. The concept, being advocated by celebrities like Arnold Schwarzenegger calls for an industrial economy that produces no waste and pollution, by design or intension and in which materials flows are of two types: biological nutrients, designed to enter the biosphere safely, and the technical nutrients, which are designed to circulate at high quality in the production system without entering the biosphere as well as being restorative and regenerative by design (Ellen MacArthur Foundation, n.d.).

The Ellen MacArthur Foundation outlined four building blocks for a Circular Economy being

1 Circular economy Design

2 New business models
3 Reverse cycles and
4 Enablers and favourable system conditions.

Several governments have started to implement these concepts, for example, the CACE association in China, the circular economy blueprint in Scotland and the European Commission's Circular Economy Framework (Perella in Guardian Sustainable Business, n.d). A practical aspect of the circular economic concept to DIY machines such as those found in Ub-Fablabs is the customer relationship with process of design and production, the product and their uses. Applying Ub-Fablab concept could place more responsibilities on the users, thus a shift in minds could go from users themselves as just consumers to seeing themselves as designers, producers as well as users. It is projected that users will develop a more responsible attitude by this approach.

Eco-design is an approach to designing products with special consideration for the environmental impacts of the product during its life cycle (Levitt, 1965). The fundamental rational for this approach is to design products that are environmentally friendly which would lead to a reduction in the consumption of materials and energy thus the concept of sustainability is upheld.

2.9.2 Embracing new Technologies

The new and emerging technologies (Bono & Pilsbury, 2016; Barlex, Given, Hardy and Steeg 2016) are impacting the design and production industries and the general society in a way that has not been in the past. The McKinsey Global Institute used the term 'disruptive technologies' when suggesting some features that mark out a technology as having the potential to be disruptive. The four features suggested were:

1 They upset the status quo, for example in overturning existing hierarchies and offering the possibilities of both more or less democratic hierarchies.
2 They alter the way people live and work, for example increasing or decreasing employment opportunities, chancing the knowledge and skills required for certain kinds of employment, shifting the expectation of education systems and alternating relationships.

3 They reorganise financial and social structures, for example by redistributing financial rewards.
4 They lead to entirely new products and services.

(Manyika et al, 2013 cited in Barlex et al, 2016, p.77).

Barlex, Givens and Steeg (Barlex, Givens & Steeg, 2015) have identified nine technologies that meet the McKinsey Criteria. These nine technologies are outlined in Table 2.3.

Table 2.3: Table outlining the nine 'disruptive technologies'

The Technology	The description
Additive Manufacturing (AM)	AM involves fabricating physical objects in successive thin horizontal layers, according to digital models derived from CAD designs, 3D scans or video games. Such printing can take place at different scales from Nano structures to complete buildings and may involve a wide range of materials: human tissue, electronics, and food as well as traditional industrial products such as polymers, metals and ceramics.
Artificial Intelligence (AI)	AI can be categorised at three different levels. First is 'narrow' AI that specializes in one area e.g. the AI that plays chess better than humans. The second and third levels are concerned with more general ability. 'General' AI can perform as well as human across the board i.e. it is an AI that can perform any intellectual task that a human can. Such AI is yet to be developed. Third is 'super intelligent' AI i.e., an AI that performs better than human brains in practically every field. This has yet to be developed but several prominent scientists and technologists (including Stephen Hawkin, Elon Musk, Bill

	Gates, and The Observer 2015) have warned that this carries with in an existential threat for the human race.
Augmented reality (AR)	Augmented reality (AR) is a live, direct or indirect view of a physical real-world environment whose elements are augmented (or supplemented) by computer generated sensory input such as sound, video, graphics or GPS data.
Big Data	Big data is data that exceeds the processing capacity of conventional database systems. The data is too big, moves too fast, or doesn't fit the structures of standard database architectures. It is collected by large corporations and governments (and, increasingly, open data from 'citizen' scientists) and when interpreted using big data analytics it can be used to give insights into behaviour of potential consumers and citizens. It is the ability to cross-reference large data sets and thus draw inferences that don't actually appear in any of the individual data sets that give rise to concerns that the availability of such data and its analysis will invade people's privacy and lead to mass manipulation.
Internet of Things (IoT)	The Internet of Things (IoT) is the networking of physical objects i.e. things that have been embedded within them electronics, software and sensors which are connected to one another over the internet and can exchange data. This allows extensive communication between the physical and digital worlds, enables remote control of devices across the internet and produces vast amounts of big data.
Neurotechnology	Neurotechnology is concerned with technologies that inform about and influence the behaviour of the brain and various aspects of consciousness. Current

	neurotechnologies include various means to image brain activity, stimulation of the brain by magnetism and electricity, measuring the electrical and magnetic brainwave activity, implant technology to monitor or regulate brain activity, pharmaceutics to normalize erratic brain function, and stem cell therapy to repair damaged brain tissue. Recently measurements of brain activity have been used to control real world artefacts.
Programmable matter	Programmable matter, is matter which has the ability to change its physical properties (shape, density, elasticity, conductivity, optical property, etc.) in a programmable fashion, based upon user input or autonomous sensing.
Robotics	A very basic definition of a robot is ‘a machine that automates a physical task’. This is limited because it gives no indication as to the intelligence and autonomy of such a machine. A microwave cooker automates the task of heating the food but is simply responding according to instructions selected from a menu of pre-programmed instructions. So a more appropriate definition is ‘a machine that carries out a physical task autonomously using a combination of embedded software and data provided by sensors’. The definition embraces relatively simple robots such as the Roomba vacuum cleaner to extremely complex robot such as the google self-driving car.
Synthetic biology	Synthetic biology is the process of designing and creating artificial genes and implanting them in in cells. In some cases, all existing genes have been removed; in others the new genetic sequences are introduced into the DNA in existing cells.

	It is far more than simply borrowing existing genes from nature. Synthetic biology is the process by which completely new life forms, i.e. life forms that have never previously existed, are created. Proponents of synthetic biology, such as David Willets (2013) when he was UK Minister for Science, argue that the technology could 'fuel us, heal us and feed us' but are concerned that there is the possibility of public rejection as was the case in the UK with GM food.

(Source: Barlex et al, (2015) cited in Barlex et al 2016, pp. 77-78).

Out of these nine technologies outlined by Barlex et al (Barlex et al, 2016), Bono and Pillsbury, (Bono & Pillsbury, 2016) signalled out four of the nine technologies that can influence design and production. These four technologies are:

1 Internet of Things (IoT)
2 Robotics
3 Augmented Reality (AR)
4 3D printing (or Additive manufacturing).

Bono and Pilsbury (Bono & Pillsbury, 2016) have stressed that these new technologies need to be embraced by industries in order to improve productivity, complete against rivals and maintain an edge with customers. They went on to discuss the impacts summarised in Table 2.4.

Table 2.4: Table showing the 4 disruptive technologies relevant in design and production industries.

Technology	**Example of Use in industries**	**Impact**	**Future Consideration**
Internet of Things (IoT)	Stanley Black & Decker has adapted the Internet of Things in a plant in Mexico to monitor	As a result, overall equipment effectiveness has increased	- To connect to information platforms the leverage data and advanced analytics to deliver higher-quality,

	the status of production lines in real time via mobile devices and Wi-Fi RFID tags.	by 24 percent, labour utilization by 10 percent, and throughput by 10 percent.	more durable, and more reliable products. Hint: Wind turbines manufactured by General Electric contains some 20,000 sensors that produce 400 data points per second. Immediate, ongoing analysis of this data allows GE and its customers to optimize turbine performance and proactively make decisions about maintenance and parts replacement. -companies must determine precisely what data is most valuable to collect, as well as gauge the efficacy of the analytical structures that will be used to assess the data. - require a next-generation mix of workers, which should include employees who can design and build IoT products as well as data

			scientists who can analyse output.
Robotics	Over the last decade, China emerged as an automated manufacturing powerhouse. Since 2013, the number of shipments of multipurpose industrial robots in China roughly doubled to an estimated 75,000 in 2015, with that number forecast to double yet again to 150,000 by 2018, according to the International Federation of Robotics. Fully automated factory in Dongguan.	Indeed, some manufacturers believe that greater automation is harmful, resulting in less innovation because only people can develop ideas to improve processes and products.	Consequently, robotic implementation is evolving on a different path in the U.S. and other mature economies. In many cases, robots are employed to complement rather than replace workers. This concept, known as “cobotics,” teams operators and machines in order to make complex parts of the assembly process faster, easier, and safer. Cobotics is rapidly gaining momentum, and successful implementations to date have focused largely on specific ergonomically challenging tasks within the aerospace and automotive industries. But these applications will expand as automation developers

			introduce more sophisticated sensors and more adaptable, highly functional robotic equipment that will let humans and machines interact deftly on the factory floor.
Augmented Reality (AR)	Some industrial manufacturing companies are using this technology to provide hands-free training, enable faster responses to maintenance requests, track inventory, increase safety, and provide a real-time view of manufacturing operations.	In more than a few instances, these added services could be sold as add-ons to the equipment itself, creating a new revenue stream for industrial manufacturing firms. Among the possible applications is an assembly-line instructional feature in which video clips or text instructions	Another possibility involves using data and physical evidence retrieved by augmented reality on the factory floor to design new equipment that addresses the shortcomings of present-day devices on the assembly line.

		walk workers through complex processes step-by-step. Mistakes resulting from fatigue or on-the-job pressure are eliminated	
3D Printing (Additive Manufacturing)	Early adopters among industrial manufacturing companies are using 3D printing to manufacture parts in small lots for product prototypes, to reduce design-to-manufacturing cycle times, and to dramatically alter the economics of production. For example, BAE Systems turned to 3D printing when it could no longer secure a critical injection-moulded	The company saved more than 60 percent on the cost of the part, avoided retooling costs, and shrank production lead times by two months.	3D printing is still in its infancy, and the technology is currently limited in the performance specifications of the products it can produce. But companies must begin planning for the incorporation of this technology now. As an initial step, industrial manufacturing companies should apply 3D printing technology to the product development and prototyping process, where its speed and flexibility can spur innovation and reduce time-to-market.

	plastic part for a regional jetliner.		The next step could be to use 3D printing to make highly specialized, low-volume parts that are components or subassemblies of finished products, or to create tools for the moulding, casting, or forming of products.

(Source: Compiled from Bono & Pilsbury, 2016).

These new and emerging technologies could directly or indirectly pave way for the future design and production industries. One of the concepts of the future design and production industries that is also starting to appear in literatures and that it is relevant for this research is the concept of **Industries 4.0**. This concept originates from the German Governmental working group on promoting the high-tech to promote computerization of manufacturing. It refers to the current trend of automation and data exchange in manufacturing technologies (Otto, Pentek & Hermann 2016). The digital revolution this century could well be seen as a catalyst for the Industries-4.0 in the sense that the Internet of Things (IoT) transforms, '…*the physical world into a type of information system through sensors and actuators embedded in physical objects and linked through wired or wireless networks via the Internet Protocol'* (Tschiesner & Loffler 2016: 1). In manufacturing, this IoT could pave way for machines, work pieces and systems to be connected and business intelligent networks could be created along the entire value chain to control each other autonomously (ibid). With the invention of CAD and CAM computer software programs and computerized production machines it has finally come to a stage when it is possible to integrate design and production.

The capacity of Ub-Fablabs to integrate the two processes where customers are empowered to design and produce using the latest high-tech digital fabrication production machines, CAD and CAM software programs will be investigated in this research.

2.10 Summary of Chapter Two

Parts one and two of this chapter began by taking a tour back in history to see how evolving technologies and education pedagogy developed over time to give rise to makerspaces like the fablab.

Part one then particularly deals with the principal concepts associated with the cognitive processes in design process in Ub-fablabs. The design process, being a problem –solving activity required review of literature into the concepts of knowledge and thinking processes involved in solving a problem, in the case of Ub-Fablabs, the solution being the product or prototype. Because the design process involves thinking processes, the brain is also discussed to see how it relates to the thinking process. The methods of aligning these cognitive processes with the design process in Ub-Fablabs brings in the discussion on the Bloom's Revised CPA Taxonomy.

Part two of this chapter discussed mainly the current practices of design and production and how it has contributed to an increase in the wastes produced, high energy consumption and the concentration of skills to only the 'experts' in each section of design and production and the need for citizens to be equipped with the 21st century skills. The new ways of addressing these issues include the components of sustainability and embracing new technologies. This thus calls for platforms like the Ub-Fablabs to incubate proactive minds for the future design and production industries.

The next chapter, chapter 3 looks at the conceptual pathway in which to take to find answers to the two research questions.

Chapter 3

3 Introducing the Nawita Design Process Model (NDPM) & the Ub-Fablab Capacity Indicator Scale (Ub-Fablab CIS)

3.1 Background

The previous chapter, chapter 2, discussed how technological/industrial and educational pedagogies contribute to the rise of fablabs. This discussion, in a way, alerts one to the fact that technologies are evolving so fast that what may be applicable today may not be applicable in ten years' time. Therefore, platforms such as the fablab platform must be one that has certain characteristics that can prepare citizens for the future. The later parts of chapter two discussed the principal concepts that pertain this research. The review of literature in chapter two therefore has enlightened the conceptual pathway that this research to take to find answers to research questions one and two that guided this research.

According to the literature review in part 1 of chapter 2, the design process in the fablabs, being classified as a problem-solving activity involves a rigorous amount of Bloom's highest level of thinking like critical thinking and creative or innovative thinking. These rigorous thinking processes are unleashed through the psychomotor and affective observable behaviours. However, these processes, being embedded in the design process itself, need a mechanism for the researcher to bring to surface those cognitive processes in order to align them with the design process. To carry out this process, the researcher developed an iterative design process called the 'Nawita Design Process Model (NDPM)' (see Model 1) to align cognitive processes during the design process. For the alignment process, the researcher used the Blooms Revised Taxonomy of cognitive, psychomotor and affective domains of learning. These are discussed in part one of this chapter.

The literature review done in part two of chapter 2 led the researcher to propose a requirement assessment matrix and an Ub-Fablab Capacity Indicator Scale (Ub-Fablab CIS) to assess the capacities of Ub-Fablabs. This is to see where Ub-Fablabs are in readiness to prepare citizens for the future design and industrial challenges. The requirement matrix and the indicator scale are discussed in part two of this chapter.

Part One

3.2 Introducing the Nawita Design Process Model (NDPM)

To study the cognitive processes embedded in the design process in the fablab, one has to follow some certain sign-posts or stages to track the activities and to be able to align the cognitive processes with the design process. Since there is no detailed design process model that students follow during the design process, the researcher has developed an iterative design process model called the '**Nawita Design Process Model (NDPM)** (Figure 3.1). The name 'nawita' is the Bislama name (Bislama is the national language of Vanuatu, an island in the Pacific Ocean) for the sea creature, the 'octopus'. The name 'nawita' is specifically chosen for two reasons:

1 *Resemblance & Cohesion:* The structure of the NDPM closely resembles the physical appearance of a nawita (an octopus). The Tentacle-like structures projecting from both ends of the model holds the stages in the design process together. This signifies cohesion and a robust nature of the model.

2 *Camouflage (Adaptive Feature):* A nawita (octopus) can camouflage to adapt to any environment to prevent itself from its predators. The NDPM consists of 4 simple stages that could be easily modified to fit in any type of learning environment.

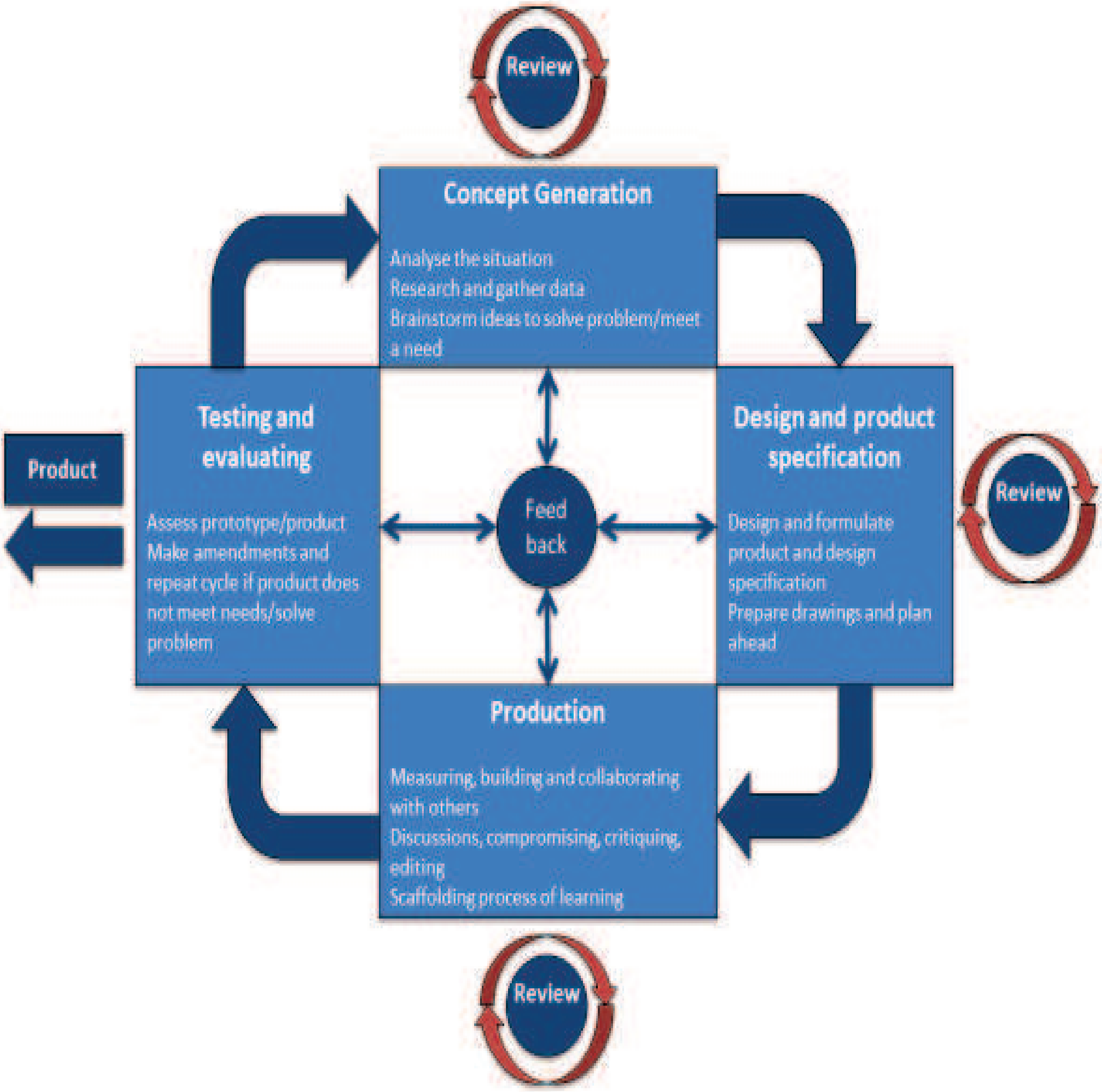


Figure 3,1 The Nawita Design Process Model (NDPM)

3.2.1 The main features of the NDPM

The Iterative nature of NDPM

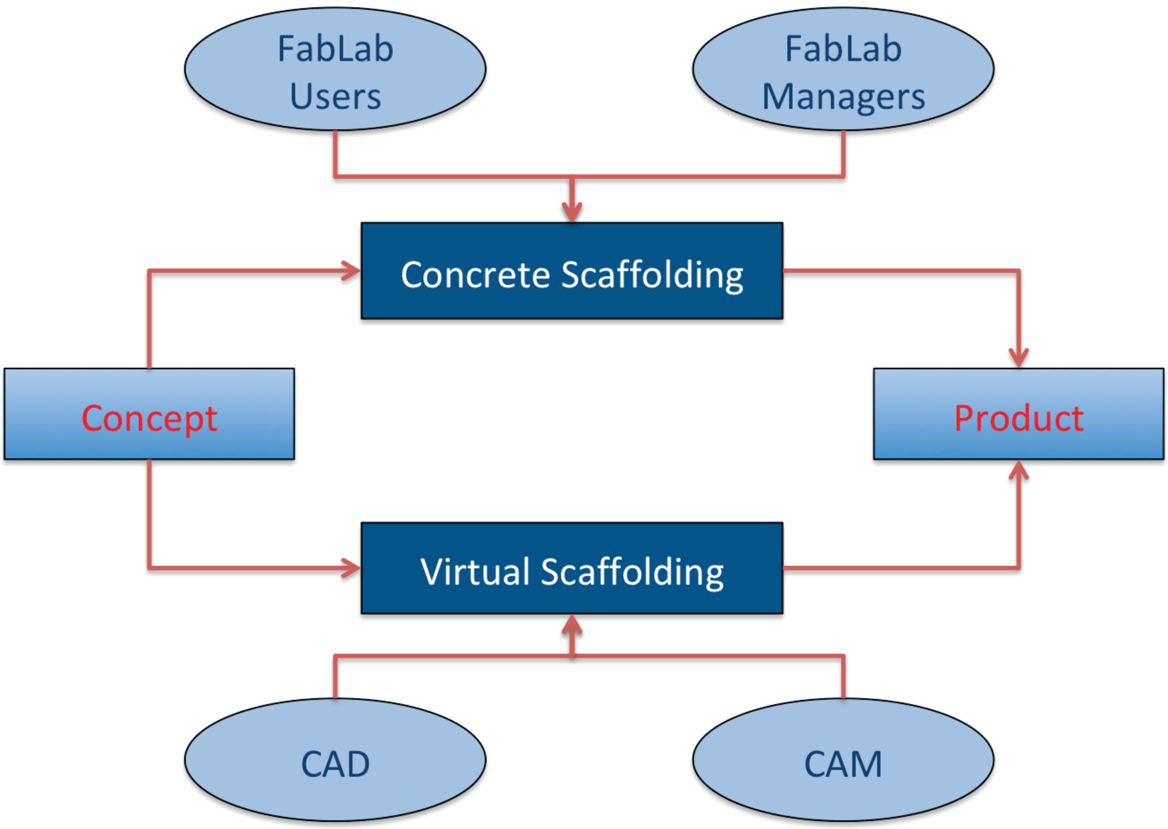
The iterative nature of the NDPM makes it a useful and relevant design model for use in Ub-Fablabs. As students iterate through the 4 stages of the NDPM, they will develop a better understanding of the materials, tools, requirements or specifications and will be more likely to arrive at a more favourable solution to the problems needed. Martinez and Stager (Martinez & Stager, 2013) stated that every time the students, '…*take a step forward, backwards or sideways they gain confidence in their own ability to decide what is worth keeping and what is needed to be tweaked* '(p. 76). According to Schunn (Schunn, 2009 cited in Martinez & Stager, 2013), multiple design cycles like the one presented in NDPM enables children to develop children to develop a more complex, more complete understanding of relevant engineering concepts. Early in a design task, students tend to focus on superficial aspects of models, often misunderstanding the functional aspects of the design and making poor conceptual connections between models and engineering designs (p.50).

The incorporation of Review and Feedback Processes into NDPM

The NDPM has incorporated into the model the *Review and Feedback processes* for each stage. This allows iterations to take place within each stage through the review process and within the cycle through the feedback process. By constantly reviewing and giving and getting feedbacks from others in the group at each stage of NDPM help students to correct their own mistakes without the facilitators' intervention. This also helps students to invent different pathways to solving a problem. The model also indicates an Exit in the cycle where the prototype or product actually leaves the design process once one is satisfied with the final product. According to Rheingold (Rheingold, 2011 cited in Martinez & Stager, 2013), '…a lot *of best experiences come when you are making use of the materials in the world around you, tinkering with the things around you, and coming up with a prototype, getting feedback, and iteratively changing it, and making new ideas, over and over, and adapting to the current situation and the new situations that arise'* (p. 37).

Vygotsky's ZPD and KMOs in NDPM

As students iterate throughout the NDPM stages, the Vygotsky's KMOs scaffolders play a very important role. The researcher in this research refer to these scaffolders of learning as 'Concrete Scaffolders' and 'Virtual Scaffolders'. Concrete Scaffolders are human helpers whom one can communicate with during the design process, for example, the other students or the fablab gurus or managers. Virtual Scaffolders, on the other hand, are the non-human helpers during the design process, for example, the embedded computer software programs such as the CAD and CAM (see Figure 3.2). These are taken into account when tracking and aligning cognitive processes with the design process using NDPM as they play a very important role in assisting the students extend their ZDP.



Fugure 3.2: the Scaffolding process in an Ub-Fablab

3.2.2 Theoretical support for NDPM

The learning by tinkering, making and engineering using NDPM is consistent with the theories of Piaget, Dewey, Vygotsky and Papert, to name a few. Piaget emphasised the need for a learning environment grounded in action. Activities in a fablab perfectly fits this description and NDPM will certainly be appropriate to analyse cognitive processes associated with this real and material actions. Using his own words, Piaget stated that:

Abstraction is only a sort of trickery and deflection of the mind if it doesn't constitute the crowning stage of a series of previously concrete actions. The real cause of failure in formal education is therefore essentially the fact that one begins with language instead of beginning with real and material action (Piaget, 1976 cited in Martinez & Stager 2013, p. 14).

The **encoding process** (see chapter 2) is enhanced by the cognitive processes in the brain (Piaget 1952). According to Piaget (Piaget, 1952) the incoming stimuli is **adapted** by the cognitive process of **assimilation, accommodation** and **equilibrium** in line with the 'schema' or '**schemata'** (plural of schema). A schema as 'a cohesive, repeatable action sequence possessing component actions that are tightly interconnected and governed by a core meaning'. Piaget called these schemas the basic building blocks of intelligent behaviour-a way of organizing knowledge. It can be thought of as 'units' of knowledge, each relating to one aspect of the world, including objects, actions and abstracts concepts (McLeod 2009, p. 3). Wadsworth (Wadsworth, 2004 cited in McLeod, 2009) suggested that the schemata (plural of schema) can be thought of as 'index cards' filed in the brain, each one telling an individual how to react to incoming stimuli or information. McLeod (McLeod, 2009) has complied a diagram depicted how these processes work (Figure 3.3).

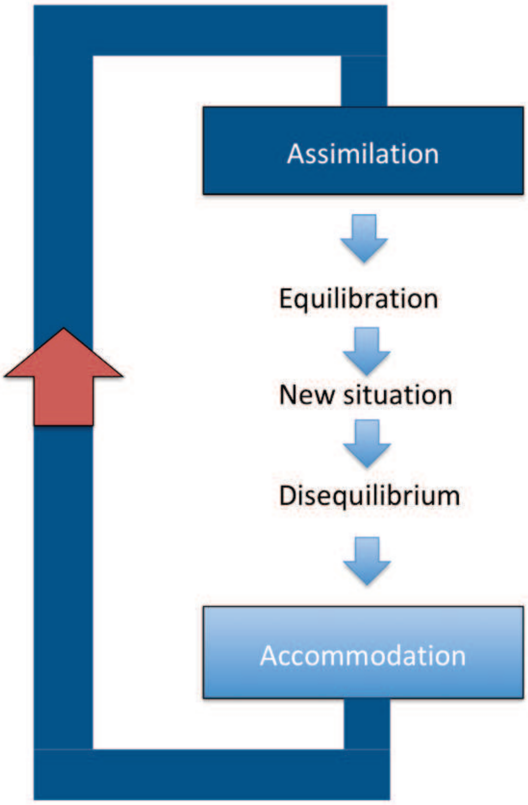


Figure 3.3 Assimilation, Accommodation & the Equilibrium Process (Piaget's Theory)

[Source: http://www.simplypsychology.org/piaget.html]

Piaget believed that the cognitive development did not take place at a steady rate, but rather in leaps and bounds driven by the equilibration force. Whenever there is an incoming stimulus, assimilation takes place using existing schema to deal with the new object or situation. Equilibrium can take place only if the child's schema can deal with the incoming stimuli or new object or situation. If the incoming stimuli does not suit the existing schema, adjustments have to be made to deal with the new object or situation, thus be accommodated. Once the new information is acquired the process of assimilation with the new schema will continue until the next time we need to make adjustments to it (McLeod 2009, p. 5). This process perfectly fits into the NDPM iterative model and will be explored in this study.

The NDPM is also consistent with John Dewey's work. John Dewey stated that in order to effectively solve problems, there are equally two things that problem solvers (in this study, the fablab users) need to know.

1 the problem grows out of the conditions of the experience being had in the present, and that it is within the range of the capacity of students

2 that it is such that it arouses in the learner an active quest for information and for production of new ideas. The new facts and new ideas thus obtained become the ground for further experiences in which new problems are presented. The process is a continuous spiral.

(Dewey, 1938 cited in Martinez & Stager 2013, p. 14).

3.3 Defining the four stages of NDPM

3.3.1 NDPM Stage 1: Concept Generation

Design being a complex activity associated with the problem-solving activity often starts with the users constructing his or her own representations of the design problem. The mental representations evolve as the problem solving progresses (Newell et al, 1962; Simon, 1995; Bonnardel & Mameche 2005; cited in Eastman, 1968). Bloom's higher-order thinking (HOT) skills that occur in this stage include critical thinking and creative thinking which involves evaluation of the ideas generated to solve the problem, synthesising ideas and developing them into design options, collecting comparing and contrasting relative strengths and weaknesses of the possible solutions, and making decisions on the best solution is needed at this stage (Ankiewicz, 2015).

This stage can involve a significant amount of time to locate information, do research and brainstorm ideas to solve the problem encountered. Locating information and researching into the alternative solutions to the problem may involve internet searches, using the libraries and collaborating with other members in the group.

Digital skills needed for the research in this stage may include googling, texting, website searches. Mechanical skills include operating a computer.

Defining the aesthetics of the product and the main functional aspects of the products are also defined in this stage.

In an Ub-Fablab where students carry out their projects, one will expect a lot of interactions and discussions between the students. These OB associated with these interactions and discussions are categorised under Bloom's Affective domains. Mercer et al (Mercer et al, n.d. cited in FitzGerald, 2012) mentions three social modes of discussions that are also relevant to this study. These are cumulative, disputational and exploratory talk. He defines these three modes as:

Cumulative dialogue centers around the contributions of others without much challenge or criticism while disputation talk, as its name suggests, contains high levels of disagreement. Exploratory talk is considered the most advantageous of the three, as it enables learners to develop shared understanding through reasoned discussions, challenging ideas and examining/evaluating evidence (p.2).

The reviewing process at this stage will help polish up the ideas before one proceeds to stage 2 of NDPM.

3.3.2 NDPM Stage 2: Design and Product Specification

Stage 2 of NDPM defines the design and product requirements. The design and product requirements include things like the functions, attributes and specification, CAD and CAM software parameters.

The concepts generated in stage 1 will start to unveil in this stage and will be translated into either 2D or 3D design. The tools needed for this stage for the unveiling process could include paper and pencil for 2D drawings, clay models or CAD software programs for 3D drawings. To produce a 3D sketch of the prototype/product in this stage using a CAD software programme like the sketchpad or solid works, this requires additional knowledge and skills in the engineering domains of electrical and embedded software operation skills.

Mathematical knowledge and skills involved in this stage includes working out the geometry and dimensions of the prototype/product. Critical analysis of the raw materials, the techniques and sequencing of the steps in assembling these components to give you the product is needed in this stage. Drawing either 2D or 3D sketches in this stage also needs mathematical knowledge and skills in order for your drawings to be drawn to scale. The dimensions of the sketched products, the orientations and also using correct measurement units. The data collected on mathematical, engineering, tools and raw material specifications are often presented in a form of a table or database. This also requires some knowledge of using the Microsoft Office tools.

Identifying and selecting raw materials at this stage requires Vries (Vries, 2002)'s cognitive (explicit) and procedural knowledge (tacit) sub-categories of technological knowledge that are listed below:

1 Physical nature knowledge – knowing the physical properties of the materials to be used and of the final prototype/product is needed
2 Functional nature knowledge- the functional properties of the materials and the prototype/product is important
3 Means end knowledge – knowing the relationship between the physical and functional properties of the materials and the products
4 Action knowledge – knowing the methods of and sequencing of steps in processing and joining processing and the sequencing of steps in production.

Identifying, locating and familiarising one-self with the machines and tools and determination of the production processes and its sequencing is also an important activity in this stage. In an Ub-fablab, there is a choice of the high-tech production machines and conventional machines and tools to use for production. Once the tools and machines are identified, it is necessary that individuals assess their own strengths/skills in operating the machines/tools or the 3D printers. This assessment might imply extra knowledge needed to state the function of the machines and training needed by the users to operate the machines/tools.

Because of the nature of the iterative NDPM, it is always possible to return to a previous phase or even to the concept or research phase if something does not work out in one of the stages. Once all the data is collected one is ready to bring the virtual representation of the product to reality in stage 3 of NDPM.

3.3.3 NDPM Stage 3: Production

The design and product specifications formulated in stage 2 of NDPM help one to materialise the virtual representations incubated in stage 1 of NDPM in this stage. The two main manufacturing processes dominate this stage of NDPM are the additive manufacturing process and the subtractive manufacturing process. Although in a much little scale compared to large manufacturing companies these processes still play critical roles in the design process in a fablab. Additive manufacturing (often a synonym for 3D printing) involves depositing materials in layers to construct the prototype/product. In the fablabs, many parts are constructed using this manufacturing process. Subtractive manufacturing, on the other hand, is a process where the prototype/product is formed by successively subtracting or cutting materials away from a solid block of material. Fablab users will be mainly using the 3D printers for the additive manufacturing process and the CNC machines and occasionally some conventional tools for the subtractive manufacturing process.

The utilisation of major engineering knowledge and skills are displayed in this stage of NDPM. The major engineering disciplines involved in this stage are the mechanical, electrical and embedded software application skills. To make analysis in chapters 4 and 5 easier for readers to follow, the researcher coined the acronym MEE to refer to these engineering disciplines. The MEE skills are categorised under Bloom's psychomotor taxonomy.

Mechanical skills in this stage involves calibration and operation of machines. Mechanical knowledge of the temperatures at which the production machines operate is also needed. For example, operating the 3D printer itself requires mechanical skills in operating and calibrating the machine. A knowledge of the difference parts of the 3D printers is also required so one correctly and safely operate the machine. In fablabs, the main filaments used by the 3D printers are either the PLA or ABS plastic filaments so knowing the properties of these filaments will help one to calibrate the 3D machines to suit the temperature required to melt the plastic filaments.

Moving from the 2D or 3D sketches to the real product requires application of knowledge and skills in running the embedded software. Due to the nature of NDPM, if one realises that he/she does not know what to do with the CAD and CAM software programs at this stage he/she can always go back to stage 2 or stage 1 of NDPM to do more research before continuing with the creating.

Mathematical knowledge and skills such as measuring and calculating the diameter, area, circumference, lengths, widths using calculators and measuring-tapes or rulers will be observed in this stage as well.

In an Ub-Fablab where students carry out their projects, it is expected that a lot of interactions between the students take place thus the OB that involves Bloom's affective domain of learning is expected to show an increase at this stage. Students will be expected to be discussing, making decisions, analysing, synthesising and making evaluations. Vygotsky's scaffolding process (both concrete and virtual scaffolding) will also be likely to be more evident in this stage.

3.3.4 NDPM Stage 4: Testing and Evaluation

This stage of NDPM involves trying out the prototype/product. For example, if it was supposed to be a motor you are building, try it out to see if it runs as intended to. If it does not run, check to see what may be causing the problem. The problems that the motor does not work might be:

1 Conceptual – you built the wrong type of motor to fix the problem you encountered. If this is the case with your product, the possible nest step to take is to repeat the NDPM cycle starting at stage 1 to rethink and research ways to solve the problem at hand.
2 Specification problems – you may find out that a wrong material was used for one of the parts of the motor. In this case the possible step to take is to iterate back to stage 2 to re-formulate dimensions and specifications
3 Mechanical problem – if it was just a little twist that has to be re-done, the possible next step is to iterate back to stage 3 to fix it

If the product (motor in this example) works as intended to then the product EXITS the NDPM cycle.

This stage also involves a lot of thinking processes. To critically evaluate the end products involves Bloom's higher order levels of thinking. These will also be investigated in those research. Ub-Fablab users will be more likely to be spending time debating, discussing, evaluating so a lot of Bloom's affective domains will also be evident in this stage of NDPM.

Part Two

3.4 Defining a criterion to assess the capacity of Ub-Fablabs.

Drawing from a whole wide range of proposals and discussions in the literatures in chapter 2 on best mechanisms and infrastructures to promote the 21st century skills and incubate proactive minds for the future design and production industries, this study proposes a requirement matrix (Figure 3.4) of aspects that are critical for the Ub-Fablabs to cater for their proposed purposes.

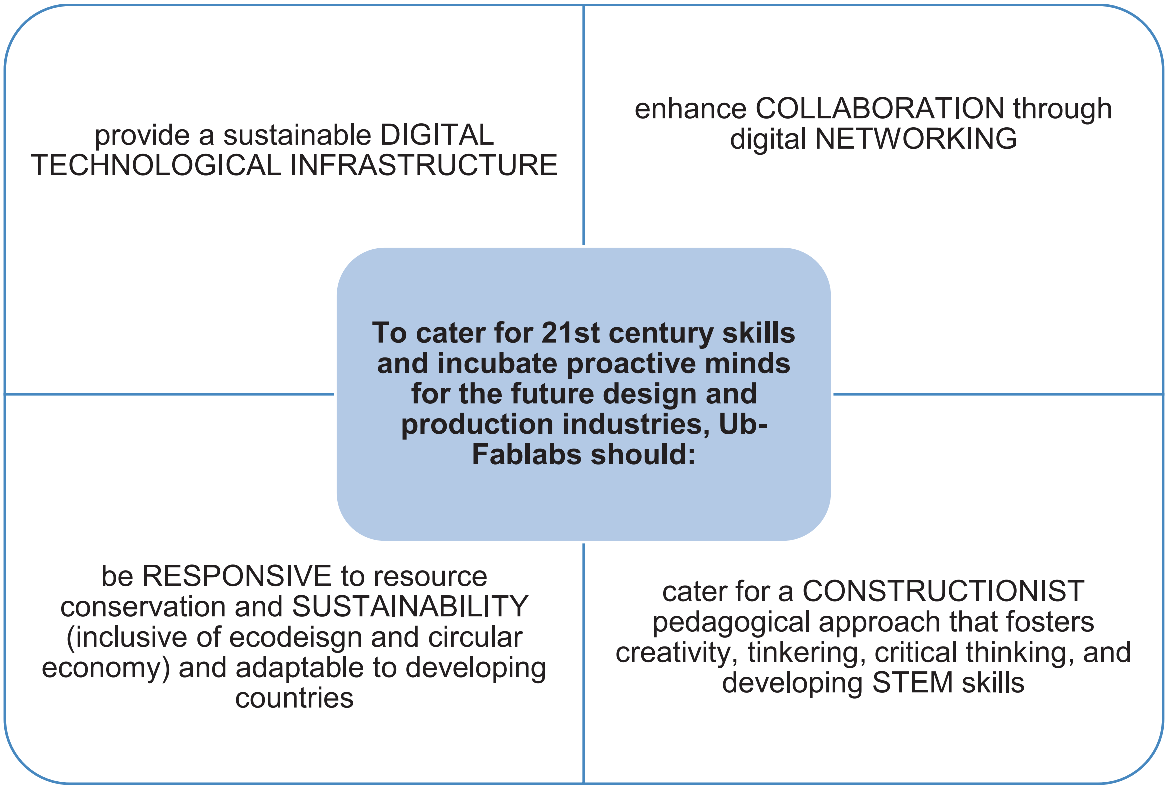


Figure 3.4: Ub-Fablabs proposed requirement matrix

The four critical aspects are:

1 provide a sustainable digital technological infrastructures (refer to chapter 1 for details of this requirement for fablabs, for which, Ub-fablabs is part)
2 enhance collaborations through digital networking (refer to chapter 1 for details of this requirement)
3 cater for a Constructionist pedagogical approach

This aspect needs special attention. In order for citizens to achieve 21st century skills from an Ub-fablab, students have to feel free to design and produce anything he/she wants to produce while at the time learns to collaborate with others. The thinking processes discussed in earlier chapters need to be utilised. Quite often when dealing with complex and abstract knowledge, there is a threat that teachers might rely on transmission models where students are asked to follow instructions and plan every step before doing. Resnick and Rosenbaum (Resnick & Rosenbaum, 2013 cited in Davies & Hardy, 2016) warns that this pedagogy '*saps all spirits from the activity'* (p.164). Several authors have offered suggestions that to deal with such situations, tangible objects can be used to construct knowledge through problem-solving activities (Perner-Wilson & Buechley, 2013; Resnick & Rosenbaum, 2013; Wilkinson & Petrich, 2013 cited in Davies & Hardy 2016). This problem-solving involving tangible objects is referred to by Resnick & Rosenbaum (Resnick & Rosenbaum, 2013 cited in Davies & Hardy, 2016) as 'tinkering'. All these approaches draw from Papert' Constructionist approach to learning which attributes 'objects-to-think-with' as a source of deeper classroom learning (Papert, 1991).

1 be responsive to resource conservation and sustainability (inclusive of eco-design and circular economy) (refer to Part two of chapter 2 for details of this requirement)

3.5 Introducing the Ub-Fablab Capacity Indicator Scale (Ub-Fabab CIS).

To be able to assess the capacities of the Ub-Fablabs to see if they meet the requirements discussed in chapter 2, the researcher developed what the researcher called an Ub-Fablab Capacity Indicator Scale (Ub-Fabab CIS). The Ub-CIS is outlined in Table 3.1.

Table 3.1: An Ub-Fablab Capacity Indicator Scale (Ub-Fablab CIS).

	The indicators of Ub-Fablab Capacity		
Aspects	**Level 3 (Outstanding Ub-Fablab mechanisms/systems and Infrastructures)**	**Level 2 (Substantial Ub-Fablab mechanism/systems and infrastructures)**	**Level 1 (Ub-Fablab yet to provide mechanism/system and infrastructures)**
Digital Technological Infrastructures	Fully equipped with the latest digital fabrication machines /tools for production : Additive machines (3D printers), subtractive machines : (CNC Milling, Laser cutters and	Equipped with only a computer with internet connectivity ; only digital subtractive and conventional machines and tools	A computer and internet connectivity without any digital fabrication machines

	Etchers, Precision Milling, Vinyl Cutter), Circuit Production, CAD and CAM software programs ; Conventional machines/tools also used to complement digital machines/tools ; Information easily accesses through internet use via the fablab website : https://www.fablabs.io/labs		
Constructionist Pedagogical approach	Fablab environment conducive to rigorous approach to hands-on constructions and an environment where users collaborate to design and produce using digital fabrication machines; CAD and CAM software programs allowing iterations between each stage of design to enhance Science, Technology, Engineering and Mathematics (STEM) knowledge and skills; Open access status to allow a gender-neutral environment to promote female participation in STEM fields.	The fablab environment is not too conducive for collaborative designs; iterations using CAD and CAM software programs restricted.	There are very little hands-on activities in the fablabs with mainly conventional machines and tools.
Collaboration through digital Networking	Internet connectivity and in-dept information accessed via the fablab website : https://www.fablabs.io/labs active participation in fablab forums, sharing of information and designs with other Ub-Fablabs	Internet connectivity accessed via the fablab website: https://www.fablabs.io/labs; sharing of designs/projects with other Ub-Fablabs, but no active participation in fablab forums.	Access to internet connectivity and information accessed via fablab website: https://www.fablabs.io/labs; but no active participation in forums and sharing of designs/projects.
Sustainability (inclusive of eco-design and circular economy)	Well ventilated, spacious and attractive fablab building, some use of renewable energy sources, and use of eco-design materials (biodegradable or compostable), and additive manufacturing process that reduces waste (indicator: use of additive machines (3D)).	Well ventilated building, but does not use any form of renewable source of energy and the use of mainly subtractive machines/tools contribute to waste production	Crowded and dull looking building /room with a lot of waste produced from subtractive and conventional machines/tools.

The Ub-Fablab CIS will be used in part II of data collecting process.

3.6 Summary of Chapter 3

Part one of chapter three discussed the tentative iterative design process model, the NDPM that the researcher intended to use to track the activities that happen during the design process in an Ub-Fablab. Because part one aims to investigate the cognitive activities that are embedded in a design process, this iterative design process model was necessary. The main features of NDPM were discussed and the main activities expected in each stage of NDPM are described. The theoretical support for NDPM was also provided.

Part two of chapter three proposed a requirement matrix outlining the proposed capacities of Ub-Fablabs that may be required to qualify it to cater for the 21st Century skills and also incubate proactive minds for the future design and production industries. An Ub-Fablab CIS was formulated to assess the capacities of these Ub-Fablabs.

The next chapter, chapter 4 discusses the methodologies that this research will employ.

Chapter 4

4 Methodology

4.1 Background

The previous chapter, chapter 3 has introduced two instruments that the researcher developed to utilise to guide the researcher in gathering data to explore answers to the 2 research questions that guided this research. The two questions that guide this research:

1. What are the cognitive processes (inclusive of cognitive, affective and psychomotor domain) embedded in the design process in the fablab?
2. How efficient are Ub-fablabs in contributing to equipping citizens with the 21st Century Skills and incubating proactive minds for the future design and production industries?

The research methodology is divided into two parts. Part I of this chapter looks at how the researcher went about finding answers to research question 1 while part II looks at the methods the researcher employed to find answers to second research question.

4.2 Rationale of main research approach chosen

This study uses a pragmatic approach of research where both quantitative and qualitative research methods, techniques and procedures are used interchangeably throughout the study. This is to complement the different limitations that each method, technique and procedures in the quantitative and qualitative research could pose at any stage of the study. In adopting the inductive-deductive approach, the nature of this approach has made it useful for the researcher to go 'back and forth' from the conceptual framework (document analysis and literature review in this study) to the empirical inquiry and vice versa checking for match and mismatch, if any, between what is written (in the documents) and what is actually happening in the Ub-Fablabs. Bechhofer (Bechhofer, 1974 cited in Burgess, 1985) has argued that the research process, "...*is a not a clear-cut sequence of procedures following a neat pattern but a messy interaction between the conceptual and empirical world, deduction and induction occurring at the same time*" (p. 7).

The approach chosen also ensured that triangulation of methods is served to enhance the credibility of this study. According to Gay and Airasian (Gay & Airasian, 2000), triangulation is a form of cross-validation that seeks regularities in the data by comparing different participants, settings and methods to identify recurring results (p. 252).

4.3 Methodology used in this study

4.3.1 Document Analysis (Literature review)

In order to gain a better understanding of the potentials of Ub-fablabs on how it could benefit the education and industrial sector, document analysis was used to provide some background information. International literature such as those of the NRC and relevant Internet sites like the MIT CBA websites were consulted to see how the development of technology and education over the decades have impacted and incubated the spur of makerspaces like the fablabs. Writings of Gershenfeld (Gershenfeld, 2012), Gershenfeld (Gershenfeld, 2007), Walter-Herrman (Walter-Herrman, 2013), Blikstein (Blikstein, 2013), Martinez & Stager (Martinez & Stager, 2013) were also consulted to see how the integration of fabrication laboratories into the society could equip citizens to meet these challenges. The following internet websites were also consulted to gather information on fablabs:

1 https://www.fablabs.io/labs
2 https://www.fab.cba.mit.edu/about/faq/
3 https://www.fabfoundation.org/fab-labs

These sources have assisted the researcher to put together the theoretical and conceptual framework in chapters 1, 2 and 3.

4.3.2 Empirical Inquiry

Data gathering involves these main techniques:

1 Observations in a Ub-Fablab in Bordeaux university in France
2 Online Content analysis

It was necessary that the researcher used more than one technique to collect data. This enabled the triangulation of data derived from the different techniques.

4.3.3 Methodology used in Part One

Because it is not possible to directly observe what a person is thinking, this research used a method that is used by theorists in the fields of cognitive psychology, cognitive science and behavioural analysis to study thinking. This method is called 'Protocol analysis' (see Crutcher 1994; Simon and Kaplan 1989; Austin and Delaney 1998 cited in Ericsson, 1993). The researcher took a non-participant observer role in part one of this research and it involved capturing and analysing the OLB aspects of individual performances during a task. This 'task' in a fablab refers to the design process as described in the preceding chapter. The NDPM was used to trace the activities at different stages of NDPM. Alignment is done using Bloom's Taxonomy of CPA.

Participants

Extreme purposive sampling (Flick, 2009) is used in this study. According to Davis (2007, 413) the core sample is the people that make up the 'pivotal target group' and are therefore able to provide the essential insights necessary to answer a projects research question. In this study, there are two separate observations that were made to study the occurrences of OLB in each scenario. To make analysis easier, the researcher calls these two observations, Production Study 1 (PS1) and Production Study 2 (PS2).

PS1: The participants are a Design class of 25 elementary teacher trainees from the Cauderan campus of Bordeaux University in France. These teacher trainees were working on several group projects including designing and creating i) stringed and percussion instruments, ii) honey boxes, iii) tree name-tags, iv) bird houses v) catapult, vi) rock grinding mills, vii) artificial arm. For the purpose of this study the researcher observed very closely the group of four teacher trainees working on the Rock Milling Machine project (RMM, for short). The RMM project involved a range of wood, stone and synthetic material technologies, skills and knowledge.

PS2: The participant in PS2 is one person, producing a chain using a 3D printer.

Data collecting method

The researcher took a non-participant observer role in PS1 and PS2. The activities were documented using field notes, video-recording and still photography.

The supplemented data collection methods involved still photography. Still photography is used in this study to capture certain activities in the design process for a more close-up detail. Photography has been used as a research tool in a lot of the qualitative researches. Photographs used in this study as used as a ‘precise machine-made record of a scene or a subject, where the primary concern is the accuracy with which the subject is recorded on film, in which the subject is the source’ (Byers, 1964; Sekula, 1975 cited in Schwartz, 1990). The photograph becomes a receptacle from which individual viewers draw meanings.

The researcher used the NDPM to track the activities at different stage of the design process. Tables 4. 1, 4.2 and 4.3 (see tables below) are used to record the OLB.

Data Analysis method and tools

The researcher explored OLBs in the categories including: Perceptive, Declarative (Explicit) and Procedural (Implicit) (discussed in chapter 2). Declarative (Explicit) is further divided into 2 sub-categories: episodic and semantic. This is in line with recent researches into brain and cognition (Baddeley 1997; Baddeley 2000; McLeod 2012; Mastin 2010; Boettcher 2008) and the concept of information processing. As recalled from chapter 2, information processing is a 2-way flow of information. These are i) processing information acquired through the senses (also called bottom-up processing) and ii) processing information stored in memory (also called Top-down processing). The discussions of the results in chapter five takes into consideration both the bottom-up processes and the top-down processes.

The first data processing from the raw data collected via field notes, video-recording and still photography as described in the previous section involved categorising the OLB captured and putting them into the appropriate tables. Tables 4.1, 4.2 & 4.3 were used to collect and align the OLB with Bloom’s Taxonomy of CPA.

A graph of behaviour versus activity stages are then plotted and analysed.

Table 4.1: A sample of the table to be used to fill in data for Blooms Cognitive Domain of Learning

Information Processing Source (brain)	Bloom's Domain of Learning	Sub-category	Code	Description of OLB	Corresponding stage of NDPM
Declarative Memory (Explicit) (Episodic and semantic)	Cognitive	Creating			
		Evaluating			
		Analysing			
		Applying			
		Understanding			
		Remembering			

Table 4.2: A sample of the table to be used to fill in data for Blooms Psychomotor Domain of Learning (from most complex to simplest)

Information Processing Source (brain)	Bloom's Domain of Learning	Sub-category	Code	Description of OLB	Corresponding stage of NDPM
Procedural (Implicit)	Psychomotor (inclusive of MEE)	Origination			
		Adaptation			
		Complex Overt Response			
		Mechanism			
		Guided Response			
		Set			
Sensory		Perception (Features, relations, implicit)			

Table 4.3: A sample of the table to be used to fill in data for Blooms Affective Domain of Learning (from most complex to simplest)

Information Processing Source (brain)	Bloom's Domain of Learning	Sub-category	Code	Description of OLB	Corresponding stage of NDPM
Declarative Memory (Explicit) (Episodic and semantic)	Affective	Internalising Values			
		Organizing Values			
		Valuing			
		Responding to phenomena			
		Receiving phenomena			

The results are then displayed using both pie and bubble-chart graphs.

Methodology used in Part Two

Research approach and participants

In part II of this research the researcher took an unobtrusive research approach involving both quantitative and qualitative methods to collect and analyse data. Data was collected from 53 Ub-Fablabs from the seven major regions in the world (Table 4.4) from the fablab website: (https://www.fablabs.io/labs). To abide with cyberspace privacy (Murphy, 2011) the researcher, being a registered member of the fablab network, solely has the access to internal information of fablabs and online projects and thus no mention of specific Ub-Fablabs accessed through the internet searches will be made. Codes were used instead to refer to the Ub-Fablabs, for example, UbF20 refers to Ub-Fablab number 20. This sample represents 90% of the Ub-Fablabs worldwide.

Table 4.4: The sample of Ub-Fablabs used in this research.

Major Region	Number of Ub-Fablabs surveyed	Codes assigned to the Ub-Fablabs
Western Europe	17	UbF1, UbF2, UbF3, UbF4, UbF5, UbF18, UbF19, UbF21, UbF22, UbF23, UbF24, UbF25, UbF26, UbF27, UbF28,UbF33, UbF37,
Eastern Europe	5	UbF16, UbF29, UbF30, UbF31, UbF32
Southern Europe	5	UbF42, UbF43, UbF44, UbF45, UbF46
Northern Europe	5	UbF17, UbF20, UbF34, UbF38, UbF47
Northern America	8	UbF9, UbF10, UbF48, UbF49, UbF50, UbF51, UbF52, UbF53
Latin America	9	UbF6, UbF7, UbF8, UbF11, UbF12, UbF15, UbF35, UbF36, UbF39
Asia	4	UbF13, UbF14, UbF40, UbF41
Total	53	

Data Collecting method and tools

Methods of collecting data involved the Online Content Analysis (OCA). Another term that is appearing now in literature that has a similar meaning is ‘web content analysis’. OCA follows a basic research procedure indistinguishable from the traditional content analysis using offline sources. Content Analysis, defined by several authors as the study of human communication. Human communication could either be oral or written. This research used written texts to collect data relevant to this research (see

Krippendorff & Klaus, 2012; Van Selm, Martine & Jankowski & Nick 2005; Mc Millan, 2000 for details of OCA).

Data Analysis method and tools

Using the Ub-Fablab CIS, a numerical score is assigned to each level. Level 3 = 3 points; Level 2= 2 points and Level 1= 1 point. The scores are tallied in a table (see Table 4.6).

Table 4.5: Table showing the sample of table used to tally scores on the potentials of Ub-Fablabs (Note: only 5 Ub-fablabs are shown here as examples)

University-based Fablabs Codes	**Digital Technological Infrastructures**	**Constructionist Pedagogical approach**	**Collaboration through digital Networking**	**Sustainability (inclusive of eco-design and circular economy)**
UbF1				
UbF2				
UbF3				
UbF4				
UbF5				

The results are displayed using bar charts.

4.4 Summary of Chapter Four

Chapter four discussed the main choice of research approach, how the methodology was implemented through the techniques used to collect and analyse data.

The data collecting method employed for part one of the research was a ‘non participant observer’ in the Ub-Fablab of Bordeaux University in France. This technique was chosen particularly to gain an insight into the activities that happen in an Ub-Fablab. The use of the camera and field note to capture the activities helped the researcher keep in track with the activities and analysis. These will make alignments with the NDPM and the Bloom’s Taxonomy easier to achieve.

The data collecting method employed for part two of this research was an OCA technique. This was used to gain an insight into the technological infrastructures, the internet networking mechanisms, the learning environment and how they cater for sustainability of Ub-Fablabs around the world. With the IoT, data collecting was made through the fablab website without having to physically travel to these Ub-Fablabs to collect data. To physically travel to these Ub-Fablabs will certainly incur a lot of finance and also the research may not be complete within the timeframe of the researcher's doctoral studies timeframe.

The methodology used in this study has now been outlined. The next chapter, chapter five, analyses the data and discusses the cognitive processes embedded in the design process in Ub-Fablabs and align them with Bloom's CPA Taxonomy. It will also analyse the data and discuss the effectiveness of Ub-fablabs in promoting the 21st Century Skills and incubate proactive minds for the future design and production industries.

Chapter 5

5 Results and Discussion

5.1 Background

The data obtained from empirical inquiry using the methodologies outlined in the previous chapter, chapter four, are analysed and discussed in this chapter. To make analysis easier for the researcher and the readers to follow them, this chapter is divided into two parts.

Part 1 of this chapter contains analysis of PS1 and PS2. In PS1, the researcher has observed a group of students working on a project to produce a Rock Milling Machine (RMM). In PS2, the researcher observed a single person using a 3D printer to produce a simple chain. The specifications and instructions have been downloaded from data files.

The NDPM was used by the researcher to track the activities during the design process. An adapted Protocol Analysis rubric was used to analyse the OLB that occurred during the design process. These OLB are aligned with Bloom's CPA domain of learning. The OLB occurring in each stage of NDPM are analysed and graphed followed by discussions of the results for each stage.

Pie charts are over the other graphs because being cyclic in nature, this type of graph could accommodate overlaps of the OLB (e.g. the OLB 'write' could classified as both a cognitive and a psychomotor OLB). Discussion for each stage of NDPM follow after the results for each stage.

Part two of this chapter analyses the capacities of Ub-Fablabs. Using the Ub-Fablab CIS developed in chapter 3 the data collected from the 53 Ub-Fablabs are analysed and results are displayed using line graphs.

5.2 Results and discussion for Part One

5.2.1 PS1 Results and Discussion

The Iterations between the stages of NDPM in PS1

In PS1, the group producing the RMM iterated around the NDPM stages twice before arriving at the final product. Routes 1- 9 are taken to finally come up with their product (see Figure 5.1).

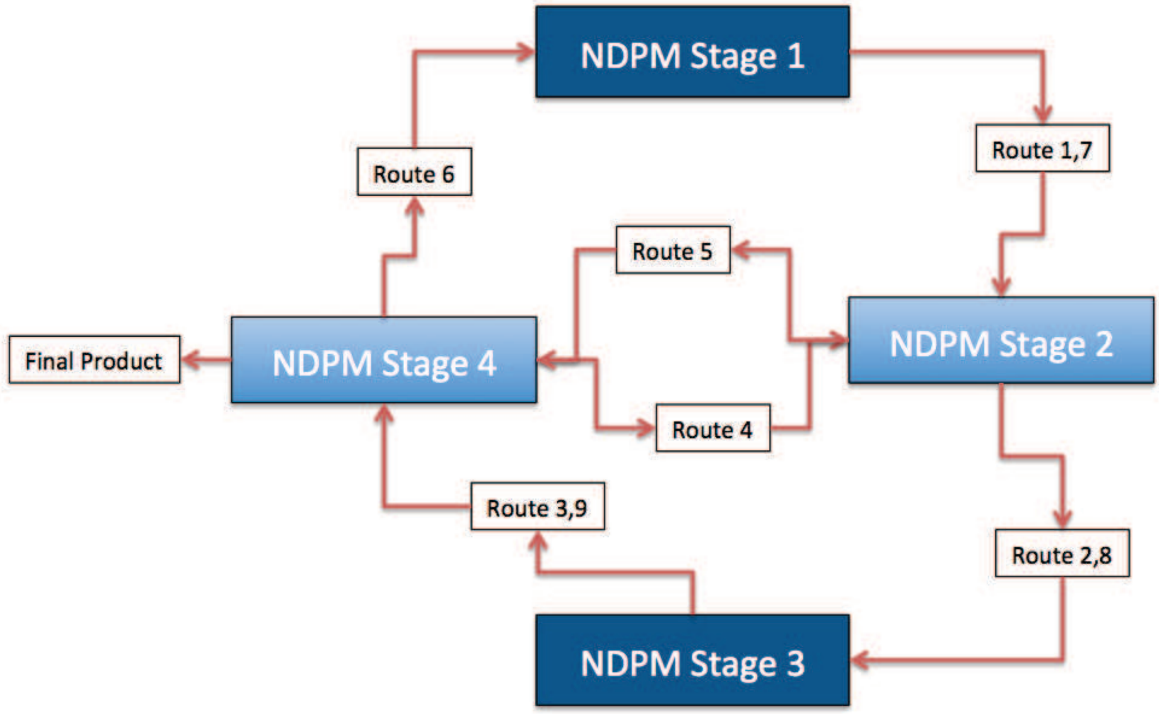


Figure 5.1 The Iteration Pathway in PS1

By iterating through the stages of the NDPM through routes 1-9, a stunning amount of OLB was observed (see Appendix 3 for photographs showing the different activities in each stage of NDPM). In the paragraphs that follow the researcher compiled the OLB results from methodologies outlined in chapter four.

NDPM Stage 1 in PS1

The group producing the RMM started at **stage 1 of NDPM**. The setting of stage 1 was in the Ub-Fablab conference room equipped with a smart white board, tables and chairs and a few computers (see Photographs in Appendix 3). The frequency with which psychomotor, cognitive and affective OLB occurred throughout the design process using the NDPM was recorded in field notes and captured using still photography. Using adapted protocol analysis method, the field notes and still photography was analysed and results are displayed in the tables and figures in this section.

Table 5.1 The types of Bloom's CPA OLB in stage 1 NDPM in (PS1)

Description of OLB	Cognitive (Knowledge)	Psychomotor (Skills)	Affective (Attitudes)
	NDPM Stage 1		
Participate in group discussion			√
Brainstorm of ideas	√		
Define the problem at hand	√		
Classify problem	√		
Operate computers quickly to look up information		√	
Download of information from computer	√		
Analyse strategies to use	√		
Group proceed upon a set of steps during the design		√	
Display of teamwork when working with others		√	
Display of professional Commitment to producing			√
Listening attentively to others in the group			√
Taking notes of what the group discusses		√	
***Google information on replacement part**	√		
*** Re-assess strategies to build replacement part**	√		
***Re-evaluate need to use an additive machine (3D printer) to print replacement part**	√		
***Research new knowledge on 3D printers**	√		
Total (%)	56	25	19

***These are OLB for the 2nd cycle of NDPM**

Analysis of field notes, video-recorded and still photographed activities revealed that NDPM Stage 1 is dominated by 56% cognitive and affective skills each having a 19% occurrences followed by only 25% psychomotor skills

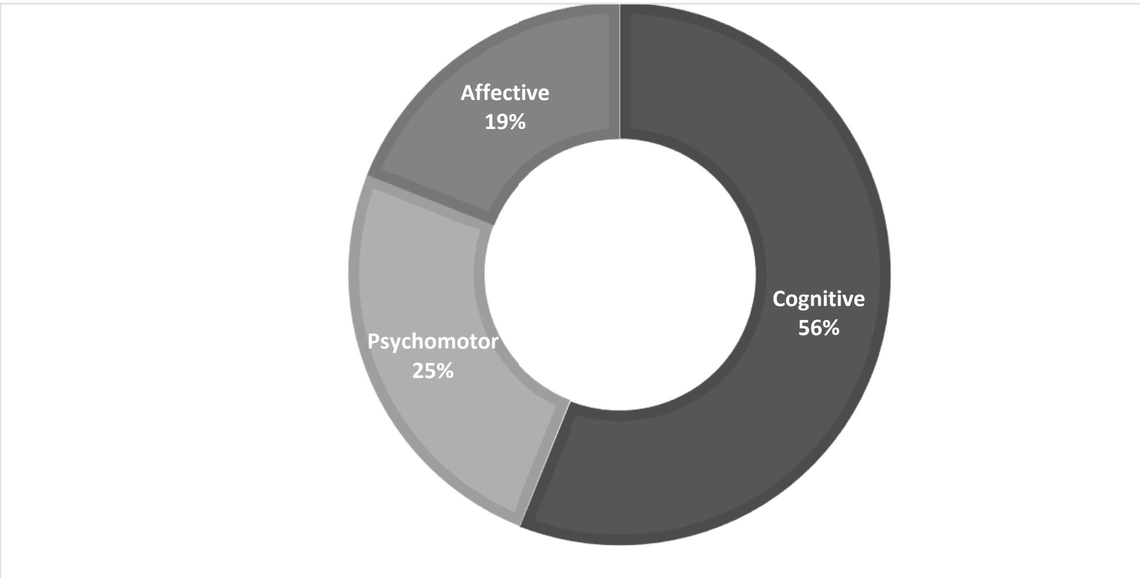


Figure 5.2 Graph showing occurrences of Blooms CPA OLB in stage 1 of NDPM in PS1

Creative thinking and critical thinking (Ankiewicz 2013 cited in Engelbrecht 2016) dominate stage 1 of the design process. This is the stage where it involves a lot of mental representations of the design process. It is a stage where students begin to think about new concepts/ideas to solve problems and also involves 'sifting of information' through critical thinking (ibid). This mental process evolves as the problem solving progresses. Retrieved from LTM to WM is mainly declarative knowledge where users define and categorise problems right through to brainstorming ideas to solve problems.

Retrieval of procedural knowledge from the LTM for processing reflected a computer-related skills or digital skills of the students, knowing how to operate a computer. In this stage it involved operating a computer quickly in this stage to look up information for clarifications and instructions.

Retrieval of metacognitive knowledge from LTM to WM is also evident at this stage as is reflected by Affective skills performed at this stage. The subcategories of 'Receiving Phenomena and Internalizing Values where users listen attentively to others in the group, display of teamwork, and display of professional commitment to producing.

NDPM Stage 2 in PS1

Once the group was satisfied with the choice of a RMM, the group took **route 2 to stage 2 of NDPM.** In stage 2 the group went from the mental representations of the RMM (in stage 1) to producing the 2D image of the product (see photograph 5.1)

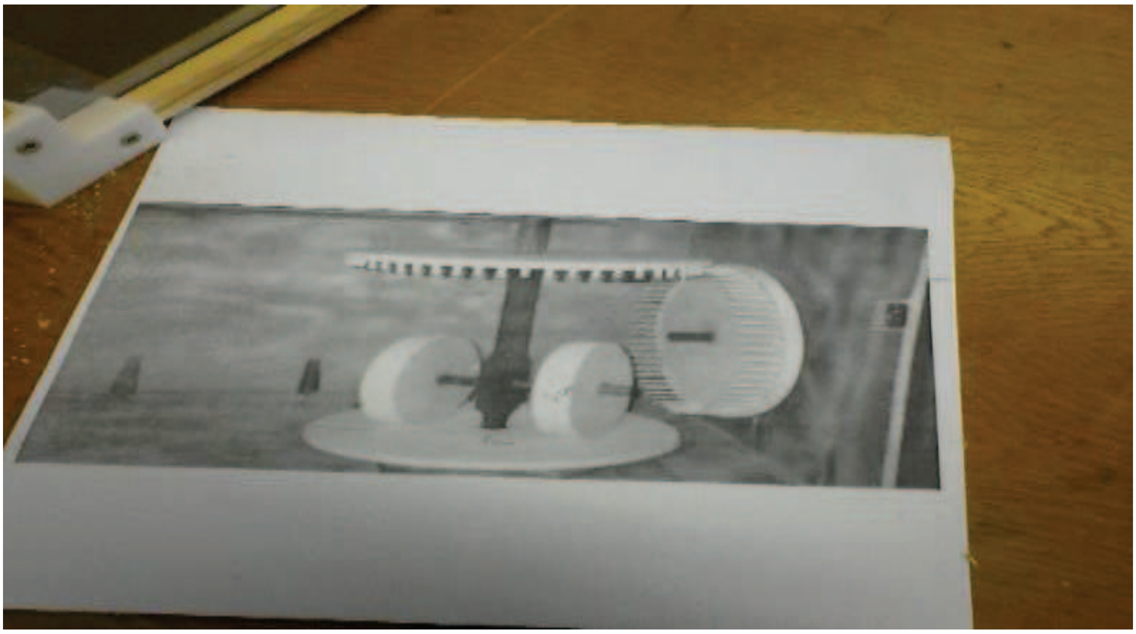


Figure 5.3: The 2D image of the RMM

Based on this image specifications of the product are formulated. The different activities that are involved in this stage of the NDPM are included in Appendix 3.

Table 5.2 The types of Bloom's CPA OLB in NDPM stage 2 of NDPM (PS1)

Description of OLB	Cognitive	Psychomotor	Affective
	NDPM Stage 2		
Participate in group discussion			√
Produce a 2D print of the desired product	√		
Attending to the features of the sketches of the product (shape, angle, size)		√	
Raising of eyebrows and smiles on the face while looking at the sketches and photographs of the product		√	
Identify the materials needed	√		
Write down a list of materials needed		√	
Categorize the materials needed	√		
Compare the properties of the materials	√		
Classify the materials according to their properties	√		
Calculate the dimensions of the product	√		
Combines all materials together for production (stage 3)		√	
Holding the materials and running fingers over them (texture)		√	
Arrange all materials in order of production		√	
Operates a computer quickly throughout the session to look up information		√	
Display of team work Display of processional commitment to producing			√ √
Listen attentively to others in the group		√	
Proceed upon a sequence of steps			√
Display of professional commitment to producing	√		
***Re-assess properties of the replacement part (Cycle2)**	√		
***Re-calculate dimensions of the PLA replacement part (thickness, circumference)**	√		
***Identify parts of 3D printers and how to operate it**	√		
***Learn how to draw a 3D model of replacement part**			
Total (%)	46	36	18

*These are cycle 2 OLB of NDPM

Stage 2 of NDPM showed a rise in psychomotor skill of 36%, 46% of cognitive skills while there is an 18% occurrence of affective skills.

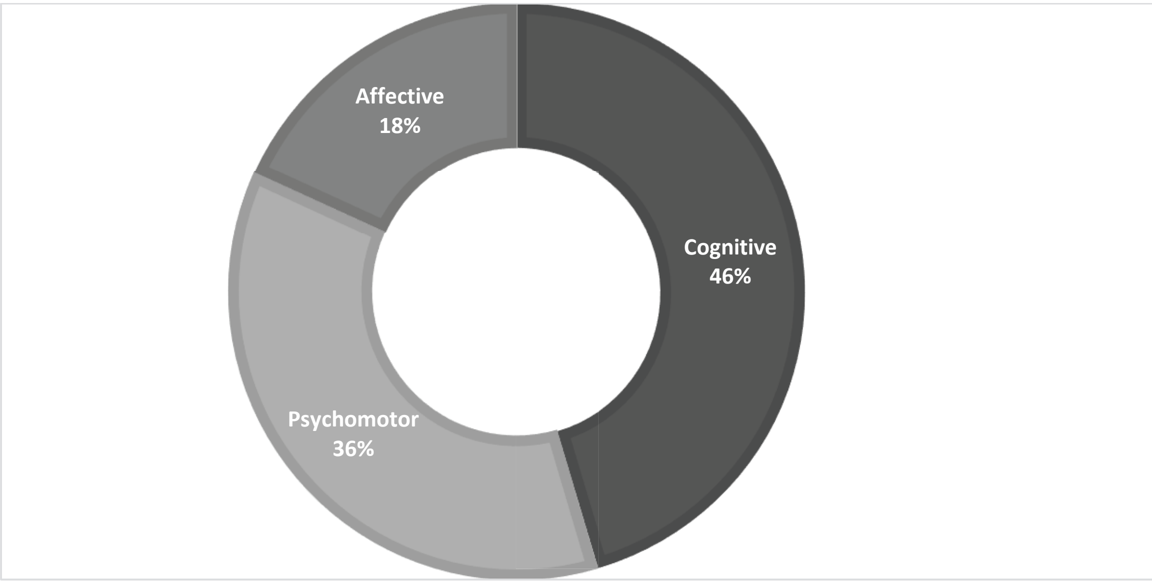


Figure 5.4 Graph showing occurrences of Bloom's CPA OLB in stage 2 of NDPM (PS1)

At this stage, cognitive processes involving the prefrontal lobe (PFL) of the brain and the cerebellum are dominant (Figure 5.4). It is a stage where decision-making, categorising, analysing, calculating, testing, synthesising and evaluating the raw materials, machines to use, product dimensions for the RMM. Retrieval of conceptual and factual information from LTM to WM is reflected by the 46% cognitive observed behaviour.

Retrieval of procedural knowledge from LTM to WM for processing is reflected by a 36% of psychomotor OLB at this stage. The psychomotor OLB falls mainly within the categories of sensory perception, organization and overt complex responses. An important process that took place in this stage involving is the translation and transforming of mental representations done in stage 1 onto paper either using 2D or 3D sketches which involved a combination of cognitive and sensory psychomotor skills.

The 18% Affective OLB falls within four (4) categories: Internalizing values; Organizing values, responding phenomena and receiving phenomena. Because they were working in groups, it was possible to observe this domain of learning in the fablab.

NDPM Stage 3 in PS1

The group then went on to routes 2 to stage 3 of NDPM.

Table 5.3 The types of Bloom's CPA OLB in NDPM stage 3 of NDPM (PS1)

Description of OLB	Cognitive	Psychomotor	Affective
		NDPM Stage 3	
Identify the machines to be used	√		
Calibrate production machines		√	
Operates a computer quickly to look up information		√	
Manipulate production machines		√	
Follow instructions given by the Fablab Manager very carefully		√	
User respond to another group member hand-signals to turn on a production machine		√	√
Display of teamwork			√
Display of professional commitment to producing			√
Show of self-reliance when working independently			√
Demonstrates respect for others during design process (i.e.no physical confrontations, etc.)			√
Offer to assist others who are having difficulties with operating the production machines		√ √	
Users move around the room to read instructions given for each production machine		√	
Proceed with cutting after discussions with other group members			√
Users proceed upon a sequence of steps during the design process		√	
Blend in well with other users in the fablab (a display of value for others for what they are and not how they look)		√	
Assembles parts for connections		√	
Measure the circumference, length and breadth of materials and the object		√	
Quickly grinds rock to shape			√
* Performs tasks using a machine that was not intended to use at the beginning of the design process due to modifications made to original sketch (3D printer to print a plastic part of the RMM)			√ √
Sharing of measuring tools and production machines with others			√
Participate in discussions			√
Questions modifications made by other group members to fully understand the change			√
Adhere to safety rules in the fablab	√		
Answers others politely when asked for assistance	√		
Listens attentively to others and the fablab manager	√		
Monitor the progress of production		√	

Align product specifications with the actual dimensions of the product		√	
Locate the parts of the machines to use		√	
Holding the materials and running fingers over them (texture)	√		
Attending to spatial relation between two space components or area of the product		√	
Attending to the location of an object in a space component of the product		√	
***Using the CAD program to redesign the part that did not fit (cycle 2 of NDPM)**		√	
***Calibration of 3D printer**		√	
***Use CAM program to build replacement part**		√	
***Attending to features of the PLA replacement part**			
***Attending to spatial relation between two space component of the replacement part**			
***Attending to the location of the new replacement part in the space of the RMM**			
Total (%)	14	54	32

***OLB in cycle 2 of NDPM**

In stage 3 of NDPM, retrieval of procedural knowledge from LTM to WM is still dominant in this stage while declarative knowledge remains constant. This is reflected by a tremendous rise in psychomotor of 54% occurrences followed by 32% of Affective skills compared to a consistent pace of cognitive skills of 14% occurrence.

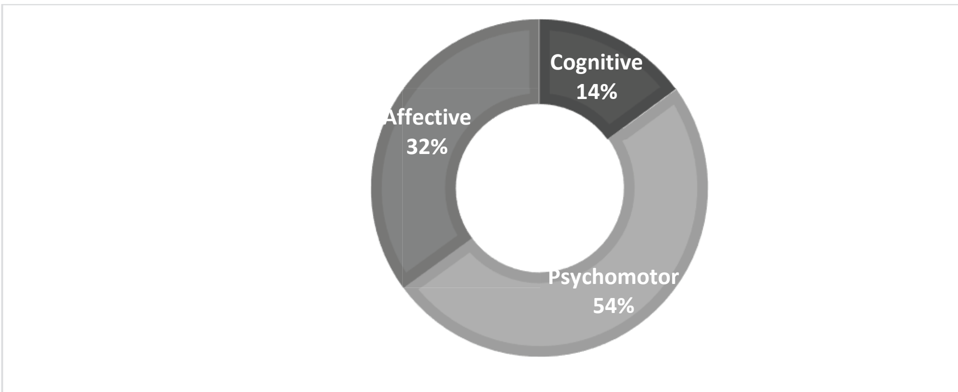


Figure 5.5 Graph showing occurrences of Bloom's CPA OLB in stage 3 of NDPM in PS1

Stage 3 of NDPM is the stage of design best described by Ackerman (Ackerman, 2010 cited in Martinez & Stager, 2013) as, '…*breaking loose from habitual ways of thinking and making dreams come true* (p.39). This dream of arriving at a prototype or product brewed and incubated in stages 1 and 2 has come to fruition at this stage. It is no longer a virtual, but a real object. In this study students have moved from the fablab conference room into the fablab production room where all the digital production machines, conventional machines/tools are and where all the excitement occurs.

Retrieval of procedural knowledge from LTM to WM is still dominant in this stage while declarative knowledge remains constant. This is reflected by a tremendous rise in psychomotor of 54% occurrences followed by 32% of affective skills compared to a consistent pace of cognitive skills of 14% occurrence affective skills consists mainly the category of Internalizing values; Valuing; Responding to Phenomena; Receiving Phenomena. Dialogues at this stage were more of the exploratory, cumulative and disputation where discussions contain high levels of disagreement whilst cumulative dialogue centres on the addition of contributions of others, without much challenge or criticism.

Scaffolding process of learning falls within the affective category of ‘Guided response’ (Figure 3.2) and is shown to consist of people and virtual objects in this study, the fablab manager, the fablab users being the concrete scaffolds while the CAD and CAM computer software the virtual scaffolds. Activities in this phase of NDPM also goes to Posch (Posch, 2013 cited in Walter-Herrman, 2013) says as one of the functions of a fablab.

“A Fablab is a place to make almost anything, and we encourage children to make as much as possible themselves- not only generating ideas but also designing adequate data and operating the machines. The goal is to show potentials and difficulties in dealing with proposed technologies. Being able to master them, with guided help where necessary is a fulfilling experience, while it also gives a realistic insight into skills needed in working with the machines and getting to know their limits (p. 80)

NDPM Stage 4 in PS1

After completing stage 3 of NDPM the students took **route 3 to stage 4 of NDPM**.

The OLB observed in stage 4 of NDPM are outlined in Table 5.4

Table 5.4 The types of Bloom's CPA OLB in NDPM stage 4 of NDPM (PS1)

Description of OLB	Cognitive	Psychomotor	Affective
	NDPM Stage 4		
Attending to features of the finished RMM (shape, size, texture)		√	
Locate all parts of the finished product	√		
Turn the handles of the RMM (test)		√	
Compare the performance of the finished RMM with a reference product	√		
Identify fault in finished RMM (the rock milling part shown in photograph 5.2)	√		
Dismantle the RMM and remove the rock component		√	
Users iterate through NDPM cycle 2 to produce a replacement part	√		
Participate in discussions			√
Demonstrate respect for each other (physical confrontations etc.)			√
Listen attentively to others in the group			√
***Attending to features of the new RMM with the replacement part**		√	
***Re-test RMM with the PLA replacement part produced in cycle 2 of NDPM**		√	
Total (%)	33	42	25

The testing and evaluation stage of NDPM sees a rise in cognitive skills (33%), and psychomotor skills (42%) and affective skills slightly declines to 25% of OLB.

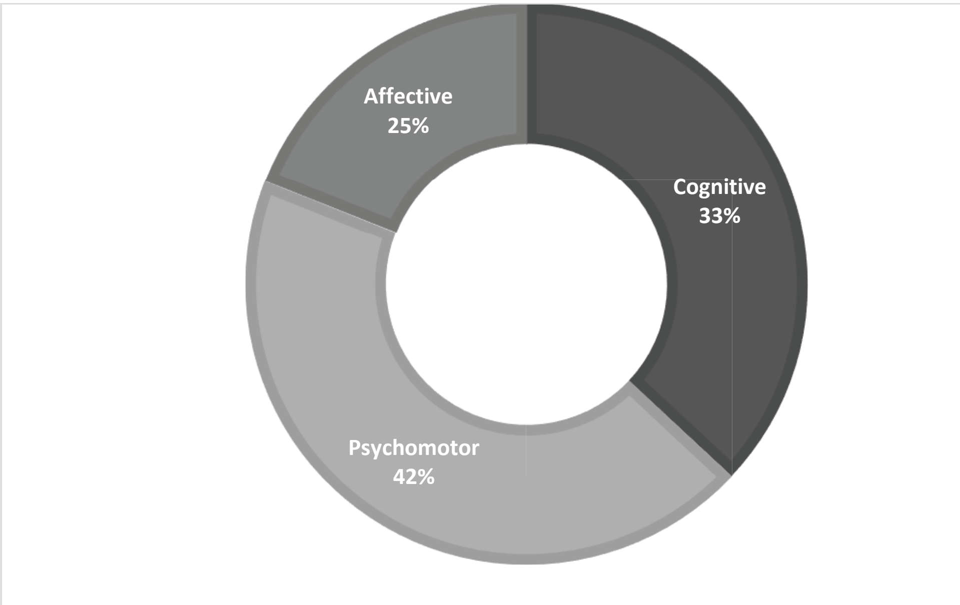
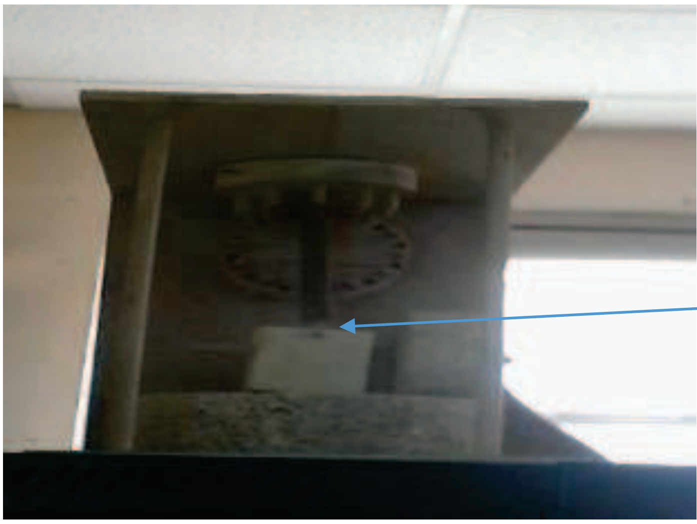


Figure 5.6 Graph showing occurrences of Bloom's CPA OLB in stage 4 of NDPM in PS1

Retrieval of declarative knowledge from LTM to WM is dominant in this stage compared to procedural Knowledge. The cognitive skills are dominant in this stage since it is a stage where testing and evaluation of the finished prototype/product. A lot of judgements and decisions are made in here as to whether or not the product requirements are met. A lot of comparison processes also take place to see if the finished product meets what is expected of the prototype/product. Affective skills are also high in this stage since it is a group project so a lot of social thinking and collaborations is needed to make final decisions about the finished prototype/product.

Routes 4 – 9 (NDPM cycle 2) in PS1

In Stage 4 of NDPM, the group revealed some misfits in the product (see photograph 5.1). One of the raw materials chosen at the beginning was a rock, however, after evaluating and testing the product, it turned out that the rock was not a good choice of material to use so route 4 was taken to specify another suitable material for the part.



This part of the RMM was initially made from rock, but after testing in stage 4 of NDPM, it did not work as intended to so the group repeated the NDPM cycle and used the 3D printer to print a replacement part made from PLA filament.

Figure 5.7 The finished product (RMM).

The new material chosen, however, was a 3D printed material so new knowledge and skills to use the 3D printer was necessary so routes 5 to 9 were taken, where students had to repeat the NDPM cycle researching new information, formulate new specification for the material and production of the part needed for the complete RMM, which, was completed after the 2nd round of the NDPM cycle.

The iterations between the NDPM stages adds and enhances new knowledge and skills, enhance confidence and moves students to a higher level of thinking. Martinez and Stager (Martinez & Stager, 2013) offers a support by stating that, "… every time the students *take a step forward, backwards or sideways they gain confidence in their own ability to decide what is worth keeping and what is needed to be tweaked* '(p. 76). According to Rheingold (2011 cited in Martinez & Stager, 2013), '*A lot of best experiences come when you are making use of the materials in the world around you, tinkering with the things around you, and coming up with a prototype, getting feedback, and iteratively changing it, and making new ideas, over and over, and adapting to the current situation and the new situations that arise'* (p. 37).

5.2.2 PS2 Results and Discussion

Iterations between the stages of NDPM in PS2

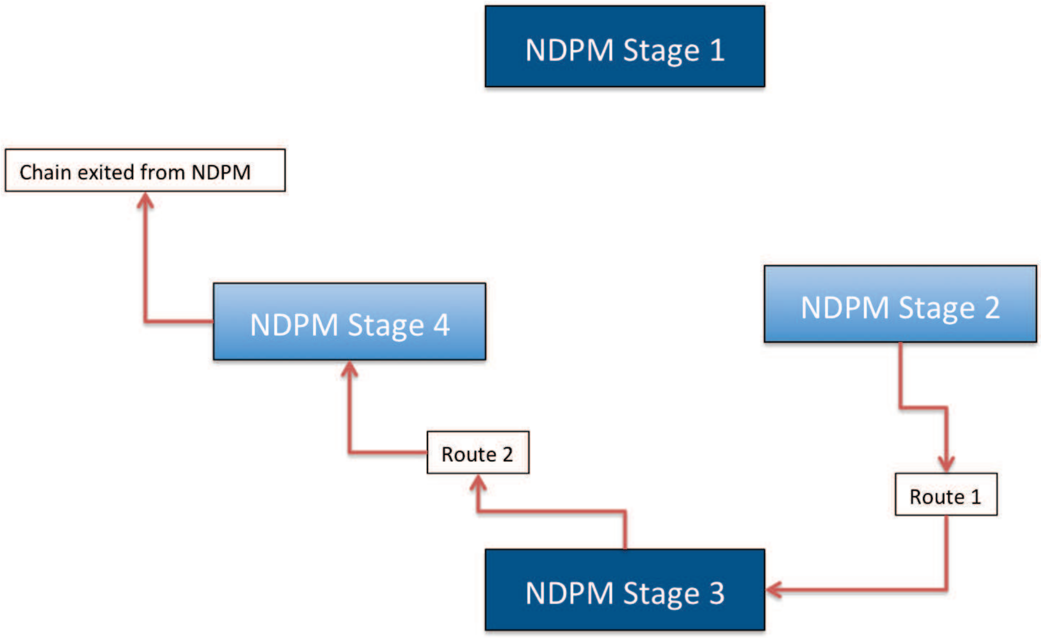


Figure 5.8 Iteration Pathways in PS2

Iterations in PS2 is very different from the iterations in PS1. Because the person is producing a product directly from data files, there was no OLB aligned for stage 1. The producer did spend some time formulating specifications for the chain in stage 2. After the formulation, route 1 was taken. Being a product exported from data files, the 3D printer printed the chain exactly as desired. There was no mistake in the chain so the chain exited stage 4 without further iterations.

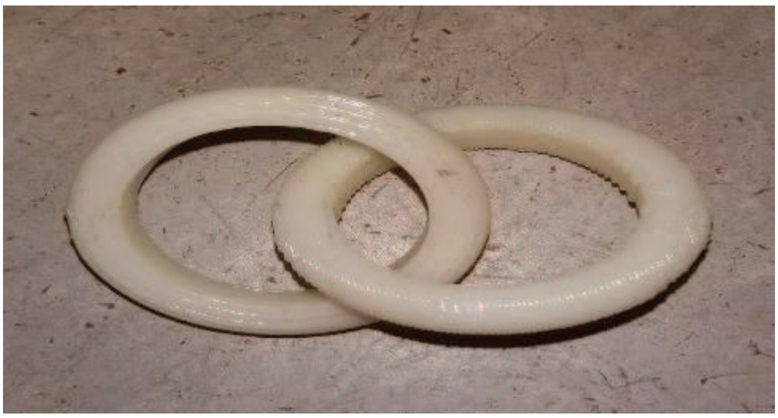


Figure 5.9 The chain produced in PS2

The details of the OLB in the 4 stages are outlined below.

NDPM Stage 1 in PS2

There was no observed OLB in stage 1.

NDPM Stage 2 in PS2

Table 5. 5 The types of Bloom's CPA OLB in NDPM stage 2 of NDPM (PS2)

Description of OLB	Cognitive	Psychomotor	Affective
Identify materials to use	√		
Calculate the dimensions of the product	√		
Operates a computer to download file		√	
Attending to the features of the sketches of the product (shape, angle, size)	√		
Application of CAD program	√		
Total (%)	80	20	0

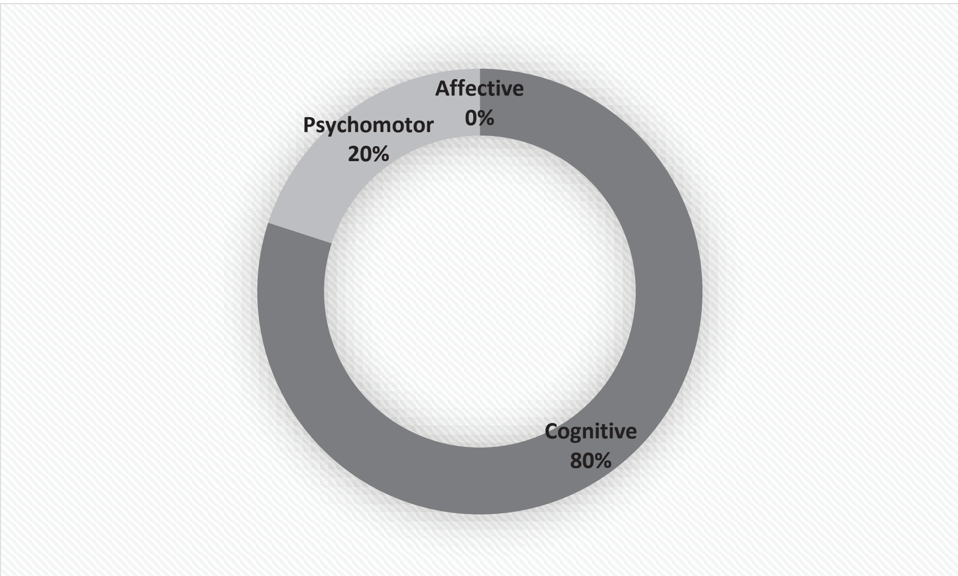


Figure 5.10 Graph showing Bloom's CPA OLB in stage 2 of NDPM in (PS2)

In stage 2 there is a 80% occurrence of Cognitive OLB and 20% occurrence of Psychomotor OLB. There is 0% occurrence of Affective OLB.

NDPM Stage 3 in PS2

Table 5.6 The types of Bloom's CPA OLB in stage 3 of NDPM (PS2)

Description of OLB	Cognitive	Psychomotor	Affective
Identify the machine to be used	√		
Calibrate production machine (3D printer)		√	
Attending to features of the PLA filament	√		
Adhere to safety rules in the fablab			√
Demonstrates professional commitment to producing			√
Application of CAM program	√		
Turns on the 3D printer		√	
Opening and placing the PLA filament in its compartment			
Adjust time settings		√	
Setting the speed at which the 3D printer will operate at		√	
Setting the Layer Height		√	
Total (%)	30	50	20

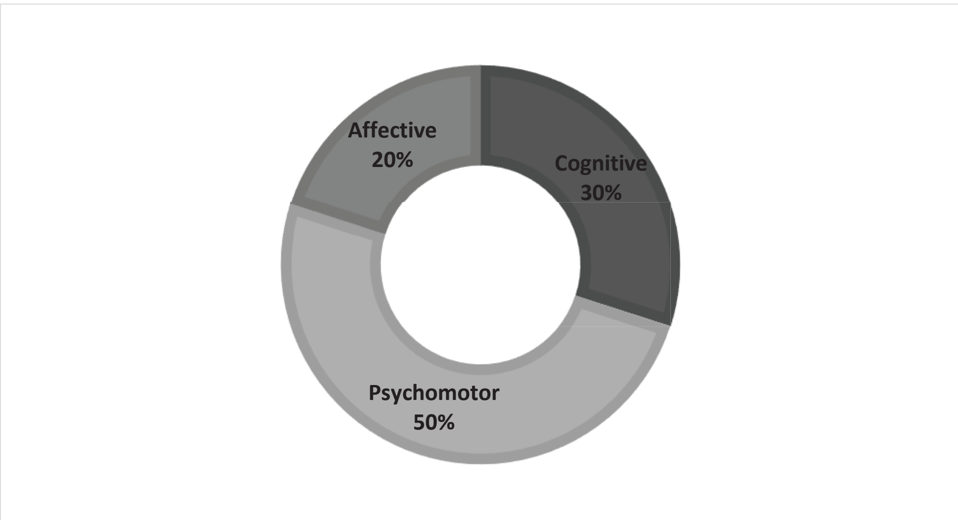


Figure 5.11 Graph showing Bloom's CPA OLB in stage 3 of NDPM (PS2).

In stage 3, retrieval of procedural knowledge from LTM to WM is still dominant in this stage. This is reflected by a rise in psychomotor OLB to 50%. The occurrences of cognitive OLB is 30% while there is a 20% occurrence of Affective OLB.

NDPM Stage 4 in PS2

There are no occurrences of OLB in stage 4.

5.2.3 Comparison of PS1 and PS2 results

The overall findings in PS1 and PS2 showed the following:

1. PS1 showed a high percentage of Bloom's CPA in ALL stages of NDPM while in PS2, there is no percentage occurrence of OLB in stages 1 and 4.
2. While there are occurrences of OLB in stages 2 & 3 for PS1 and PS2, the percentages are higher in PS1.
3. PS1 showed an almost consistent percentage occurrences of the Affective OLB in ALL stages while PS2 showed a small percentage of Affective OLB only in stage 3.

5.2.4 The aspects of design and production that influence the % occurrences of OLB in PS1 versus PS2

Producing an original thought-out product versus producing a product downloaded from data files

In PS1, the RMM produced was an original product born out from the group itself. Therefore it required a lot of cognitive skills to start forming a mental representation of the product. Creative thinking and critical thinking (Ankiewicz, 2013 cited in Engelbrecht 2016) are dominant in stage 1. Retrieved from the Long Term Memory (LTM) to the Working Memory (WM) is mainly declarative and procedural knowledge. Being an original thought out product, students had to operate computers to search the internet for information that may assist them on how to produce the RMM. Working in groups in PS1 has been reflected by a high percentage of Affective OLB.

Being an originally-thought-out product, a sketch of the RMM was also made. This task alone required a lot of cognitive and psychomotor OLB in the task of translating and transforming mental representations onto paper using 2D sketches. This is reflected in a great portion of the Cognitive and Psychomotor OLB in PS1.

In PS2, on the other hand, the chain was downloaded from data files. The individual did not have to spend time to brainstorm ideas or do research to come up with the product. Working on his own to produce the chain, there was no observation of Affective OLB. No Blooms CPA were observed in stages 1 and 4. Since it is a pre-determined product from pre-determined specifications from the data files, the chain once produced had little or no defect to allow further manipulations.

Producing a product composed of many raw materials versus producing a product composed of only 1 raw material

The RMM in PS1 is made of many different types of materials: rock, wood and PLA filament. A lot of cognitive OLB is expected as decisions have to be made on the best material to use. The physical and chemical properties of the wood, rock and PLA filament used to make the RMM has to be researched and known. The circumference of the rock has to be calculated and also come knowledge on how to use the 3D was evident in cycle 2 of PS1.

In PS2, on the other hand, the chain is only made of a PLA filament. The knowledge required for this therefore is just the knowledge of the types of PLA filaments and the choice of the colour of filament.

Producing a product using many types of different production machines versus producing a product using just one type of production machine

In PS1, a range of traditional and modern production machines and tools are used to produce the RMM. For example a hand saw was used to cut the rock into a circle while an electric drill was used to bore holes in the rock and wood. Measuring tapes were used to measure the circumference of the rock. Calibrations were also done on the 3D printer to print a part for the RMM. This thus involved a lot of cognitive processes involving the prefrontal lobe (PFL) of the brain and the cerebellum. This is reflected in the Cognitive and Psychomotor OLB in stage 2.

In PS2, on the other hand, the chain was produced using only one production machine, the 3D printer. The knowledge required for specifications in stage 2 and production in stage 3 are limited to i) the knowledge required to set the working temperature of the 3D printer; ii) a knowledge of the types of the filament to use and the choice of colour; iii) knowing the speed at which to set the 3D printer at; iv) setting the Layer Height (either 0.4mm, 0.3mm or 0.1mm).

Producing a product in groups versus one person producing a product

Throughout stages 1 – 4 of NDPM in PS1, there is somewhat a consistent occurrence of Affective OLB compared to PS2. Because the students are working in groups, Blooms Affective categories of Internalizing values; Valuing; Responding to Phenomena; Receiving Phenomena (see Simpson, 1972 for details) are observed in all stages of NDPM.

In PS2, there was no Affective OLB in stages 1, 2 and 4. The only Affective OLB in PS2 was displayed in stage 3. This Affective OLB falls under Bloom's category of 'Internalising Values' (Simpson, 1972). This was displayed through the adherence to safety in the Ub-Fablab production room. Interactive affective OB was not observed at all in all stages since the person was producing the chain on his own.

5.3 Results and Discussion for Part Two

Data collected from the 53 Ub-Fablabs using the Ub-Fablab CIS are tallied (see Appendix 2). Note that Ub-Fablabs scoring 3 points meet Level 3 standard; 2 points = Level 2 standard and 1 point = Level 1 standard.

Analysis of data collected showed the following results depicted in Graphs 5.1, Graph 5.2, Graph 5.3 and Graph 5.4. The results are discussed in the paragraphs that follow.

5.3.1 Ub-Fablab CIS Assessment: Technological Infrastructure Capacity

Out of the 53 Ub-Fablab researched, 91% of the Ub-Fablabs meet Level 3 capacity to provide Technological Infrastructures that can integrate design and production while 9% of the Ub-Fablabs meet a Level 2 capacity (see Graph 5.1).

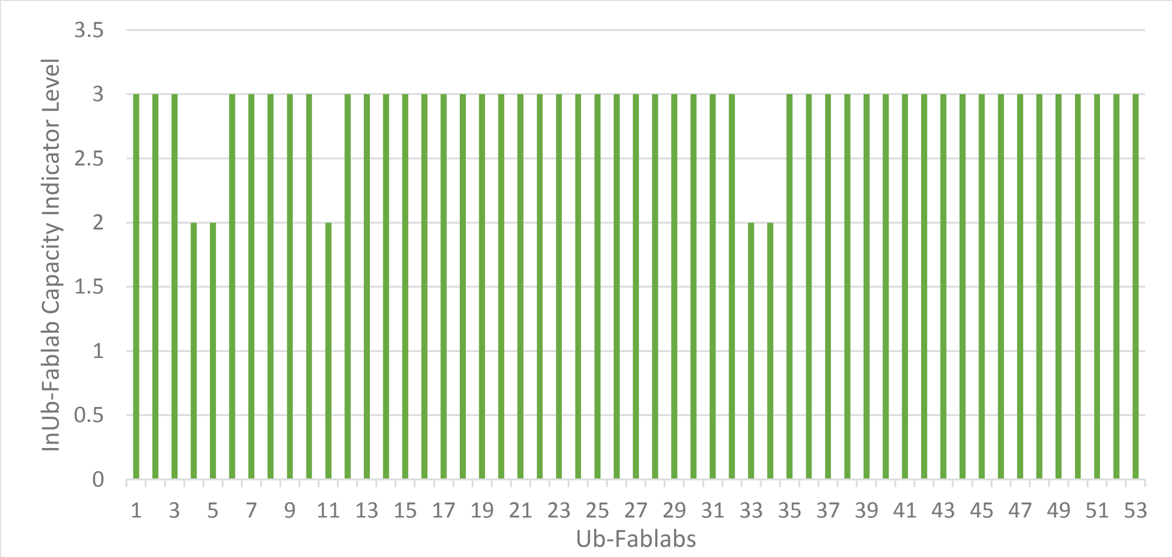


Figure 5.12 Graph showing Ub-Fablabs vs Ub-Fablab CIS of Technological Infrastructures.

The latest high-tech digital production machines in these Ub-Fablabs include standardised machines produced by the MIIT CBA such as the 3D printers (Additive manufacturing machine), CNC Millers, Laser cutters and etchers, Vinyl cutters, Precision milling (subtractive manufacturing machines) and Circuit Productions. These machines are able to print, cut or mill objects from CAD files (data files). The standardised computers are the IBM-compatible computers supported by Computer – Aided Engineering (CAE) software such as the Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) software. These production machines and software being standardised enhance fablab collaborations and avoids the problems of compatibility of machines between the fablabs. The software used in fablabs are also available under the Open-source (or comparable) licenses therefore are adaptable and developable (Walter-Herrman & Buching, 2013, p.2).

5.3.2 Ub-Fablab CIS Assessment: Constructionist Pedagogical approaches

There are 57% of the Ub-Fablabs that meet Level 3 Capacity, 38% at level 2 and 5% at Level 1 (see Graph 5.9) that provide a pedagogical approach to facilitate the processes of tinkering or meddling with digital fabrication machines and experimenting in universities.

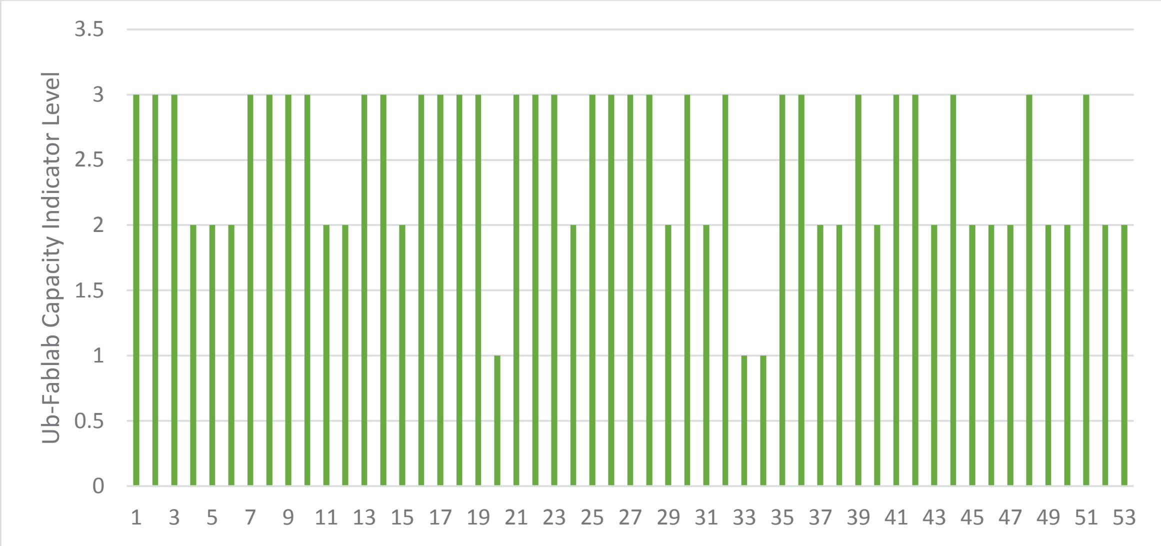


Figure 5.13 Graph showing Ub-Fablabs vs Ub-Fablab CIS of Constructionist Pedagogical Approach

Ub-Fablabs users are mainly students from the STEM fields who go into the fablabs to use the machines to invent or create prototypes. The Ub-Fablabs adopting the open-access status the Ub-Fablabs offer an inviting and gender-free environment where individuals, including novices can create or construct. The use of computers, CAD and CAM software programs allow an iterative approach to design and production allows one enhance cognitive skills and reinforces engineering, electrical and mechanical skills.

5.3.3 Ub-Fabab CIS Assessment: Collaboration through digital networking

There are only 6% of the Ub-Fablabs which reached Level 3, 64% at level 2 and 30% at level 1 (see Figure 5.10)

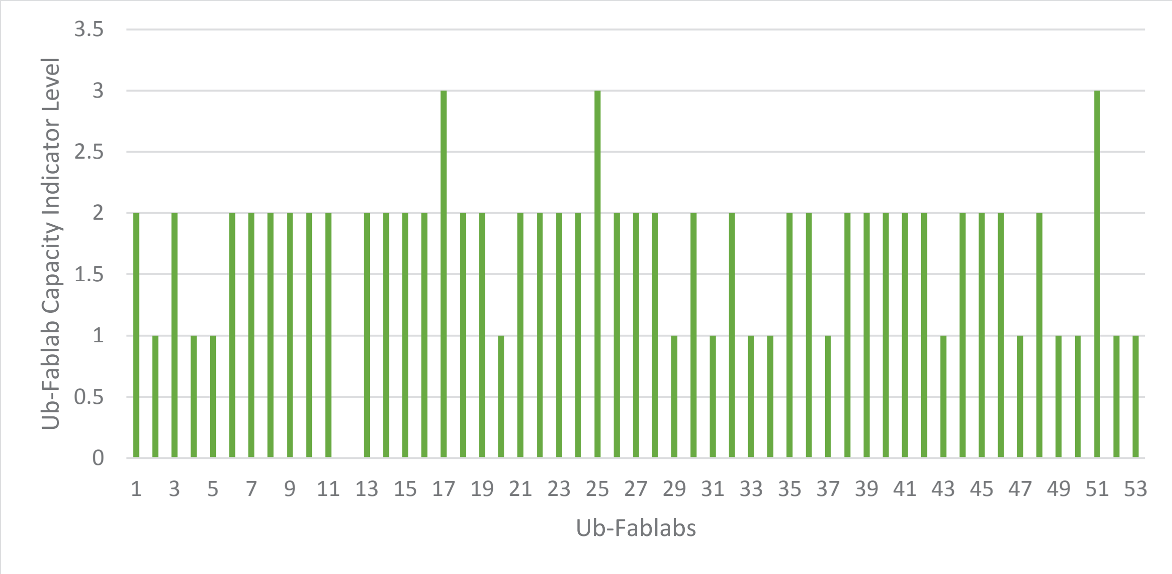


Figure 5.14 Graph showing Ub-Fablabs vs Ub-Fablab CIS of Collaboration through digital networking

A combined research by the Lucerne University of Applied Sciences and Arts and Rotterdam University of Applied Sciences into Open Knowledge Sharing in Fab Labs gave one reason for this as *'…the rapidly growing size of the network …impeding the development of interconnections between the fablabs as there were more people with different backgrounds and for the time it takes to know each other'* (Wolf, Troxler et al 2014, p. 16). However, with the Internet of Things (IoT) capacity of these fablabs, users from the Ub-Fablabs access projects and designs from other fablabs via the website: https://www.fablabs.io/labs more readily. Individuals can also upload their designs online so others can use. The built-in mechanism for all users to gain computer skills in order to access the designs and projects is supported by courses run by the MIT Fablab and supporting organizations like the Fablab Academy and the Fablab Ed.

5.3.4 Ub-Fablab CIS Assessment: Sustainability (inclusive of eco-design and circular economy)

There are 15% Ub-Fablabs which reached level 3, 51% at Level 2 and 34% at Level 1 (see Figure 5.11).

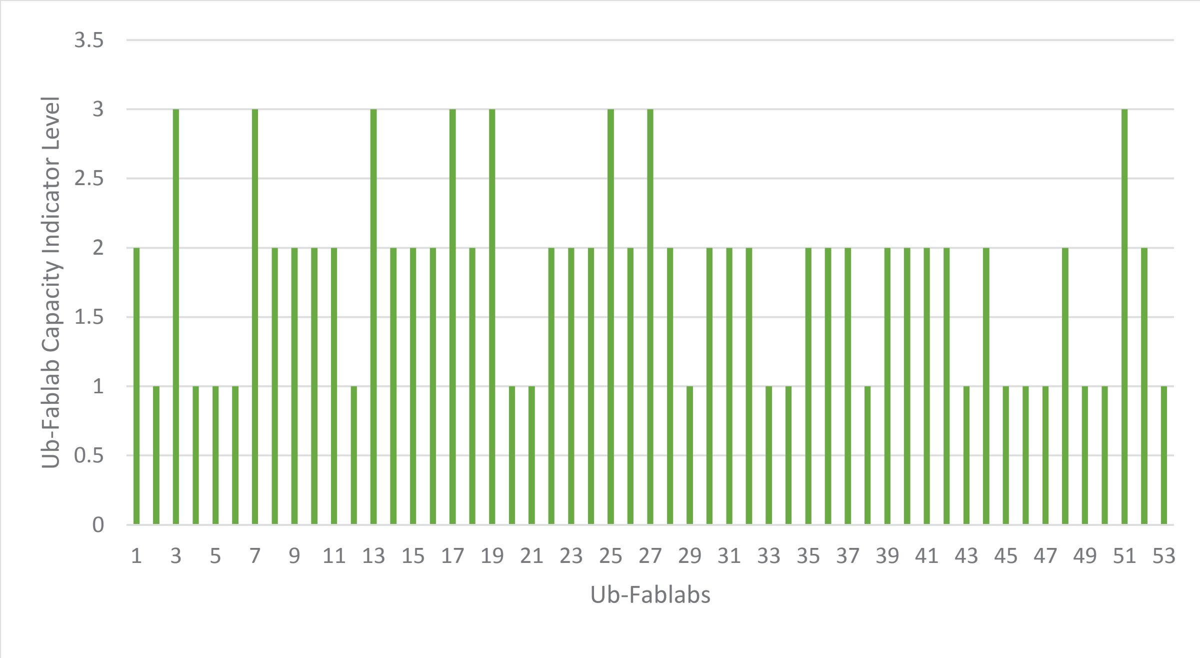


Figure 5.15 Graph showing Ub-Fablabs vs Ub-Fablab CIS of Sustainability

Being responsive to the environment has shown the least weighting here of 41% strength. While there is still a lot of things to do by these Ub-Fablabs to bring this status up in the near future, these fablabs are already taking some lead in eco-design and showing some good signs of contributing to a circular economy in the future. All the Ub-Fablabs surveyed are using a 3D printer which pose a very promising future for the platform to be utilised. The 3D printers, being an additive manufacturing machine involves mainly depositing materials in layers to construct the prototype/product compared to subtractive manufacturing process involving subtractive machines where prototypes/products are formed by successively subtracting or cutting materials away from a solid block of material which could leave up to 60% of waste during production alone. The 3D printers in these fablabs use mainly the Fused Deposit Modelling method of production where Polylactide (PLA) plastic filament for a sturdier product, the Acrylonitrile butadiene styrene (ABS) is melted and squirted out in computer controlled patterns and the materials quickly fuses together and cools to create the finished product. The PLA filaments, being made out of corn-starch or sugar are potentially biodegradable if not composting.

5.4 Summary of Chapter 5

The results obtained from applying the methodologies outlined in chapter four are analysed and discussed in this chapter, chapter 5.

PS1 study in part one of the research showed a high percentage of Bloom's CPA OLB in ALL stages of NDPM. PS2, however, showed a big difference in the percentage occurrences of Bloom's CPA OLB in each stage. The results have been discussed considering the following aspects that can influence the OLB. The apsects discussed were i) producing an original thought-out product versus producing a product downloaded from data files; ii) Producing a product composed of many raw materials versus a producing a product product composed of only 1 raw material; iii) producing a product using many types of production machines versus producing a product using just one type of production machine; iv) producing a product in groups vs one person producing a product.

Analysis of the data collected for part two of this research revealed that Ub-Fablabs do have the capacities to incubate proactive minds for the future design and production industries. Although two of the aspects (Sustainability and Collaboration through digital networking) need improvements, the results of this research are already showing good signs for Ub-Fablabs to be used as support platforms.

The next chapter, chapter six will make final overall conclusions of the research by providing some answers to the two research questions that have guided this research and thenprovide recommendations for future research.

Chapter 6

6 Conclusion and Recommendations

6.1 Summary of Previous Chapters

The introductory chapter, chapter one, has introduced the concept of fablabs and discussed the problems of narrowly perceiving fablabs as just ‘spaces for people meeting face to face to create things together’. The cognitive processes embedded in the design process and the capacities of the Ub-fablabs as support platforms to incubate proactive minds for the future design and production industries are often overlooked or undermined. The two principal aims of this research were therefore

1 To investigate and align cognitive processes with the design process in a Ub-Fablab
2 To critically assess the capacity of Ub-Fablabs to prepare citizens for the future design and production industries.

The research questions that guided this research were:

1 What are the types of cognitive processes embedded in the design process in Ub-Fablabs?
2 How efficient are Ub-Fablabs preparing citizens for the future design and production industries?

Chapter two discussed the main concepts pertaining this research. Part I of the chapter discussed the definition and concepts of cognitive processes, the brain and its role in learning, the definition and concepts of design process and iterative design processes. Bloom’s Taxonomy was also introduced. Part II of the chapter discussed the current practices of design and production industries. The concepts of 21st century skills, sustainability and how to embrace new technologies were also discussed.

Based on literature review of chapter one and chapter two, chapter three developed the conceptual pathway to achieving the aims of this research. In part I, an iterative design process model, the NDPM was introduced. Its features, theoretical support and the four stages were clearly defined. In part II, a requirement matrix was introduced along with the introduction of the Ub-Fablab CIS.

Chapter four outlined the methodologies used in this research to find answers to the two research questions. Chapter five discussed the data collected using methodologies outlined in chapter four. The analysis of results in chapter five gave answers to the two research questions that guided this research. Therefore, in this chapter, chapter 6, overall conclusions will be made concerning the two questions and also recommendations for future research will be made.

6.2 Overall Conclusion

This researcher has finally come up with answers to the research questions that guided this research.

Part 1 Question 1: What are the types of cognitive processes embedded in the design process in Ub-Fablabs?

The PS1 findings in chapter 5 revealed that cognitive, affective and psychomotor skills (inclusive of mechanical, electrical and embedded software operational skills) can be nurtured, enhanced and aligned with the design process in Ub-Fablabs. In summary, combining all OLBs in the four stages of NDPM (see Figure 6.1) cognitive skills are dominated in stages 1, 2 of NDPM, while psychomotor (MEE) skills are greatest in stage 3 of NDPM and stage 4 of NDPM. In stage 3 of NDPM most of the 'hands-on activities' take place using the production machines in the fablab production room. The affective skills, however, is almost consistent throughout the four stages of NDPM.

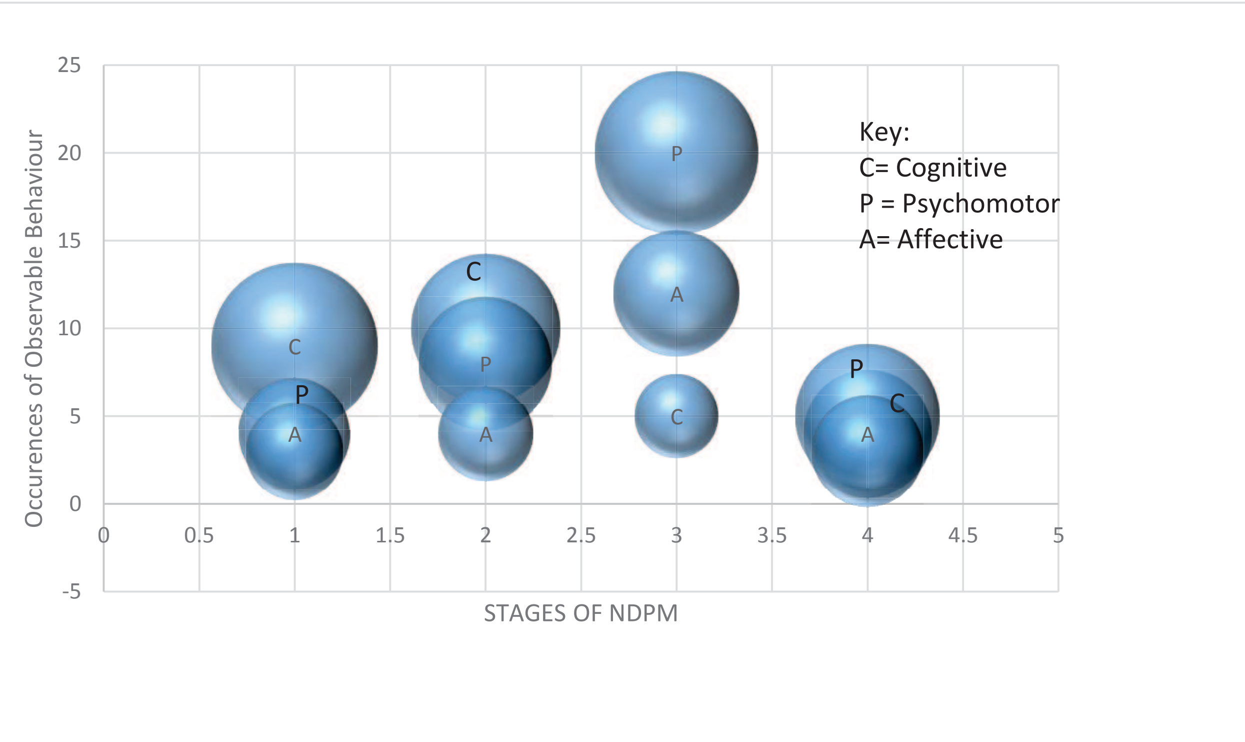


Figure 6.1 Graph showing Bloom's CPA OLB in ALL stages of NDPM (PS1).

The PS2 findings in chapter 5 serves as a guideline for educators designing projects in education settings for the purpose of learning. The findings in chapter 5 showed a big variation in the occurrences of OLB (see Figure 6.2).Table 6.1 shows an overall occurrences of Bloom's CPA OLB in all stages of NDPM and Figure 6.2 depicts the occurrences and magnitude of each OLB in each stage.

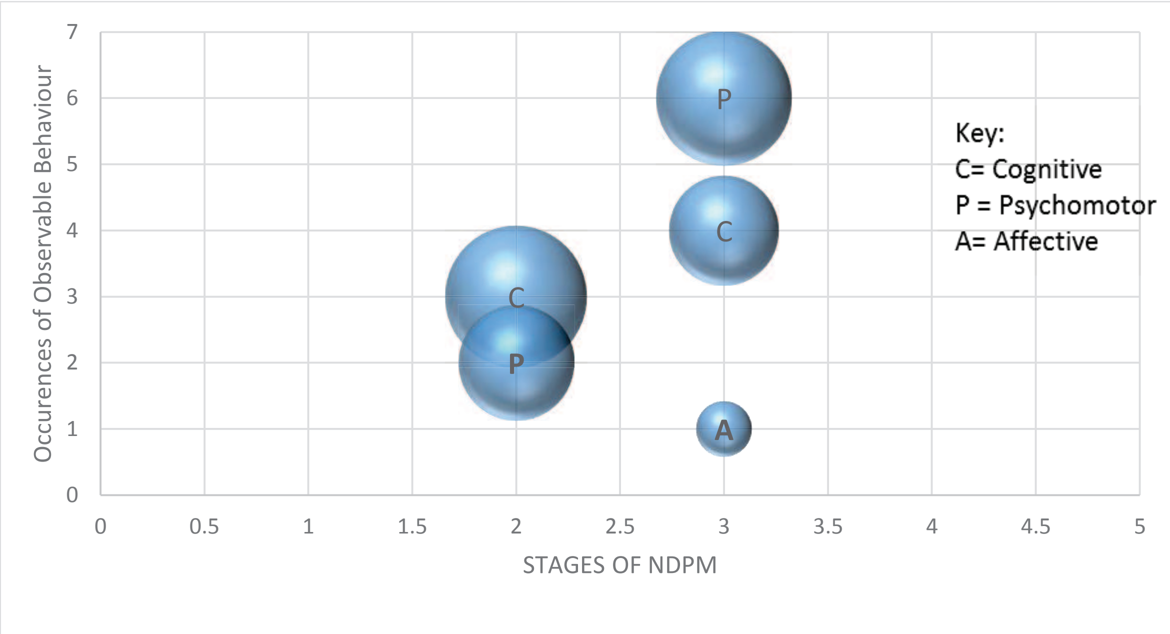


Figure 6.2 Graph showing occurrences of Bloom's CPA OLB in all stages (PS2).

This study has highlighted how the four aspects of design and production in an Ub-Fablab can influence Bloom's CPA OLB at different the different stages of the design process. To help students or Ub-Fablab users maximise the unleash of Higher-order Thinking skills (HOTs), complex Psychomotor and Affective skills, the research showed that a tremendous amount of Bloom's CPA OLB are harnessed when:

1 producing an originally-thought-out product
2 producing a product composed of many raw materials
3 producing a product using many types of production machines
4 producing a product in groups

The findings of this study would in a way give some guidelines to educators on how to best harness cognitive, affective and psychomotor (MEE) knowledge and skills in project-based learning in Ub-Falabs.

Overall the results from this research shows users iterating through design processes in an Ub-fablabs can help a citizen with the cognitive, psychomotor and affective domains of his/her life. This gives the Ub-Fablab a strong hold in confirming it as a robust and vigorous way to equip citizens with the so-called 21st Century skills and knowledge to cope with the technological challenges.

Part Two Question: How efficient are fablabs in contributing to incubating proactive minds for the future design and production industries?

The capacity of Ub-Fablabs to contribute to the 21st Century skills and incubate proactive minds for the future design and production industries. The results from this research could briefly be summarised and presented using a radar graph (see figure 6.3). The Ub-Fablabs have a big strength in providing digital technological infrastructure and in enabling a constructionist pedagogical approach that will enhance STEM knowledge and skills, which are required knowledge and skills for design and production. The other two aspects, collaboration through digital networking and sustainability (inclusive of eco-design and circular economy) need more emphasis by the universities.

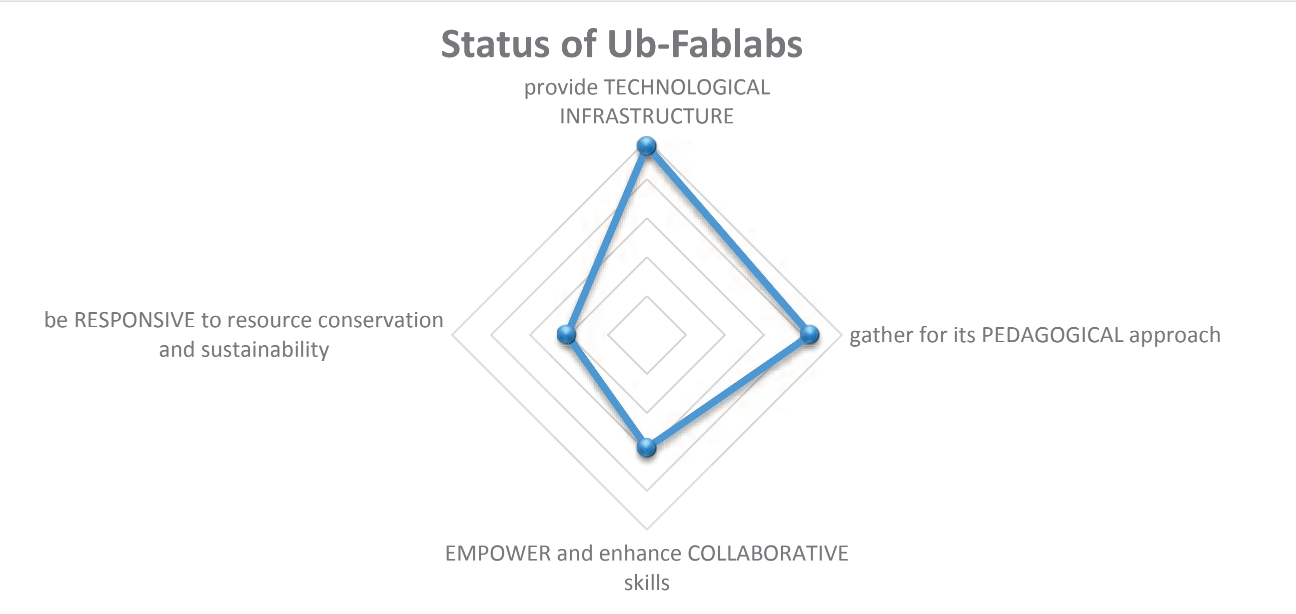


Figure 6.2: Graph showing the overall strengths of Ub-Fablabs

Although there are aspects where Ub-Fablabs need improving, overall the results of this research have shown that the enhanced and nurtured skills harnessed by the use of the technological infrastructure and mechanisms in an Ub-Fablab could contribute to equipping citizens with the 21st Century Skills and incubating minds for the future design and production industries.

6.3 Limitations of this study and recommendations for future research

While all steps in the research design are thoroughly planned and revised in order to investigate the research questions that guide this research study, there are limitations worth mentioning that may have impacted the results in chapter 5 of this thesis. These are some limitations:

6.3.1 Lack of prior research studies on the topic:

The concept of fablab only emerged in 2001 is still a new concept to many. From the information gathered from a wide range of publications, researches and reports, many of these discussed mainly the industrial applications of makerspaces in general and a few on the industrial /economic benefits and social aspects of fablabs but there is very little, if any, prior research study into its integration into the educational setting and apparently no prior research study into the alignment of cognitive processes with the design process in fablabs. Due to lack of prior research studies into this topic, this research may serve as an exploratory research study to lay some groundwork for future researches into the cognitive processes in the fablab.

6.3.2 Measure used to collect and analyse data:

Because this research study is carried out into a little-researched field there are no tracking of activities model, no data collection and analysis tools from prior researches therefore the model/tools/instruments used in this research study are either originally created by the researcher (e.g. the Nawita Design Process Model, NDPM) or adapted from various sources in related field of research (see Crutcher 1994; Simon and Kaplan 1989; Austin and Delaney 1998 cited in Ericsson 1993 ; Bloom 1956 ; Suwa et al (1997) ; Baddeley 1997; Baddeley 2000; McLeod 2012; Mastin 2010; Boettcher 2008). Applying Bloom’s taxonomies of cognitive, psychomotor and affective domains to align ‘observable behaviour’ in the fablab is a first of its kind of approach to analyse activities in an Ub-Fablab thus may have an impact on the results. These model/tools/instruments would make a good starting point in developing research tools for future research into this field.

6.3.3 Access and longitudinal effects

This research study was part of a ‘Co-tutelle’ partnership arrangement under the Erasmus Mundus STETTIN project and Vanuatu Institute of Teacher Education (VITE), which, only allowed the researcher to collect data in a very short period of time in Bordeaux University’s ‘Fablab for Education’ in France. This has limited the researcher chances to trial the NDPM in other fablabs and has somewhat restricted data collection, which, may in turn impact the results in this research study. The remote status of the researcher has also restricted access and support from the host university.

6.3.4 Focus of this Study:

This study focuses only on activities centred on projects and innovations in fablabs established in universities (Ub-Fablabs). This however does not undermine the entrepreneurship-related activities in fablabs in communities. This research design could therefore be applied to entrepreneurship-related activities to see if the same cognitive, psychomotor and affective results are replicated.

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Appendices

Appendix 1: Countries and number of fablabs /country- September 2017

Country	# Fablab	Country	# Fablab
	Western Europe		
France	152	Netherlands	32
Austria	9	Luxembourg	2
Lettonie	2	Belgium	19
Germany	46	Switzerland	16
	Southern Europe		
Italy	133	Portugal	19
Greece	3	Spain	47
Croatia	1	Malta	1
Serbia	4		
	Eastern Europe		
Bulgaria	1	Slovakia	3
Czech Republic	3	Georgia	25
Hungary	1	Ukraine	4
Poland	13	Romania	1
Slovenia	3	Crna Gora	1
	Northern Europe		
UK	41	Sweden	1
Iceland	8	Denmark	7
Ireland	4	Finland	4
Latvia	2	Norway	5
Lithuania	2		
	Northern America		
USA			

Canada	159		
	22		
Argentina	South America	Suriname	1
Brazil	12	Ecuador	6
Chile	40	Uruguay	1
Columbia	8	Peru	10
Bolivia	7	Panama	1
Paraguay	1		
	2		
Costa Rica	Central America	Mexico	14
El Salvador	3	Guatemala	1
	1		
Afghanistan	Middle East	Lebanon	2
Bahrain	1	Saudi Arabia	10
Iran	2	Morocco	6
Israel	4	Turkey	7
Jordan	4	United Arab Emirates	6
Kuwait	3	Oman	1
Palestine	3	Qatar	2
	1		
South Africa	South Africa		
	8		
Kenya	Eastern Africa	Namibia	1
Reunion	2	Ethiopia	1
Rwanda	2		
	3		
Egypt	Northern Africa		3

	9	Tunisia	
Cameroon	Central Africa		
	1		
Burgina Faso	Western Africa		1
Ivory Coast	2	Ghana	2
Senegal	3	Mali	1
Nigeria	2	Togo	2
	1	Benin	
Australia	Oceania		6
	3	New Zealand	
Puerto Rico	Caribbean		1
Guadelope	4	Trinidad & Tobago	1
	1	Jamaica	
Russia	Eurasia		2
	31	Kazakhstan	
India	South Asia		1
	42	Bangladesh	
Indonesia	South East Asia		1
Thailand	3	Myanmar	7
Singapore	1	Philippines	7
Cambodia	2	Vietnam	1
	1	Malaysia	
China	Eastern Asia		17
Japan	20	South Korea	13
Hong Kong	16	Taiwan	1
TOTAL # Fablabs	1	Macao	
	1,180		

Source: Fablab website, n.d.

Appendix 2: Photographs showing the different activities in stages 1 – 4 of NDPM

1. Examples of NDPM stage 1 activities

Fablab Conference room where group members work together to define problems, seek solutions and formulate product specifications.

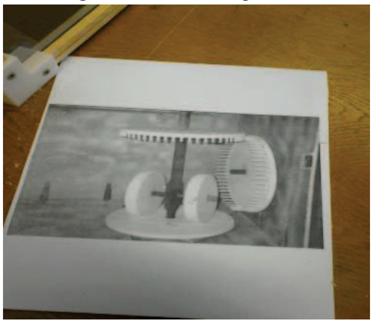
STAGE 1

CONCEPT GENERATION

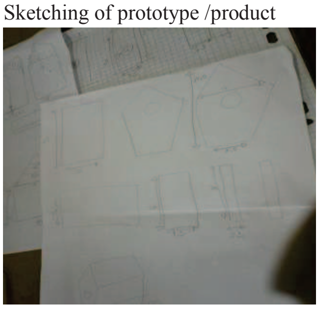
Use computer to google and download information

EXAMPLES OF NDPM STAGE 2 ACTIVITIES

Attending to features of the product



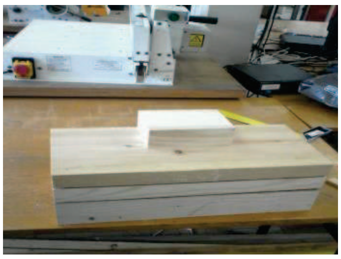
Sketching of prototype /product



Choosing digital machines to use for production.

Arranging

Materials



PRODUCT SPECIFICATIONS

Choosing conventional tools to use during production

EXAMPLES OF NDPM STAGE 3 ACTVIITIES

Chipping, hammering,

Paying attention to details, comparing with sketches

Collaborating, discussion, sharing ideas

Cutting materials to size

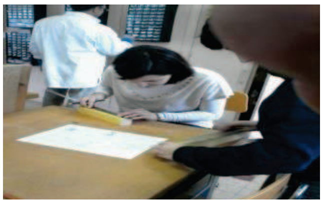
Discuss and work out ways to solve a problem

Attending to a spatial relation between two space components or area of the prototype/product

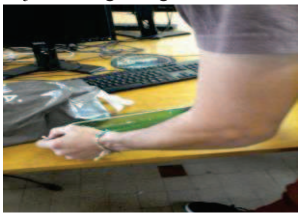
Paying attention to details, students discussing with Fablab Manager

PRODUCTION IN THE UB-FABLAB USING THE FABLAB PRODUCTION MACHINES

Measuring, calculating , drawing lines



Measuring length of irregular objects using strings



Calibrating and using production machines

Measuring, calibrating, adjusting

Discussions, critique, feedback, reviewing

Listening attentively, discussions, commenting

Comparing parts with design, making decisions, modifying

Appendix 3: Summary of tally for Level 3, Level 2 & Level 1 using the Ub-Fablab CIS

Ub-Fablabs	Digital Technological Infrastructures	**Constructionist Pedagogical approach**	**Collaboration through digital Networking**	**Sustainability (inclusive of eco-design and circular economy)**
Ub-Fablab1	3	3	2	2
Ub-Fablab2	3	3	1	1
Ub-Fablab3	3	3	2	3
Ub-Fablab4	2	2	1	1
Ub-Fablab5	2	2	1	1
Ub-Fablab6	3	2	2	1
Ub-Fablab7	3	3	2	3
Ub-Fablab8	3	3	2	2
Ub-Fablab9	3	3	2	2
Ub-Fablab10	3	3	2	2
Ub-Fablab11	2	2	2	2
Ub-Fablab12	3	2	1	1
Ub-Fablab13	3	3	2	3
Ub-Fablab14	3	3	2	2
Ub-Fablab15	3	2	2	2
Ub-Fablab16	3	3	2	2
Ub-Fablab17	3	3	3	3
Ub-Fablab18	3	3	2	2
Ub-Fablab19	3	3	2	3
Ub-Fablab20	3	1	1	1
Ub-Fablab21	3	3	2	1
Ub-Fablab 22	3	3	2	2
Ub-Fablab23	3	3	2	2
Ub-Fablab24	3	2	2	2

Ub-Fablab25	3	3	3	3
Ub-Fablab26	3	3	2	2
Ub-Fablab27	3	3	2	3
Ub-Fablab28	3	3	2	2
Ub-Fablab29	3	2	1	1
Ub-Fablab30	3	3	2	2
Ub-Fablab31	3	2	1	2
Ub-Fablab32	3	3	2	2
Ub-Fablab33	2	1	1	1
Ub-Fablab34	2	1	1	1
Ub-Fablab35	3	3	2	2
Ub-Fablab36	3	3	2	2
Ub-Fablab37	3	2	1	2
Ub-Fablab38	3	2	2	1
Ub-Fablab39	3	3	2	2
Ub-Fablab40	3	2	2	2
Ub-Fablab41	3	3	2	2
Ub-Fablab42	3	3	2	2
Ub-Fablab43	3	2	1	1
Ub-Fablab44	3	3	2	2
Ub-Fablab45	3	2	2	1
Ub-Fablab46	3	2	2	1
Ub-Fablab47	3	2	1	1
Ub-Fablab48	3	3	2	2
Ub-Fablab49	3	2	1	1
Ub-Fablab50	3	2	1	1
Ub-Fablab51	3	3	3	3
Ub-Fablab52	3	2	1	2
Ub-Fablab53	3	2	1	1