CATÓLICA LISBON
BVSINESS & ECONOMICS

Barriers to the Diffusion of Microfluidics from Research to Market

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Abstract

Dissertation Title: “Barriers to the Diffusion of Microfluidics from Research to Market”

Author: Gonçalo Martim Gomes Branco Mafra Salgado

Microfluidics is an interdisciplinary science that brings together such fields as: material engineering, physics, chemistry, biochemistry and nanotechnology, among others. It has the potential to affect such fields as: clinical diagnostics, flow chemistry, pharmaceutical and life sciences, drug delivery and point-of-care.

Microfluidics potentialities have been realized in product such as: 4KScore Prostate Cancer Test and LabChip Systems, nevertheless there’s still a very limited number of microfluidic devices that have had an impact in broader audiences.

The methodology for this dissertation comprised of a management and scientific based literature review, and an online questionnaire, in order to leverage the anticipation power of managerial concepts to improve microfluidics spread and adoption.

It was found that the main barriers to the diffusion of microfluidics are: lack of standards and integration, lack of communication between academia and industry, technology for technology’s sake mentality and lack of focused work. Furthermore, these barriers are predicted by managerial frameworks and are characteristic of emerging technologies, and where supported by survey data.

Solutions to overcome these barriers were suggested such as: implementing the concept of strategy (what to do, and what not to do), switch to a market pull mindset, foster academia to increase the cooperation with manufacturers and implement quality control processes.

Lastly, microfluidics has a higher likelihood to reach broader markets in areas as: Point-of-care (POC), Pharmaceutical and life science research, Clinical & veterinary diagnostics, and arguably Analytical Devices.

Resumo

Dissertation Title: “Barriers to the Diffusion of Microfluidics from Research to Market”

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A microfluídica é uma ciência interdisciplinar que junta áreas como: ciência dos materiais, física, química, bioquímica, nanotecnologia, entre outras. Tem o potencial para revolucionar campos como: diagnósticos clínicos, química, ciências da vida e farmacêuticas, administração de medicamentos e point-of-care.

As potencialidades da microfluídica têm sido concretizadas em produtos como: 4KScore ProstateCancer Test e LabChip Systems, no entanto existe um número muito limitado de dispositivos de microfluídica que têm alcançado grandes multidões.

A metodologia para esta dissertação compreendeu uma revisão da literatura baseada em ciência e em gestão, e um questionário online, de forma a conseguir alavancar o poder de antecipação de conceitos de gestão para melhorarar a proliferação e adopção da microfludica.

Verificou-se que as barreiras principais a difusão da microfluídica são: falta de normas e integração, falta de comunicação entre universidades e industria, uma mentalidade de “tecnologia pela tecnologia” e falta de trabalho focado. Para além disso, estas barreiras são antevistas por sistemas de gestão e são características de tecnologias emergentes, como também são suportadas pelos resultados do questionário.

Soluções sugeridas para ultrapassar estas barreiras são: implementação do conceito de estratégia (o que fazer, e o que não fazer), mudar a mentalidade para uma de mercado, instigar as universidades a aumentarem a cooperação com os fabricantes e implementar processos de controlo de qualidade.

Por último, a microfluídica tem mais possibilidades de alcançar grandes mercados nas seguintes áreas: point-of-care (POC), investigação nas ciências da vida e farmacêuticas, diagnósticos clínicos e veterinários, e discutivelmente nos dispositivos analíticos.

List of Acronyms

µTAS	Micro total analysis systems
FCT	Faculdade de Ciências e Tecnologia
FCT-UNL	Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa
INESC-MN	Instituto de Engenharia de Sistemas e Computadores para os Microsistemas e as Nanotecnologias
IST	Instituto Superior Técnico
ITQB	Instituto de Tecnologia Química e Biológica
LOC	Lab-on-a-chip
MEMS	Micro-Electro-Mechanical Systems
MIT	Massachusetts Institute of Technology
PDMS	Polydimethylsiloxane
PLC	Product Life Cycle
R&D	Research and Development

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1. Introduction

It’s not a recent issue of how emerging technologies struggle to make it to the market. It’s also perceptible the belief of the scientific community that technology can make it on its own, meaning, that can find commercial success solely based if the technology competency. However, that’s not the case. Commercial success entails more complex issues than just mere technology performance.

Microfluidics is just one example of a technology with a multitude of potentialities (e.g. molecular biology, proteomics, genomics, drug delivery, among others), but which has only found success in few niche markets, and has yet to reach broader audiences.

The scientific literature reveals that the microfluidic community is beginning to understand how other players are crucial for the commercialization of microfluidics.

The Yole Department report by (Roussel & Clerc, 2015) is the most recent and broader study about microfluidics market, however it wasn’t possible to access it, except through a sample. Additionally, (Yadav, 2010) is one of the few, if only, academic works about microfluidics – “*Analysis of Value Creation and Value Capture in the Microfluidics Market*”. Nevertheless, the conclusions for the failure of microfluidics benefits capture reach by the end of (Yadav, 2010) dissertation were rather vague.

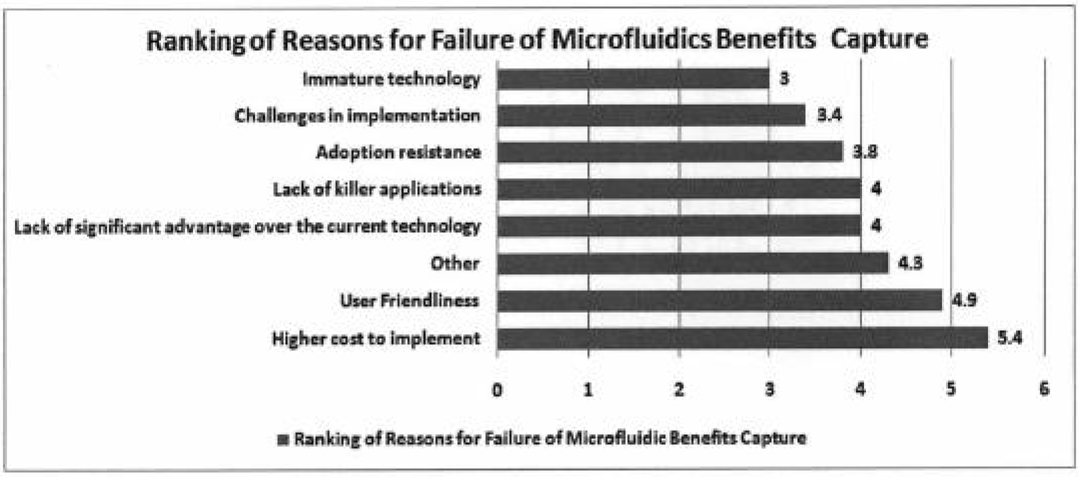


Figure 1 - Ranking of reasons for the failure of microfluidics benefits capture (Yadav, 2010).

For example: *Challenges in implementation*, *Adoption resistance*, *High cost to implement*, just stated the obvious: that microfluidics can’t make it to the market. These reasons didn’t provide any clarity, or a better understanding of which specific problems to act upon in order to increase the likelihood of microfluidics market success.

Reflecting these issues, this dissertation aims to identify, analyze and explore the *Barriers to the Diffusion of Microfluidics from Research to Market*, through a managerial point-of-view, in order that management can aid microfluidics to become a more pressing market reality, and thus have greater impact in our lives and in the world. Align with this purpose this dissertation will address the two following research questions:

1. What are the biggest barriers to the diffusion of microfluidics from research to market?
2. What are plausible solutions to overcome these barriers?

2. Methodology

One of the few quantitative data studies on how the microfluidic community perceives microfluidic is of (Yadav, 2010), which, as explained before, didn't bring that much clarity to the reasons why microfluidics is still a laboratory technology. As so, to answer the research questions presented in the introduction chapter, the following structure was adopted:

Firstly, a literature review was conducted using academic databases such as Google Scholar, Science Direct, and Research Gate, and it was organized under four main areas:

- Section 3.1 – Microfluidics: The Science - will introduce the science of microfluidics to provide the necessary basic support to understand what the technology is about.
- Section 3.2 – Current State of the Microfluidics Market - provides an overview of the market growth, prospects, companies and successful applications.
- Section 3.3 – Managerial Frameworks - intends to provide managerial frameworks to later analyze the current state of microfluidics through a management perspective.
- Section 3.4 – Barriers to the Diffusion of Microfluidics - aims to understand how the microfluidic community perceive as the biggest barriers to microfluidics commercialization.

Secondly, the factors influencing the choice of research methodology for this dissertation were the following – minimum targeted of users, possibility to reach more microfluidics experts (there are few). Based on this factor, a web-based survey was the best method of collecting data in terms of convenience, cost and time. The online survey tool (www.qualitrics.com) was used to design and disseminate the survey to 60 users representing the microfluidic community. The manipulation and the analysis of the data was done using (RStudio) and (Excel 2013), respectively.

The survey, which is present in the *Appendices* Section, is comprised of a total of 13 questions organized in two areas – *Participant Background* and *Technology Parameters*. The survey data was collected between a five day period (7th – 11th March). A total of 42 responses, yet only 34 were considered based on participants having completed the questionnaire. Nevertheless, it is assumed that 34 responses capture sufficient information on the current state of microfluidics, and based on the study by

(Griffin & Hauser, 1993) a user group survey is able to capture well over 90% of needs by collecting responses of only 30 customers”(Yadav, 2010).

Section 4 - Data Collection and Analysis – aims to provide additional quantitative data, based on the perception of the microfluidic community, to complement the literature review.

The following Section 5 - Discussion - brings together Section 3.3 and Section 3.4 in order to understand the hurdles and struggles of the microfluidics fields through a managerial lenses. It relates the barriers identified by scientist, research and engineers, to the “usual frameworks applied to understand other types of emerging technologies.

Finally, Section 6 - Conclusions, Limitations and Future Research - will be devoted to the conclusion of the main points, limitation and possibilities for future research of this dissertation.

Additionally, prior to the survey and after the scientific literature review, informal interviews with professors at Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa (FCT-UNL) Rui Igreja - *PhD in Material Engineering and CENIMAT researcher in Condensed Matter Physics and Sensors* - and Hugo Águas – *PhD in Material Engineering, Researcher in Microfabrication and Microfluidics, and with more than 100 published papers on international journals* - were conducted in order to have a fluid” conversation about the current state of microfluidics and their perception regarding the technology’s roadblocks. The aim was also to receive constructive criticism from individuals with a purely scientific background and perspective.

3. Literature Review

3.1. Microfluidics: The Science

3.1.1. What is Microfluidics?

Microfluidics is the science and technology of manipulating small amounts of fluids, in the range of microliters ($1\mu L = 10^{-6}L$) to picoliters ($1pL = 10^{-12}L$), in a network of microscopic channels. It's an interdisciplinary science that brings together such fields as: material engineering, physics, chemistry, biochemistry, nanotechnology, among others (Volpatti & Yetisen, 2014).

The behaviors of fluids at the microscopic scale are different from the macroscopic scale. Microfluidics studies phenomenon such as: surface tension, capillary forces and laminar flow, among others, and how they can exploit these unusual physics of fluids at the small scale to accomplish what laboratories can't (Hansen & Quake, 2003).

3.1.2. How does Microfluidics work?

Microchips are the devices used in microfluidics to carve out a network of micro-channels (Figure 2). Micro pumps, used to control the fluid dosage, and microvalves, used to direct the fluid, are some of the components often used to manipulate the fluid on the chip(Capretto, Cheng, Hill, & Zhang, 2011).

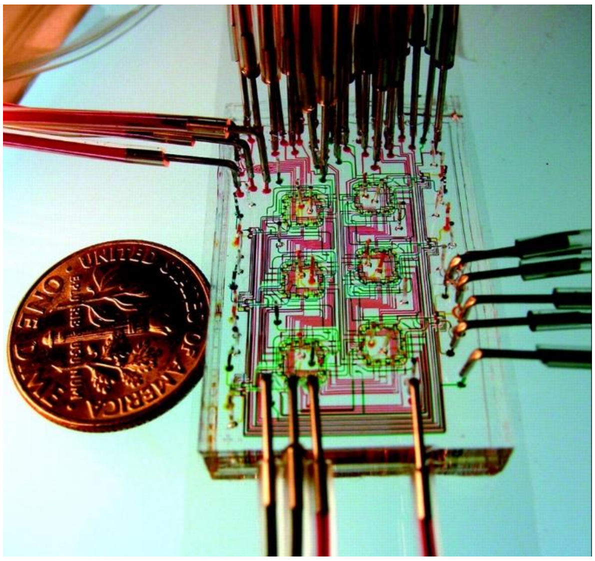


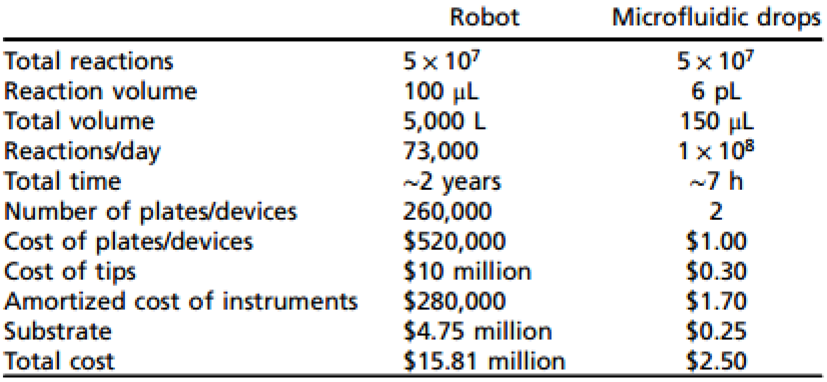
Figure 2 - A microfluidic chip with six parallel microchemostat reactors, used to study the growth of microbial populations. The coin is 18mm in diameter (Marguet, Balagadde, Tan, & You, 2007).

Microchips are normally made of materials such as: glass, silicon and polymers. The criteria for choosing the material depends on the microchip's application - each material has its specific properties (Yadav, 2010).

Polydimethylsiloxane (PDMS) is the most widely used material for research in microfluidics. PDMS is a polymer which has very different properties from silicon and glass. It has a faster fabrication process (easier to build valves, mixers and pumps), it's cheaper and more robust (Whitesides, 2006).

3.1.3. Advantages of Microfluidics

The small scale of microfluidics and the capacity to work with extremely low volume of samples and reagent (µL, nL, pL) confer unprecedented advantages (Figure 3) to microfluidics such as: **faster analysis** (faster detection of chemical specimens), **high sensitivity** (very small quantities of chemical specimens can be detected**)**, **high throughput analyses** (large number of parallel reactions without increasing control complexity), **scalability/economies of scale** (to process 400 PCR reactions microfluidic uses 41 steps, while conventional methods use 1200 steps), **portability/small footprint** (small size and light weight of devices)**,** and at the same time **reducing cost** (reduced amounts of reagents) (Hansen & Quake, 2003; Melin & Quake, 2007; Yadav, 2010).



	Robot	Microfluidic drops
Total reactions	5×10^7	5×10^7
Reaction volume	100 µL	6 pL
Total volume	5,000 L	150 µL
Reactions/day	73,000	1×10^8
Total time	~2 years	~7 h
Number of plates/devices	260,000	2
Cost of plates/devices	$520,000	$1.00
Cost of tips	$10 million	$0.30
Amortized cost of instruments	$280,000	$1.70
Substrate	$4.75 million	$0.25
Total cost	$15.81 million	$2.50

Figure 3 - Comparison of time and costs for the complete screen using traditional methods and in microfluidic emulsions (Agresti et al., 2010).

3.1.4. Microfluidics Applications and Fields

Microfluidics has a wide range of applications. According to (Mukhopadhyay, 2009) even when defining microfluidics as an analysis system that's small, it's very difficult to name every field which microfluidics touches. Therefore, the division used in this dissertation will be the same used by (Roussel & Clerc, 2015) in the Yole Development report (Figure 4).

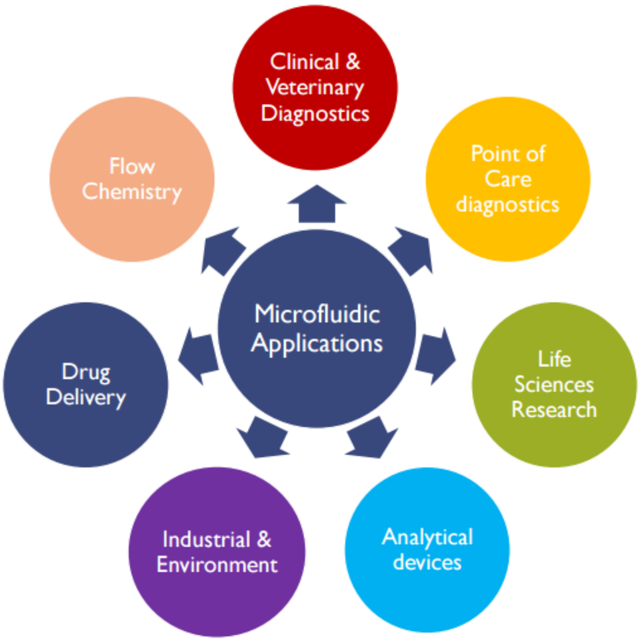


Figure 4 - Microfluidic applications (Roussel & Clerc, 2015).

- *Clinical & veterinary diagnostics* – microfluidic devices have the capacity to provide faster analysis and shorter waiting periods, and this improves the response time of doctors and veterinaries to the patient's needs (Sia & Kricka, 2008).
- *Life sciences research and Pharmaceutical* – encompasses the research in fields of biotechnology, biomedical technologies, biomedical devices, pharmaceutical among others. According to (Streets & Huang, 2013) microfluidic technology has become a key tool in life science research.
- *Analytical devices* – are the devices which analysts use to identify and quantify the chemical specimens in samples. The ability of microfluidics devices to perform this tests better, faster and cheaper opens new possibilities for analytical chemistry, medicine, genetics, among others (Lisowski & Zarzycki, 2013).
- *Industrial and Environmental* – the cost advantages and sustainability of green chemistry have been a topic of interest to the industry. The inherent possibilities

brought by microfluidic reactor systems (Figure 5) of decreasing energy requirements in chemical synthesis, decreasing reagent consumption and using less hazardous chemicals are incredible for green industrial chemistry (Elvira, i Solvas, Wootton, & deMello, 2013).

- *Drug delivery* – to enhance the specificity of drug treatment - to deliver exactly at the target site - and reduce their toxicity to the patient, and thus improving the treatment process, have been the extraordinary aim of researchers in recent years (Figure 6). Recently microfluidic smart systems have been develop for transdermal drug administration and controlled drug release (Riahi et al., 2015).
- *Point-of-care* – it's a diagnostic test performed (Figure 7) in the doctor's office without needing a clinical lab, and waiting hours, or days, for results (Sia & Kricka, 2008). For example, Claros Diagnostics, a microfluidic company, developed a microfluidic analyzer capable of performing multiple tests for urology and infectious disease (Curtis D. Chin et al., 2011; Volpatti & Yetisen, 2014)
- *Flow chemistry* – is a typical method implied to manufacture large quantities of a material. Microfluidic reactors can aid flow chemistry by providing unprecedented advantages, e.g., enhanced heat transfer, rapid mixing times, and small volumes (Elvira et al., 2013).

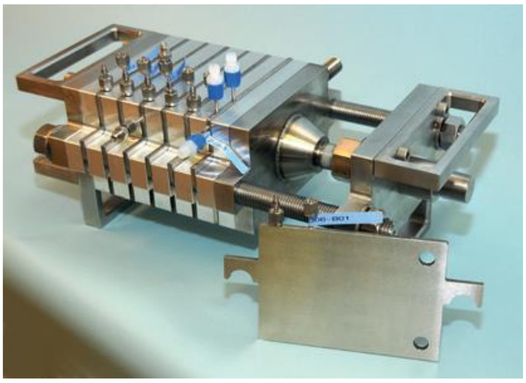


Figure 5 - The Lonza FlowPlate A6 microfluidic reactor can be used for process development in the kilogram range (Elvira et al., 2013) .

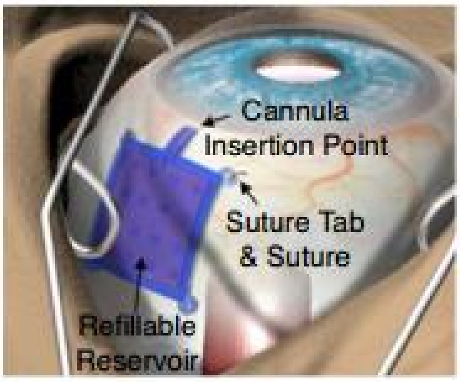


Figure 6 - Implantation of a microfluidic drug delivery platform for ocular applications, where the drug reservoir was sutured to the sclera and placed underneath the conjunctiva (Riahi et al., 2015).

Figure 7 - Daktari microfluidic-based HIV/AIDS POC test (Continuum Advanced Systems, 2016) .

3.1.5. History and Evolution of Technology

3.1.5.1. The fifties (50’s)

The techniques used in the fifties (50's) in the microelectronic industry (e.g. photolithography) to fabricate semiconductors were then later applied to build the first microfluidic-based devices. For example, the technology basis for the modern ink jet printer comes from the early efforts to dispense small amounts of liquids at high precision (van den Berg, Craighead, & Yang, 2010). Additionally, strips for diabetes (Figure 8) and pregnancy emerged in the fifties, which are based on microfluidic principles.

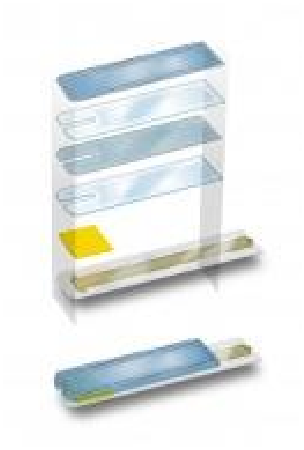


Figure 8 - Microfluidic test strip (Fontanazza, 2016).

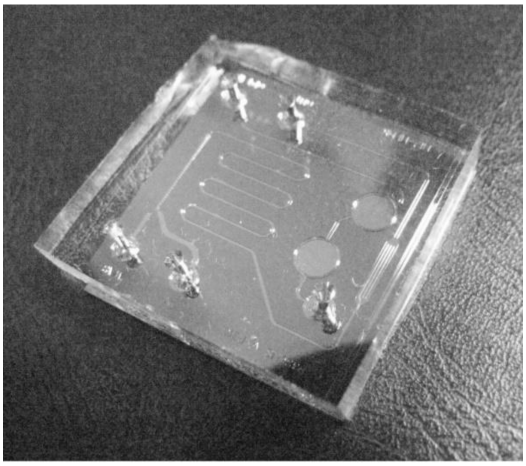


Figure 9 - A series of silicon-glass based microfluidic chip was designed and fabricated by conventional MEMS technology (Hungarian Academy of Sciences, 2016).

3.1.5.2. The eighties (80's) and nineties (90's)

In 1979 a milestone was set in microfluidics when S.C Terry develop the first lab-on-a-chip (LOC) analysis system - a miniaturized gas chromatograph (van den Berg et al., 2010). Over the 80's, the Micro-Electro-Mechanical Systems (MEMS) field - which is the "father" of microfluidics - emerged and was the basis of pressure sensors and printheads (Figure 9). The devices based on microfluidic technologies are one of the earliest successes of the commercialization of MEMS (Ducrée et al., 2004).

By the end of the 1980s, and beginning of the 90's, the microfluidics field started to emerge as a separated field from inkjet world, with its unique microfluidic concepts, which couldn't be just realized by downscaling traditional concepts (Ducrée et al., 2004). Besides, several microvalves and micropumps had been develop through silicon micromachining which set the foundation for microfluidics, also called "micro total analysis systems" (μTAS), or "lab-on-a-chip" (LOC) (van den Berg et al., 2010).

As noted by (Yadav, 2010), the innovations in the microelectronic field were a crucial foundation for microfluidics to become an independent field. Examples of simple microfluidic analysis systems present on the market today are test strips for pregnancy, drug abuse, cardiac makers and bio-warfare protection (van den Berg et al., 2010).

In the first decade of the 2000's technologies to produce micro channels in PDMS provided a cost effective way to advance with microfluidic research. Today researchers use PDMS extensively to build microfluidic components (Elveflow, 2016).

3.2. Current State of the Microfluidics Market

3.2.1. Overview Market and Market Growth

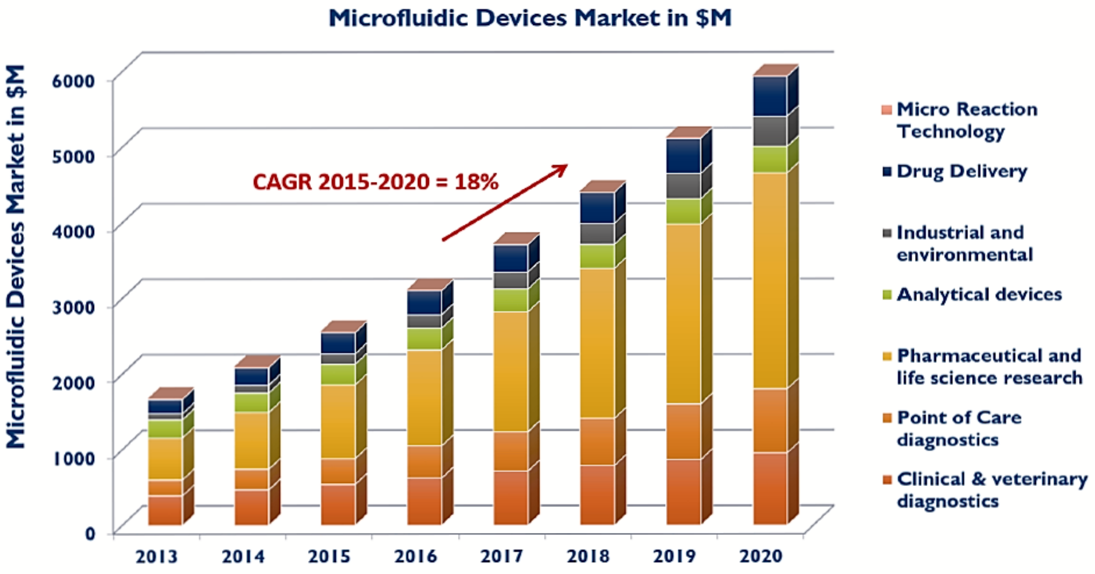


Figure 10 - Microfluidic devices market in $M (Roussel & Clerc, 2015).

Based on Yole Development report (Roussel & Clerc, 2015) - the most recent report about the microfluidic market - the microfluidic industry will experience a steady growth from $2.56B in 2015, to $5.95B in 2020, ($CAGR_{2015-2020} = 18\%$). The main drivers of this growth will be “Pharmaceutical and life science research” and “Point-of-care diagnostics” which will have the biggest growth comparing to the other microfluidic fields (Figure 10).

(Roussel & Clerc, 2015) highlight that the latest advancements in genomics were made thanks to breakthroughs in drug discovery by microfluidics. The Ebola epidemic raised considerable concern about avoiding future epidemics and thus has fostered Point-of-care (POC) innovation (Cai et al., 2015). Moreover, the strengthening of regulations in agro-food and water industries increased the demand for bacterial detection, and so the “Industrial and Environmental” field is experiencing a steady growth.

Despite the fact that microfluidics has offered unparalleled advantages - abundant amount of academic publication of proof-of-concept devices - it’s diffusion has been strongly limited (Yetisen & Volpatti, 2014). However, according to (Roussel & Clerc, 2015), nowadays the technology has evolved to fit the requirements and has become a well structure industry for further growth.

3.2.2. Market Companies

Microfluidics is now showing cumulatively more evidence of its potential - its foundation have become more solid. The reducing risk raised the interest among investors, and several microfluidic companies managed to raise funds by entering the stock market. Most have been focused in constructing multidisciplinary teams through collaborations and acquisitions. New competencies and activities have been develop - which doesn't come as a surprised, since microfluidics is a multidisciplinary field – in order to provide unique offers. (Roussel & Clerc, 2015). In (Figure 11) it's possible to notice that microfluidic companies are experiencing a substantial amount of growth in the last years.

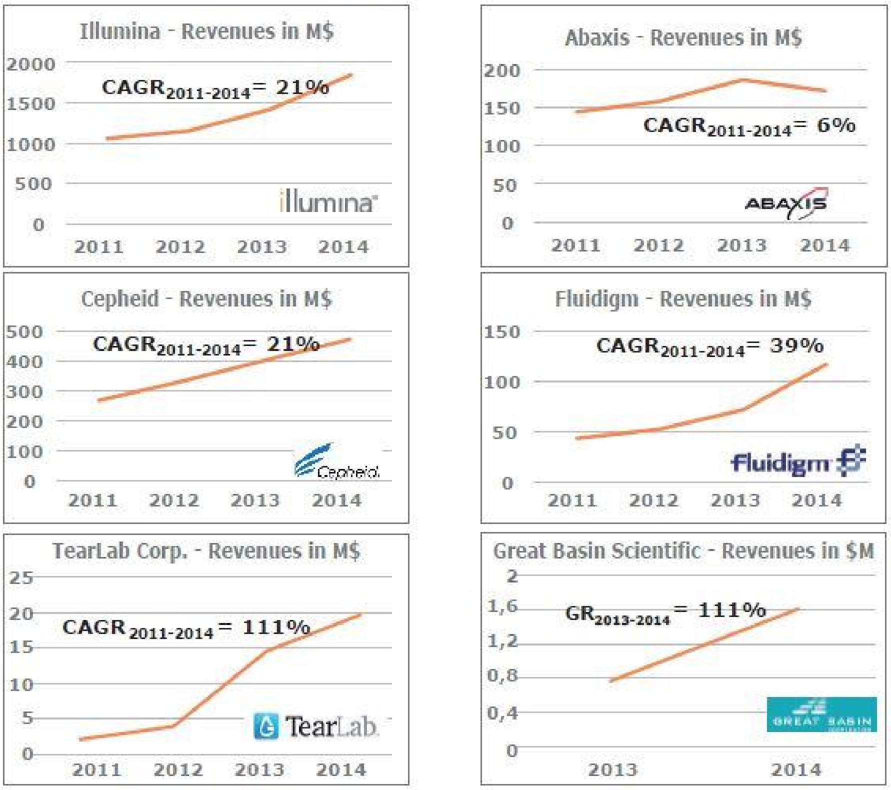


Figure 11 - Microfluidic companies on the Stock Market (Roussel & Clerc, 2015).

3.3. Managerial Frameworks

This section is the third (managerial) part of the literature review and aims to provide the necessary managerial frameworks to analyze the subsequent barriers detected in the fourth (scientific) part of the literature review.

3.3.1. Product Life Cycle

The first notion about a product life cycle was popularized by Dean who researched how the product life cycle (PLC) could capture the similarities between different emerging industries - there are characteristic patterns to all new industries. However, it was Abernathy, Utterback and later Kim Clark that summarized a clear concept of the PLC and its drivers (Klepper, 1997).

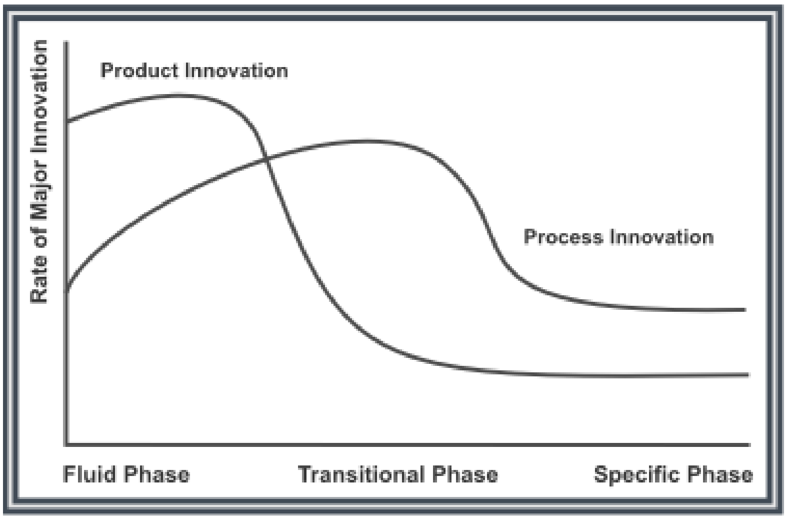


Figure 12 - Utterback-Abernathy model(J. Utterback, 1994)

The (J. Utterback, 1994) model (Figure 12) describes the different rates of product and process innovation through time. It identifies three distinct phases: fluid, transitional and specific; and each phase crucial concepts can be summarized as (Klepper, 1997):

- **First Stage –** Fluid phase
    - Design is primitive and frequently changing. There's a lot of different products in the market and a variety of designs. Innovation is quick, and so devices are always evolving.
    - Manufacturing and marketing are improvised.
    - There are few defined patterns, standards or rules.
    - Competition is based on product innovation/differentiation.
    - There's a high degree of experimentation, and therefore of uncertainty.

- Product output volume is low. The production process is flexible and requires considerable workforce.
- Performance criteria is uncertain and the workflow is messy.

Second Stage – Transitional phase

- A standard design starts to emerge. Industry starts to conform to the dominant design.
- Product innovation slows, as the ideal design has been found. Occurs only small modification of the dominant design - slow refinement.
- Reduce in product diversity – producers and users adopt dominant design and its benefits.
- Standardization begins.
- Performance criteria and processes are more defined.
- Companies invest in precise production equipment because they are less reluctant about production processes becoming obsolete due to significant product innovations.
- Equipment is more specific. Workflow is aligned and defined.
- Product output increases.

Third Stage – Specific phase

- Shift from differentiation to product performance and cost competition.
- Both product and process innovation decrease.
- Low probability of radical changes – which are costly - due to high integration and standardization.
- Production system is standardized and product cost minimization is key.

3.3.2. The Dominant Design

Dominant design is a technology management concept which refers to essential technological features and design architecture that the bulk of the industry conforms to (Abernathy & Utterback, 1978; Srinivasan, Lilien, & Rangaswamt, 2006). Thus, companies must adhere to this standard configuration if they wish to be competitive in the marketplace. For example: in the computer operating systems industry there were a few alternative designs (e.g. Windows, Mac OS, OS/2) until one became accepted as the industry standard: the Microsoft Windows (Anderson & Tushman, 1990). Furthermore, the dominant design is often the product which is the best overall package, rather than the one with state-of-the-art technology (Veloso, 2015).

3.3.2.1. Emergence of Dominant Design

The emergence of the dominant design signals the industry's entry into the transitional phase of the Utterback-Abernathy model and it alters the direction of technological development, the rate of the development, and the competition dynamics (J. M. Utterback & Suarez, 1993).

In accordance with (Uusitalo, 2014) companies to avoid uncertainty adopt the dominant design, and start to produce standardized and more compatible parts to improve organizational processes, volumes and efficiency. Cumulative learning enables cost-reduction by making processes more efficient, and therefore boosts mass adoption and volume production. There is a decrease in product-class: products are similar, only differentiated by minor differences from the dominant design. Innovation is accomplished only by incremental improvements on the accepted design – there is less experimentation. The dominant design is a decisive step towards standardization.

3.3.3. Technology S-Curve

The Technology S-curve (Figure 13), introduced by (Foster, 1986), is an indispensable framework used in technology strategy to gauge how new technologies progress and how they take over existing ones.

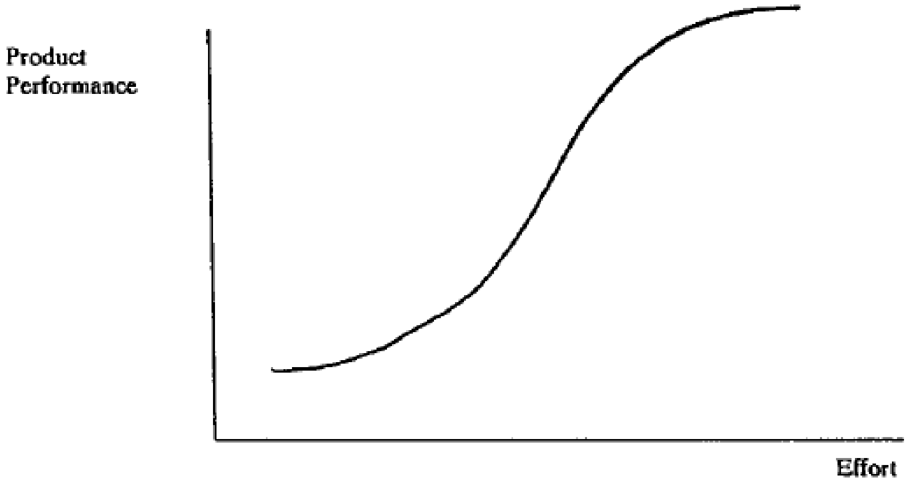


Figure 13 - Technology S-Curve (Christensen, 1992)

The S-curve represents the relation between effort (investment) and technological performance (return) by plotting performance against effort[1]. In the early stages technology's rate of evolution is slow. It's necessary to put significant amount of effort to make little progress in technology performance. Once learning starts, players get more experienced and progressively extract higher returns for little amounts of effort. After a while we approach the limits of the technology - the S-curve starts to bend downwards. In this stage it's required gradually more effort to obtain smaller marginal improvements in performance – diminishing returns (Foster, 1986).

Why is important?

This pattern described by the S-curve can be found in different industries such as: artificial hearts, pocket watches and calculators. The conventional belief that more effort put in equals more results, goes contrary to what is represented in the curve. The ratio between effort and results changes depending where the company is on the curve.

---

[1] "You might think you should be plotting results against the amount of time involved. But that would be an error. It's not the passage of time that leads to progress, but the application of effort." (Foster, 1986)

Therefore, if key performance parameters are defined, the company can grasp where they are in the S-curve, and thus make future plans (Foster, 1986).

3.3.3.1. Technological Discontinuities

A crucial concept about S-curves is that they often come in pair. The gap between S-curves represents a technology discontinuity (Figure 14). The S-curve often corresponds to a specific technology with a defined performance parameter. Yet, there's always more competing technologies, each with their own S-curves. In the beginning, even if the emerging technology bring innovative processes, the existing technology often can still do the job more effectively. That's why the second S-curve ranks lower in performance than the first S-curve (Foster, 1986).

A technological discontinuity happens when one technology replaces another – when an emerging technology is capable to provide better performance, or lower costs, than the existing one (Foster, 1986).

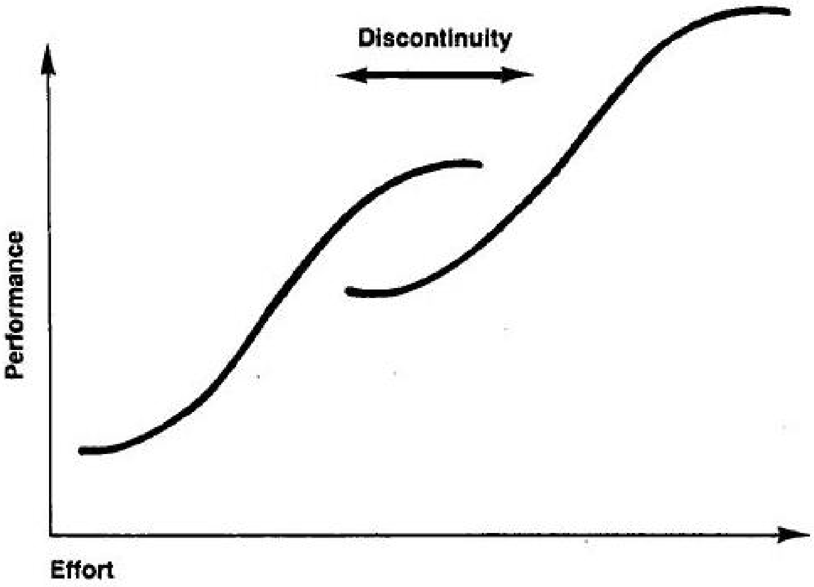


Figure 14 - S-Curves and technological discontinuity (Foster, 1986).

3.3.4. Gartner's Hype Cycle

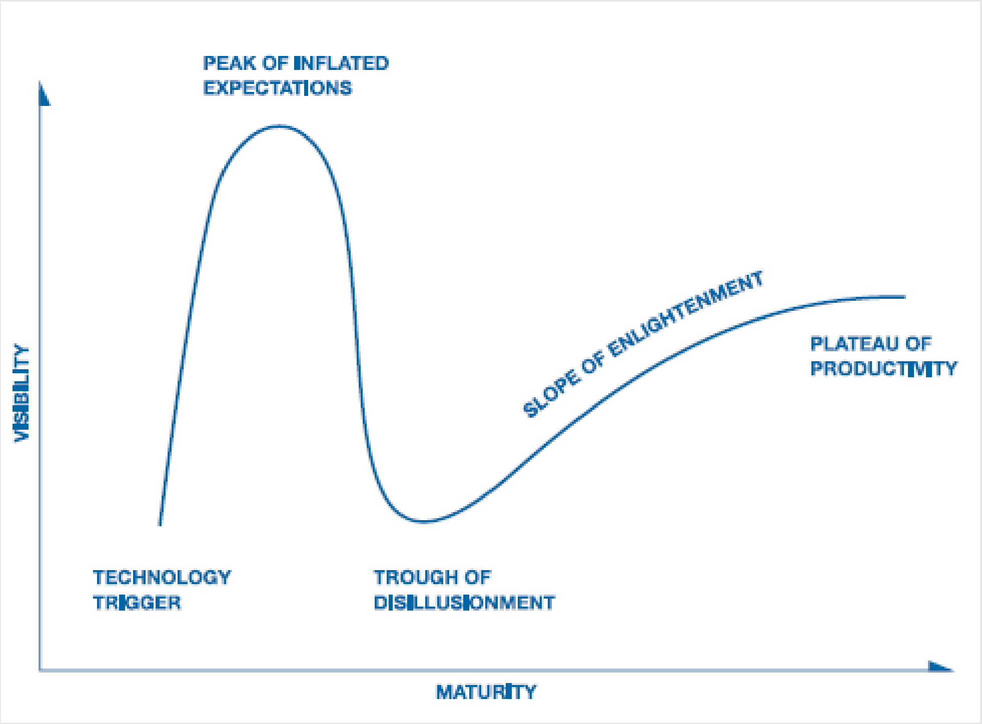


Figure 15 - Gartner Hype Cycle (Mukhopadhyay, 2009).

What is?

The Hype Cycle model was introduced by Gartner, a technology advisory company, in 1995 and it represents how emerging technologies mature over time and the society's attitude towards it (Linden & Fenn, 2003).

Why is useful?

Most emerging technologies evolve through a period of overenthusiasm, followed by a pit of disillusionment. In the early stages expectations build up due to media speculation about the technology's prospects – which often is poorly founded and contributes to widening the gap between "what the technology can do" and "what the technology is doing".

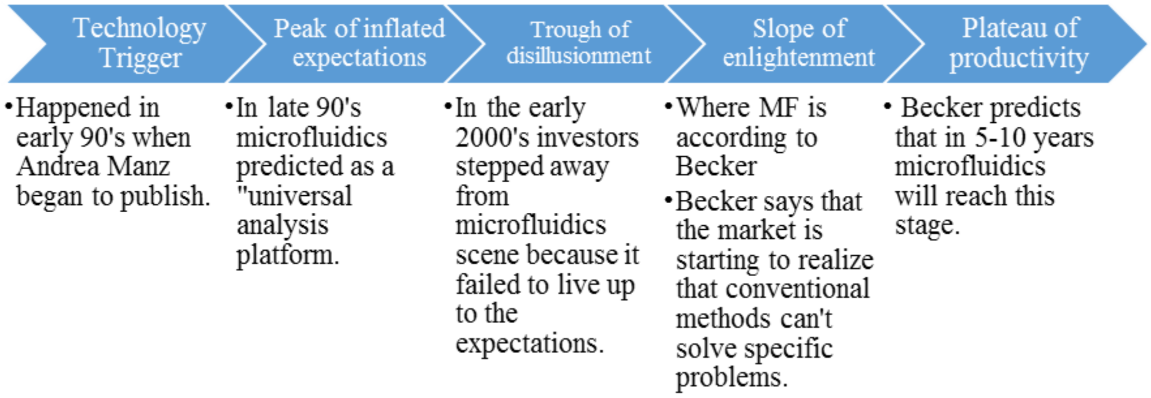
The Gartner Cycle acknowledges this variable hype stages, thus managers who understand this cycle can take prudent measures to discern what is real, or mere infatuation. By understanding the cycle, managers improve their decision-making skills, and in turn avoid getting lured by the media buzz (Linden & Fenn, 2003). The patterns described by the Gartner Cycle can be identified in such industries as the automotive industry, railroads, elevators, oil and the internet (Hastings-Simon, Pinner, & Stuchtey, 2014; Mukhopadhyay, 2009).

Explanation

The Hype Cycle (Linden & Fenn, 2003) is made up of five stages (Figure 15):

1. *Technological trigger* – is the first technological breakthrough and the press generates a lot of publicity. Normally in this phase there are no products, just research based devices.
2. *Peak of inflated expectations* – emerge first products which are very expensive, specialized and difficult to use. Nevertheless, the media continues to increase the hype.
3. *Trough of disillusionment* - because the technology doesn't live to the expectation, it is quickly discredited by the media and public. During this stage the vendors which didn't disappear start to improve their products.
4. *Slope of enlightenment* – an increasing understanding of the technology's capacities come from different enterprises which survived the previous phase. The second and third generation products are launched, and process innovation starts to increase (Figure 12).
5. *Plateau of productivity* – this phase encompasses mainstream adoption, when the real-world benefits of the technology are proven and accepted.

Regarding microfluidics, their future progress is of much debate. Yet, Holger Becker (Mukhopadhyay, 2009) says it's normal that there are divergent opinions about it. He believes this confusion is natural and is represented in the Gartner's Cycle. Becker's view of microfluidics evolution is resumed in (Figure 16). According to Berker, microfluidics is already on the slope of enlightenment phase. It's already working as an enabling technology by providing a variety of solutions, and is becoming present in a myriad of products in fields such as: clinical diagnostics, drug discoveries and the food industry, among others. Additionally, the Yole Developpement report by (Roussel & Clerc, 2015) supports Becker's view. According to Roussel and Clerc, microfluidic applications are now well established and their advantages are well-known.



- Happened in early 90's when Andrea Manz began to publish.

- In late 90's microfluidics predicted as a "universal analysis platform.

- In the early 2000's investors stepped away from microfluidics scene because it failed to live up to the expectations.

- Where MF is according to Becker
- Becker says that the market is starting to realize that conventional methods can't solve specific problems.

- Becker predicts that in 5-10 years microfluidics will reach this stage.

Figure 16 - Resume of Becker view (Mukhopadhyay, 2009).

3.3.5. Strategy

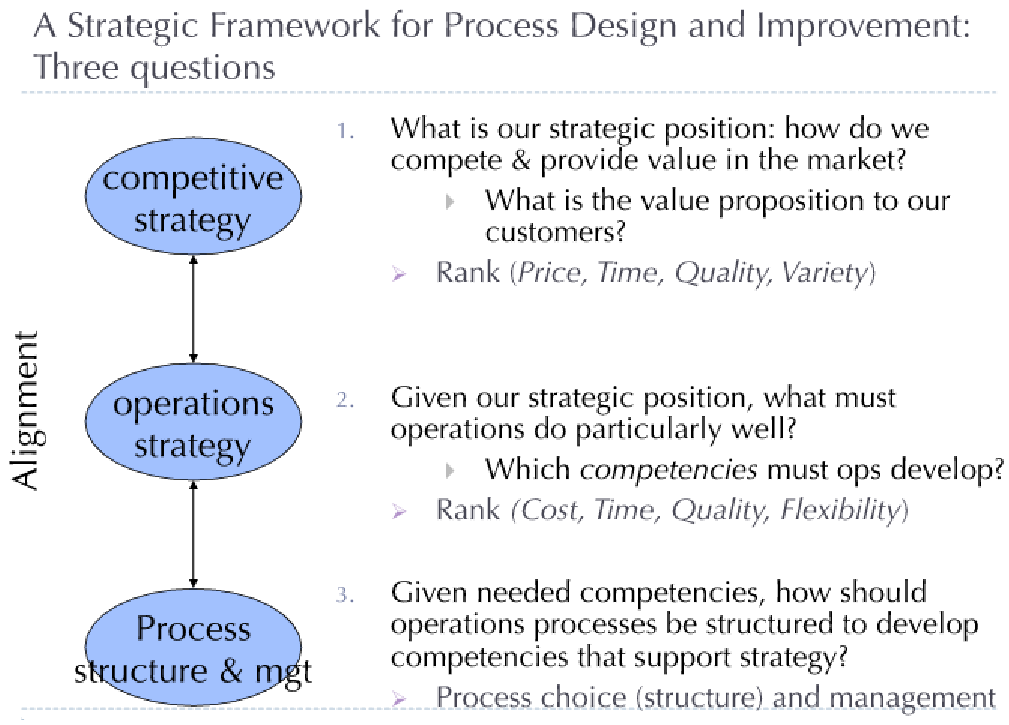
Strategy is to create a unique valuable position by synchronizing different set of activities. There's no one right way to do everything - if there was a specific right set of activities to produce all the varieties which would meet all users' needs, the best company would be the one which performed the activities in the most efficient way. Because that's not true, depending on what the company wants to offer, it should align its activities properly in order to provide the best economic value (Porter, 1996).

Companies which try to do all things to meet all customer needs are always running an inefficient machine. Resources which are put into one type of activity implies that they will be missed in others. This is where trade-offs come into play - when certain activities are incompatible, and a decision to which one to pick must be made. Tradeoffs should be planned because there are limits to coordination and control. Therefore by choosing which types of activities to engage, and those to which purposefully disengage from, makes organizational priorities clear, keep objectives defined, and ultimately supports a focused decision making workforce (Porter, 1996).

3.3.5.1. Strategic Fit

According to (Porter, 1996) how well do you perform single activities is termed as operational effectiveness. But, strategy is about combining activities. Strategic fit, or strategic alignment, is the term normally attributed to how effective is the firm in combining their core capabilities with their resources in order to provide the most efficient value proposition to customers (Figure 17).

Activities should be arranged in a way that they complement each other. Certain activities if coupled with others can, for example, reduce fixed costs, thus have a better performance. A proper fit is fundamental to run an efficient, more focused institution, and to drive competitive advantage and sustainability. According to (Porter, 1996), "positions built on system of activities are far more sustainable than those built on individual activities".



A Strategic Framework for Process Design and Improvement: Three questions

1. What is our strategic position: how do we compete & provide value in the market?
    - What is the value proposition to our customers?
   - Rank (*Price, Time, Quality, Variety*)
2. Given our strategic position, what must operations do particularly well?
    - Which *competencies* must ops develop?
   - Rank (*Cost, Time, Quality, Flexibility*)
3. Given needed competencies, how should operations processes be structured to develop competencies that support strategy?
   - Process choice (structure) and management

Figure 17 – Strategic framework for process design (Allon, 2016).

3.3.6. Market Pull vs. Technology Push

"Know why": Market and Competitive Strategy
Understand customer's buying behavior (customer drivers) and feasible strategies. Target key segments. Identify competitors, complementors and partners.

"Know what": Product Roadmap
Decide how the product will be differentiated to win in key segments. Translate overall customer drivers into product drivers for this specific product. Set multi-year targets.

"Know how": Technology Roadmap
What technologies are most important? Link product drivers to hardware, software, and manufacturing technologies. Identify multi-generation technology investments to maintain competitiveness.

"Know when": Summary and Action Plan
What resources and investments are needed? Plan projects with the highest priorities. Are technology investments in the most important areas? Identify and track risk areas.

Figure 18 – Different stages in roadmap development process (Luggen, 2004)

Market pull and technology push are concepts typically applied to describe the business strategy of a company (Figure 18). According to (Luggen, 2004) an oriented technology push strategy implies that a new innovation is pushed through R&D and attempts to be successful in the market, without taking into consideration of whether or not will satisfy the needs of customers. A technology push strategy starts with the invention and then attempts to build a product under which to better capitalize their capabilities.

Conversely, an oriented market pull strategy has first the customer's needs in mind - the market demand is the starting point. The company works backwards: first starts with the market needs, then understand how the product functions have to be design to satisfy those needs, followed by how the already understood technologies can work together to generate the greatest value to the customer, and finally pinpoints which competencies are a priority and should be devoted more time and effort in order to have a better chance of supporting their action plan (Luggen, 2004).

3.4. Barriers to the Diffusion of Microfluidics

This section is the forth (scientific) part of the literature review and aims to understand what the microfluidic community (researchers, scientist and engineers) perceive as the biggest problems for the commercialization of microfluidics.

3.4.1. Microfluidic Platform, Standards and Integration

Microfluidic Platform

(Zengerle & Ducrée, 2007) believe that a microfluidic platform will facilitate a system oriented approach, instead of a device oriented approach. It will enable the microfluidic community to engage towards a flexible and cost efficient design research model. This will facilitate the creation of economical and practical devices, and so will improve their commercialization and spread in the market.

What is a microfluidic platform?

A microfluidic platform is a set of intuitively combinable microfluidic modules that allow assay miniaturization through a consistent fabrication technology (van den Berg et al., 2010). The validated modules should perform basic operation such as: fluid transport, fluid meeting, fluid mixing, valving, and separation or concentration of molecules or particles (Lily, 2009a). The platform's most vital characteristic is convenience - the user should be able to combine basic modules in a straight forward and instinctive way. The company which can excel in user-friendliness will have a remarkable advantage over other platform companies (Zengerle & Ducrée, 2007).

(Zengerle & Ducrée, 2007) highlight three microfluidic platforms:

1. **PDMS based Microfluidics for Large Scale Integration (Fluidigm platform Fluidigm/Integrated Fluidic Circuit)** - It's expected that integrated microfluidics will revolutionize chemical and biological procedures, identically to what the integrated circuit did for electronics (Bousse, Kopf-Sill, & Parce, 1998; Hansen & Quake, 2003). Unfortunately, a comparable integrated circuit for microfluidics doesn't come as easily as it did for microelectronics (Nelson, 2012) (Figure 19).
2. **Microfluidics on rotating CD (Lab-CD)** – its inspired by the compact disk and uses centrifugal forces to transport the fluid to microfluidic channels and mixing chambers. It's an alternative set-up which also provides a cost effective integration of microfluidic operations that are used in lab-on-a-chip and has its own specific

advantages (e.g. can process hundreds of parallel tests and is more efficient when compared with microchips) (Figure 20 and Figure 21).

3. **Droplet based microfluidics (DBM)** – a basic droplet microfluidic platform leverages the interfacial forces of droplets to manipulate reagents under defined areas (Figure 22).

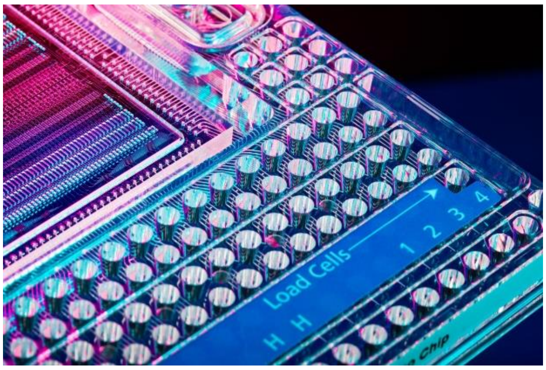


Figure 19 - The C1 Single-Cell Auto Prep System uses an integrated fluidic circuit, or chip, (shown here) to isolate single cells and prepare them for next generation sequencing, mRNA analysis, or other forms of genomic analysis (Fluidigm, 2016).

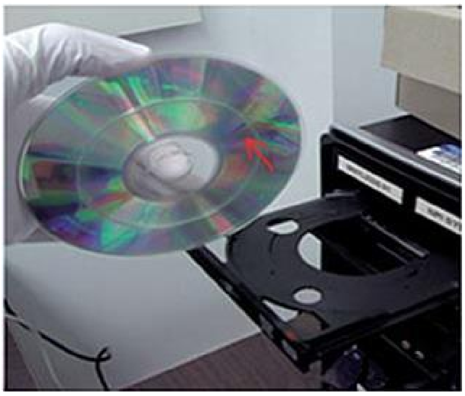


Figure 20 - Lab-CD before fluid mixing (Imaad, Lord, Kulsharova, & Liu, 2011).

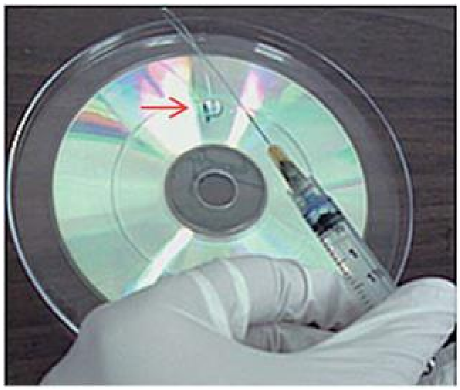


Figure 21 – Lab-CD (Imaad et al., 2011)

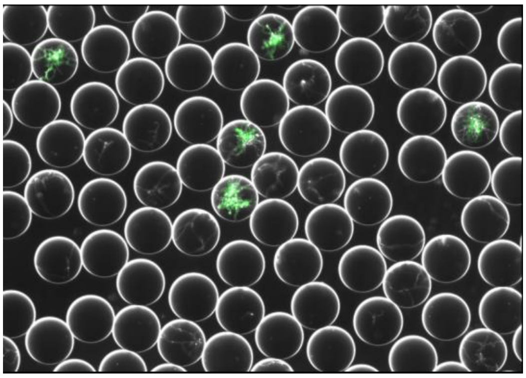


Figure 22 - Streptomyces aureofaciens and Streptomyces lividans in 170 pL droplets (Leibniz Institute, 2016).

The Benefits of a Microfluidic Platform

Collaboration

According to (Mark, Haeberle, Roth, von Stetten, & Zengerle, 2010) a standard platform will direct researchers to build and design their components to fit into it. Making components' parameters and its design match the platforms' scheme will make them more compatible. A component made to fit into a set standards can be later used by other researchers using the same platform to complement their device, and thus contribute to building highly integrated microfluidic systems. This better care for standards and compatibility will promote an iterative work between researchers.

(Blow, 2009) notes that the current paradigm is that there are a lot of outstanding researchers and engineers producing novel microfluidic devices and fabrication techniques, but many researches don't collaborate with their peers.

Less work lost

Academic researchers normally develop fully customized prototypes, and their components are only compatible within that specific system. Therefore a myriad of components such as micropumps, microvalves and mixers, are obsolete because they are only compatible with the system they were built on (Zengerle & Ducrée, 2007).

No need to start from scratch

There's always the struggle to build the prototype from scratch, because there is a lack of compatible complementary components. Building prototypes is also time consuming and costly, and most of them turn out to not have commercial level functionality (Lily, 2009a; Zengerle & Ducrée, 2007).

i. Suggested Solutions:

As mentioned before the dominant design in any industry is a major step towards standardization, it increases commercial viability by shifting gears to an improvement in processes. (Volpatti & Yetisen, 2014) remark how important is for developers - if they wish microfluidics to see commercial daylight - to think of it as a component of a much bigger commercial technology by making it compatible with existing workflows. Volpatti and Yetisen precisely point out two key areas which microfluidics disregards, but that are key to prosper: **Standardization** and **Integration**.

Standards

There's a lack of perspective to understand that research and development (R&D) is part of the value chain towards commercialization. Academia disregards providing accurate reproducibility and variability statistics (parameters standards). This reinforces the current paradigm of lack of standards. As so, a lot of protocols, materials, and equipment only work with very particular system configurations – they aren't compatible with existing technologies workflows(Volpatti & Yetisen, 2014).

(Volpatti & Yetisen, 2014) use PDMS as an example of a material which is extensively used in R&D, but that microfluidic companies abstain from, with the exception of Fluidigm, because of problems with scaling and manufacturing (Volpatti & Yetisen, 2014). PDMS brought exceptional advancements to glass and silicon, however most of the microfluidics critical functions (e.g., displacement valves and pumps) developed in PDMS fail to be practically transferable to industry cost-effective polymers.

Integration

Integration only has a chance if there's a solid foundation of standards precluding. Problems with standardization directly affect the capacity for components to be easily integrated to form functional integrated devices. It's imperative that each developer considers the compatibility of the components which they design from the beginning, in order to foster unity, rather than reinforce the current environment of discord. Considerable research has been done in LOC components, only later to understand that they don't function in accordance with other elements (Volpatti & Yetisen, 2014).

To ensure that products and components pass through rigorous performance and quality tests (e.g. product qualification) is the first step to instill in the microfluidic community a continual underlying concern with compatibility. (Tantra & van Heeren, 2013) note the importance of: defining standards for connectors such as dimension, durability and strength; adopting generic test methods to evaluate device characteristics such as: microchannel surface roughness, capillary and adsorption effects; and having strict quality control processes to ensure the quality of substrates and etching processes.

(Volpatti & Yetisen, 2014) conclude that to speed up the maturation of microfluidics, hence improve the likelihood of success, is necessary that the industry and academia align strategies: lack of standardization and integration are most evident in the transition from prototype to fully commercialized product. Therefore researchers should be supported by a solid market feedback loop provided by industrial partners, because commercial success involves more than just technical expertise.

3.4.2. Lack of Communication between Academia and Industry

Tech is not the end of it

Researchers are the spark of technology progress, nevertheless to come up with a viable effective solution involves more than just technological expertise. Cost of capital, market access and politics are some of the crucial factors to consider in the path to commercialization (Whitesides, 2013). According to Whitesides the academic research is one part of the value chain. The ratio of money invested to: develop an idea, turn it into a prototype, making it possible to manufacture, and manufacturing it, is very qualitatively 1: 10: 100: 1000.

Manz (Mukhopadhyay, 2009) believes that the divergent reward system of academia (publish) and industry (sell) is keeping the status quo of microfluids and is a pressing underlying obstacles to its the proliferation.

i. Suggested Solution:

Nevertheless, (Blow, 2009) believes that things have been changing. Although a lot of researchers and companies have been looking out for the killer app that would change the microfluidics panorama, several are now clearly focusing in improving the communication between academia and the industry in order to use microfluidics has an enabling technology for life science applications. Nevertheless, Blow highlights that there is a clearly misalignment between what is being develop in academia and the needs and efforts of the industry. (Mukhopadhyay, 2009) gives as an example the annual µTAS conference where it's possible to see a lot of excited researchers who bring the latest widget, which probably got plenty of scientific compliments, but that doesn't lead to anywhere.

The essential question that remains is: how to go from the laboratory to a ready-to-be-commercialized product. The total inclusion of a third party – commercial producer – is vital for the successful transition from laboratory to ready to market product (Whitesides, 2013).

Soper (Mukhopadhyay, 2009) highlights how contributors outside of the microfluidic scene have been extremely valuable by keeping them from spinning their wheels ingloriously. Frequent communication with them have helped Soper's company to be aligned with the market needs, rather than being obsessed with the latest widget. Developing complex devices is useless if the market needs aren't met.

(Whitesides, 2013) outlines how different is to demonstrate a concept in laboratory, but more complex is to turn it into a quality controlled, registered, commercialized product. Just because a researcher developed a remarkable new prototype, it doesn’t mean that there’s a machine ready to manufacturing the gadget in a cost efficient way. The manufacturing technology it’s absolutely crucial in the path to commercialization (Lily, 2009b).

Lee (Blow, 2009) recognizes the need for communication and collaboration between researchers and big manufacturers. The bridge has to be closed in order to spread the use of microfluidic. For example, to facilitate this transition from lab to industry, Lee notes that most of his project are developed from the beginning in accordance with the center's manufacturing capabilities to ensure compatibility.

(Whitesides, 2006) supports Lee noting that the manufacturing technology is crucial in the commercial development of microfluidics. To define what types of material and processes will bring the device from a prototype to a solid product should be done in the early stages of development.

3.4.3. Technology for Technology’s Sake

It's very common in academia that researchers heedlessly focus in building novel devices with state-of-the-art technology, yet disregard their practicality and therefore fail to solve real word problems and have greater broader impact in the world (Whitesides, 2013). The main goal of academia is to publish (Man, Weinkauf, Tsang, & Sin, 2004), and so academic researchers disregard the disadvantages of the complexity of operating a prototype in the race to publish. To make it functional and commercial viable it’s irrelevant and someone else’s task (Lily, 2009a).

However, it’s important to understand that users are plainly interested in how technology translates to function – the value comes from the benefits of the technology, and not from the technology itself. They care about the computer, and not about the transistor or the microprocessor. They want technology to be simple and invisible (Whitesides, 2013). Unfortunately this overemphasis’s in science and the impatience to publish contribute to the gap of what universities are developing and what the market needs.

According to (Mark et al., 2010) thousands of papers have been published on microfluidics in the past 10 years and the annual publications continuously increase. However, few viable microfluidic devices are making an impact in the world (van den Berg et al., 2010).

Functional Successful Examples

(Whitesides, 2013) mentions the 96 well and the glucometer, both remarkable examples of how a product succeeded by matching users’ expectations. Two perfect examples of simple, yet – not surprisingly - effective technology.

96-well plate

The 96-well plate and pipetter have been around chemistry for two hundred years. They are familiar, simple and cheap, and more importantly they are adaptable and flexible to a wide range of applications. They have been enabling rookie scientists to carry out complex manipulations, such as serial dilutions with small quantity of reagents.

The Glucometer

(Whitesides, 2013) attributes part of the success of the glucometer to the uncomplicated set up it has. It transports the blood to an electrochemical analyzer, and performs enzymology and electrochemistry, but in the end – because the user doesn’t know, or care, about all the mechanisms - it displays the result in a user-friendly way to the diabetic user.

The Revival of the DNA Sequencer

A different example illustrated by (Rotman, 2009) which reinforces the same principle, is the DNA sequencer. A technological product revived because the company which produced it made it functional. The DNA sequencer was being commercialized since 1986, but only became popular six years later when the company managed to sell a sample preparation kit. In spite of the kit not being a major technological advancement, it made the sequencer functional and accessible, and thus realized the sequencer's potential. Even if the DNA sequencer produced in 1986 was cutting edge technology, it only found commercial daylight when it was turned accessible.

i. Suggested Solutions:

According to (Whitesides, 2013) the first considerable change needs to happen among scientists: the academic culture needs to shift to bring together "simple" and "useful", with "highly cited" and "fashionable". Simple devices most often are economical and practically efficient (commercial viable), even if they fail to make a significant impression in academia. Their value comes – not from creating a device that mesmerizes and astonishes their scientific peers with an embellished widget - but from being commercially viable. Academia needs to change this contemptuous outlook towards research which aims to ultimately develop cheap and practical technology.

Additionally, (Whitesides, 2013) defends that new technologies should start with the problem, instead of random inventions. If there's no focus on delivering a tangible, cheap, useful product, research will continue to funnel towards a mindless experimentation with the latest gadgets. Moreover, scientists and manufactures should coordinate their efforts to build practical and easy to manufacture technology so they can effectively solve important problems and make money along the way.

3.4.4. Lack of Focus

Academics do the fundamental work, but it’s random and not focused. Industry experts can detect that these method of unfocused work is one of the key bottlenecks towards the path to commercialization (Blow, 2009).

Academia has the luxury to sustain this obsession and the perpetual fiddle of researchers who are plainly unfocused and just waste energy in developing outrageous devices. However, the industry doesn't withstand this paradigm. The industry looks for robust analytical devices, which are often the ones with simple and effective architecture. However, the current academic reward system rewards researchers for building complex systems, yet fail every time to be commercial viable (Mukhopadhyay, 2009).

i. Suggested Solutions:

(C. D. Chin, Linder, & Sia, 2012) emphasize how a focused product development implies denying tempting opportunities, which could be beneficial, but that are currently misaligned with the work in progress, and thus – even if beneficial - are detrimental with the current goals. Resources are limited, hence should be used sparingly and strategically. To pursue disparate offers squanders efforts: a diluted workforce is a weak workforce. Therefore, goals should be kept in sight to avoid a slower product development, subsequent missed milestones, and a stress in the company to go after worse short term funding opportunities, ending up creating a vicious compensation cycle.

Unfortunately, (C. D. Chin et al., 2012) mention that a lot of investments in microfluidics companies have been about producing a platform product with a realm of diverse markets, while failing to deliver one specific POC product, and so come short to make an impact. The biggest obstacle in POC companies is lack of focus. Even if several opportunities (e.g. collaborations, investment, acquisitions) were proposed to Claros laboratories, they weren’t aligned with the work being developed, thus would just stall their progress towards their already established mission. To not break a sweat over these opportunities is was crucial.

4. Data Collection and Analysis

The priority of the previous chapters has been to: describe the technology of microfluidics, grasp the microfluidic market, provide managerial frameworks, and finally outline the most pressing concern and roadblock of the microfluidic community.

To that end, the aim of this chapter is to complement the literature reviews (managerial and scientific) with insights from the microfluidic community. Based on the data collected through this survey it will be possible to quantitatively analyze the perspective of microfluidics experts on the current state of microfluidics. The following section will interpret the results from the survey.

4.1. Participant Background

Survey Group, Roles and Workplace

The sample was divided in two groups: Academia composed by: *Graduated Master* (MSc) students, *Doctorate* (PhD) students and *Researchers*, and Industry composed only by *Industry Engineers*. The sample was unevenly split with 82% from *Academia* (28 respondents) and 18% from *Industry* (6 respondents) (Figure 23).

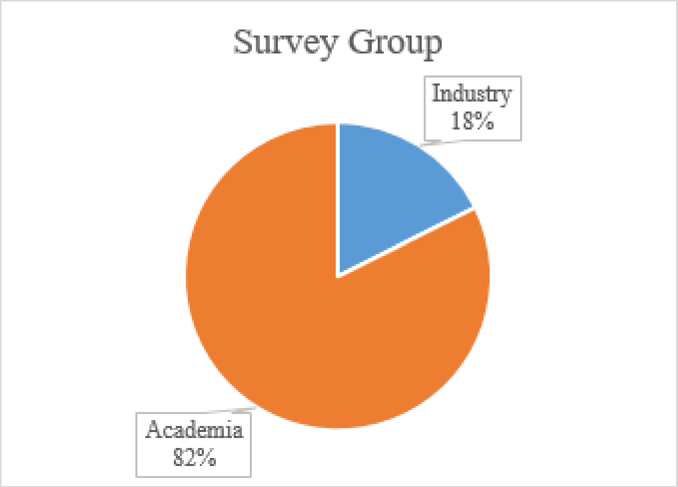


Figure 23 - Survey Group.

The roles titles of the respondents were divided into four groups. As shown in (Figure 24) the Academia (82%) group is composed of 38% Master (MSc), 26%

Researchers and 18% Doctorate (PhD). The Graduated Master group is the largest subgroup, nevertheless the other 62% are composed of people with higher degrees.

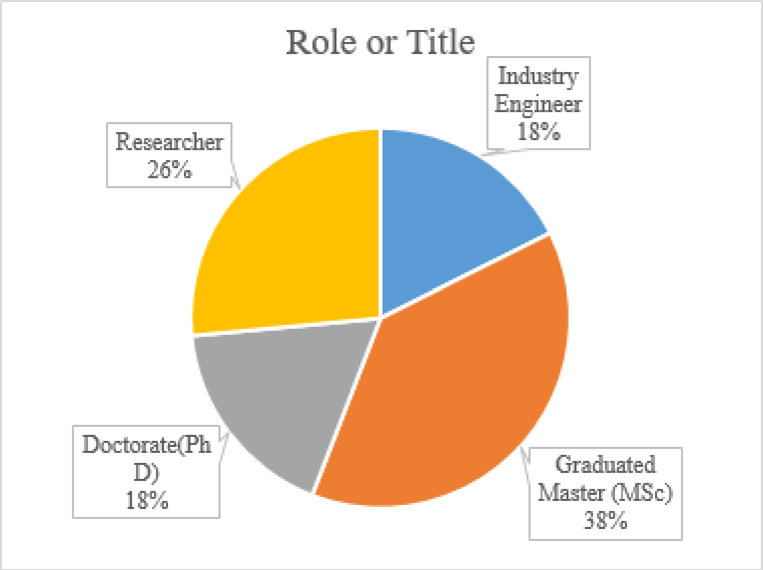


Figure 24 - Role or Title.

In Academia, a significant large number of respondents come from (9) Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa (FCT-UNL) and from (8) Instituto de Engenharia de Sistemas e Computadores para os Microsistemas e as Nanotecnologias (INESC-MN), the rest of respondents come from (2) Instituto Superior Técnico (IST), (1) Massachutes Institute of Technology (MIT), (1) University of Cambridge, (1) Instituto de Tecnologia Química e Biológica (ITQB), (1) Stockholm University, (1) University of Rome and 4 are currently unemployed (Figure 25).

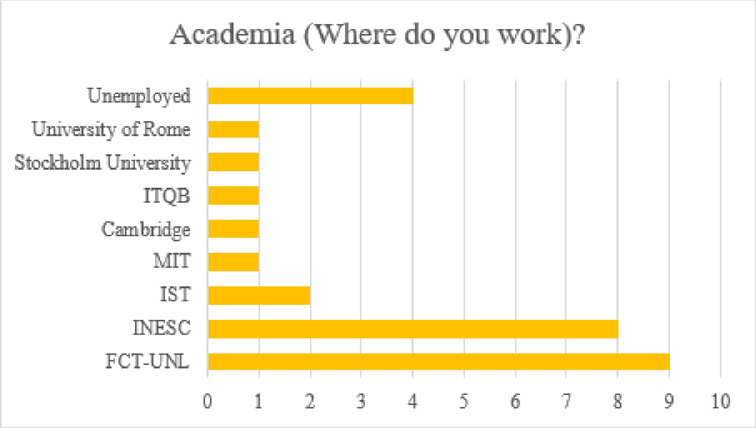


Figure 25 - Academia group work.

Industry respondents are currently working in (1) Magnomics and (5) Biosurfit - both Portuguese companies at the forefront of in-vitro diagnostic testing (Figure 26).

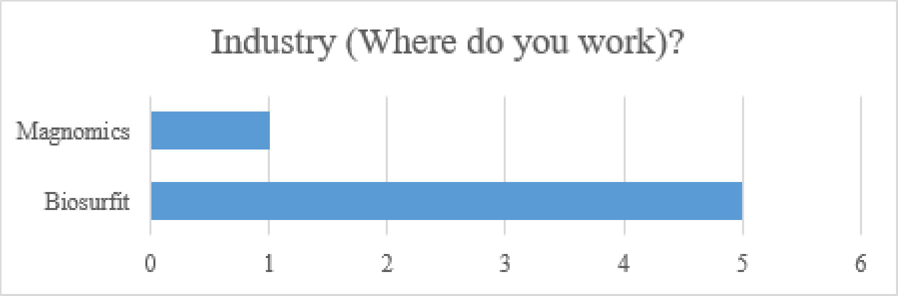


Figure 26 - Industry group work.

Source of Microfluidics Expertise and Publishing groups

Regarding how respondents relate to microfluidics, their source of expertise, shown in (Figure 27), comes in major part from: *Reading academic literature/articles* (6.91), *Discussion with other researchers* (6.41), *Work experience* (6.00), followed by *BSc/MSc or PhD studies* (5.94), *Conference/Workshop/Seminars* (4.18), and last *Published literature* (2.97). Additionally, as shown in (Appendix 5) respondents have an average of 3 (3.18) *Years of Experience with Microfluidic*s, which range from 1 year to 10 years.

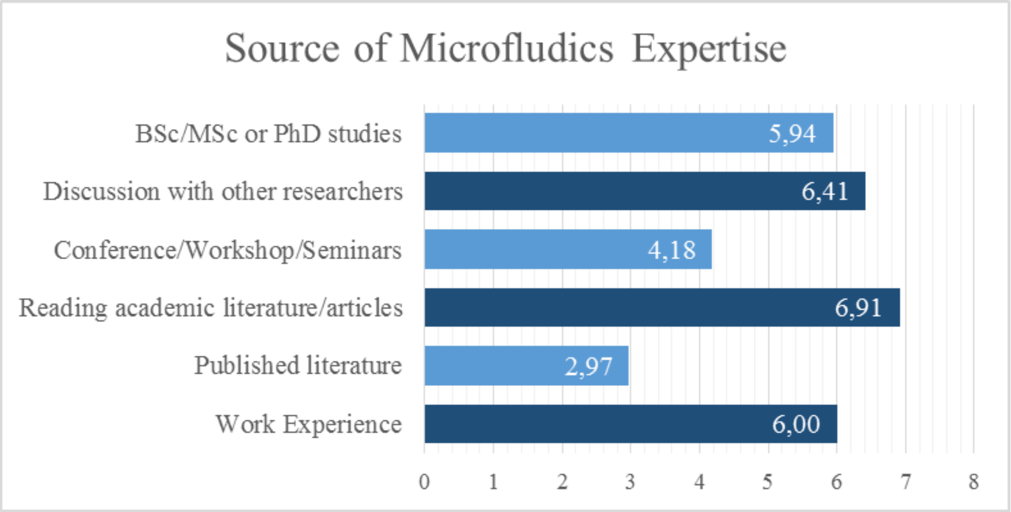


Figure 27 - Average Rank of Source of Microfluidic Expertise.

It's important to note that: *Published literature* and *Work Experience* (Figure 27) are the most valued types of experience since both imply direct hands-on-experience (practical), while the other types are considered indirect contact (theoretical).

The group division made between those who publish and those who didn't publish is shown in (Figure 28). The groups are evenly split with 56% "*Publishing = 0*" and 44% "*Publishing > 0*". As expected there's a considerable difference of 2.46 *Years of Experience* between those who published (4.26 years) and those who didn't (1.80 years) (Figure 29); and also a difference in *Work Experience* of 1.91 between those who published (6.84) and those who didn't (4.93) (Figure 30). Concluding, those who publish have more Work Experience and Years of Experience which means that they have a higher contact and experience than those who didn't publish.

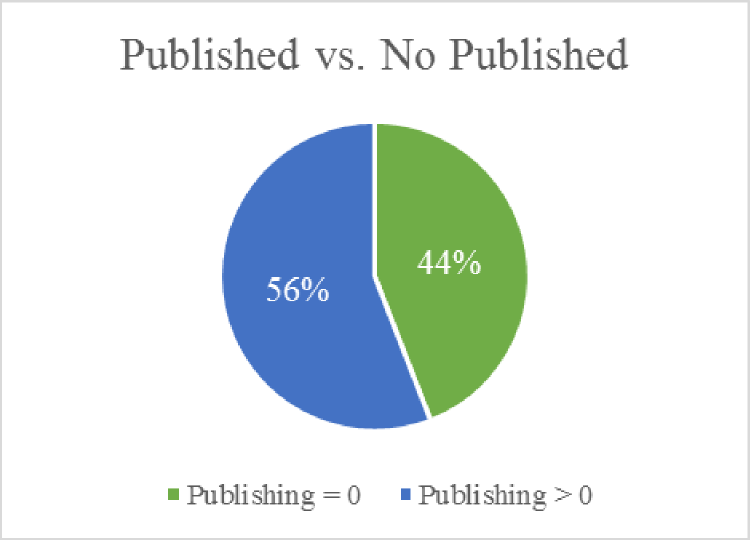


Figure 28 – Publishing group division (Percentage)

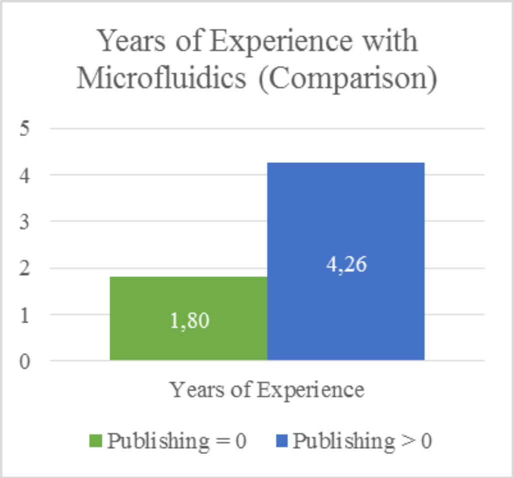


Figure 29 – Comparing Years of Experience with Microfluidics between groups

Figure 30 – Comparing Work Experience between groups

Nationality and Age

Lastly, the average age of the respondents is 28-years-old, which range from 22-year-old to 58-year-old (Appendix 5); and respondents are for the most part (30) Portuguese, and also (1) British, (1) Indian, (1) Italian, (1) American (Appendix 6).

4.2. Technology Parameters

Expectations, Microfluidics Growth (2016-2020) and Hype Cycle

Respondents considered microfluidics to meet 6.24 (from 0 to 10) of the expectations hitherto (Appendix 2). Regarding the spread of microfluidics from 2016 scored 27.4 %, and 2020 scored 59.4 % (Table 1), which represent a 32% growth over the next four years (2016-2020) and a Compound Annual Growth Rate (CARG) of 21.34% (Table 1), which is approximate to what (Roussel & Clerc, 2015) report predicted: CARG of 18% (2015-2020) (Figure 10).

Table 1 - Survey estimated CARG (2016-2020)

CARG	**21,34%**				
Year	2016	2017	2018	2019	2020
Spread	27,4	33,2	40,3	49,0	59,4

The respondents rated the state of microfluidics on the Gartner Hype cycle (Figure 31) with 2.74 (Appendix 4 - Hype Cycle and Barriers), which corresponds to the exit from the *Peak of Inflated Expectations* and entering the *Through of Disillusionment.* This doesn't support Becker's current belief that microfluidics is in the slope on enlightenment phase.

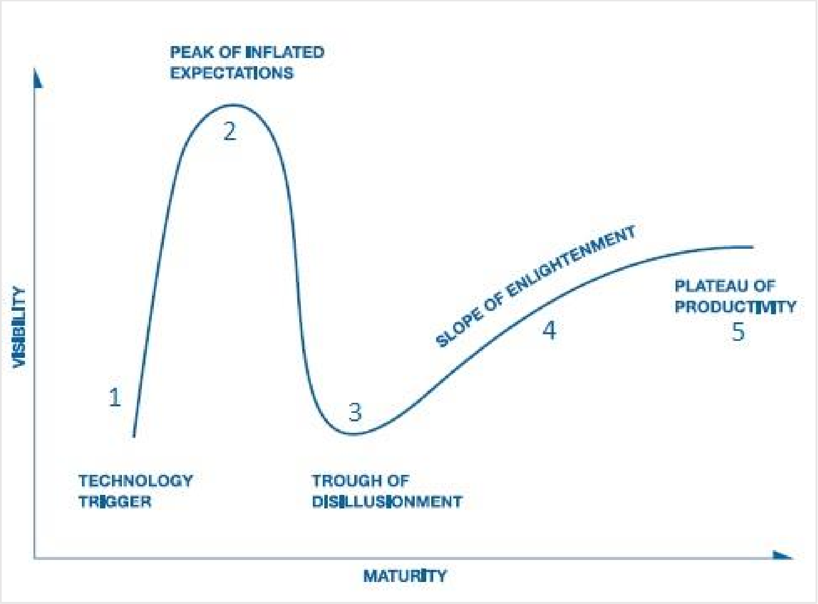


Figure 31 - Gartner Hype Cycle adapted for the survey, adapted from: (Mukhopadhyay, 2009).

Drivers, Submitted Barriers and Barriers

Drivers

Point-of-care (8.68) ranked has the primary driver with. Second on the list is *Clinical & veterinary diagnostics* (7.62), followed by Analytical Devices (7.06) and *Pharmaceutical and life science research* (6.71). In fifth came *Drug Delivery* (6.12), in sixth *Flow Chemistry* (5.88), and in last *Industrial and Environmental* (5.82) (Figure 32).

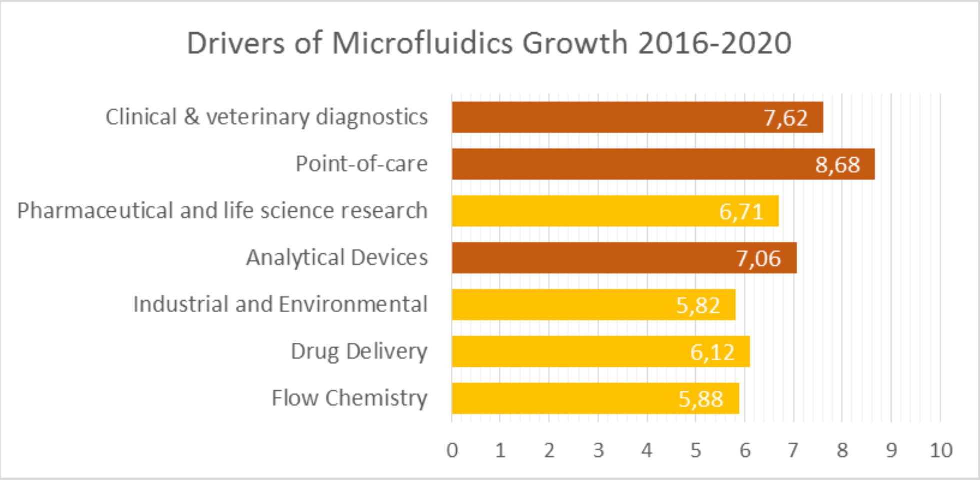


Figure 32 - Drivers of Microfluidics Growth between 2016-2010

Survey responses match the main three drivers of microfluidics growth of Yole Report by (Roussel & Clerc, 2015) (Figure 10), with the exception of *Pharmaceutical and life science research* – which ranked in fourth. The comparison between Yole and Survey respondents top three drivers of microfluidics growth are shown in (Table 2).

Table 2 - Top three Drivers of Microfluidics Growth (Yole and survey)

	Yole (Figure 10)	**Survey (Figure 32)**
1st	Pharmaceutical and life science research	Point-of-care
2nd	Clinical & veterinary diagnostics	Clinical & veterinary diagnostics
3rd	Point-of-care	Analytical Devices

There are no significant difference in the responses of *publishing groups* regarding this section’s topic (Appendix 7).

The following topic - *Barriers to the Diffusion of Microfluidics* - is the key topic of this dissertation. The first group of barriers are the submitted by the respondents without any previous suggestion. After, respondents were presented with the barriers found in the Literature Review and asked to rate them from 0 to 10.

Submitted Barriers

Survey Participants were asked to name up to three barriers which they thought would prevent the transitioning of microfluidics from research to market. A total of 31 participants responded (3 abstained). The suggested barriers sum up to 76, but only 66

(Figure 33) were considered since some of them were either too vague, incomprehensible or reductant.

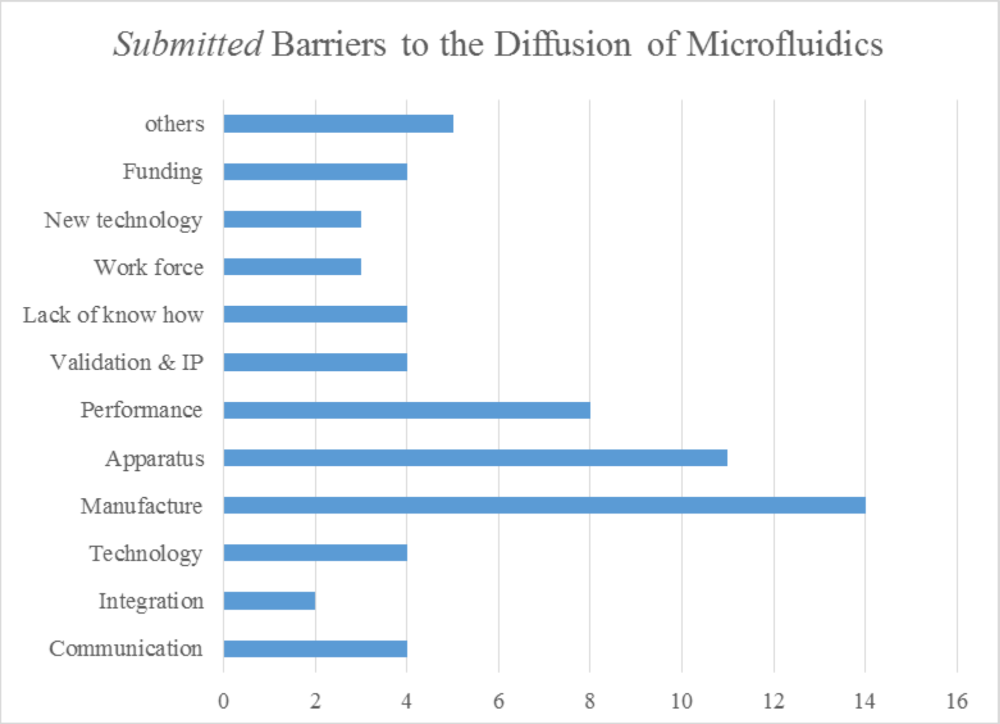


Figure 33 - Submitted barriers of survey respondents

Manufacture leads the rank with 14 responses, and is concerned with cost and transition of, and to, manufacturing. Examples of responses are: *"cost of production*", "*difficult in fabrication*" and "*mass production technology issues*".

Apparatus (second place - 11 responses) and *Performance* (third place - 8 responses) are related with engineering and the resolution of problems at the microscale. Examples of responses are: "*low yield of PDMS*", "*reagent storage*" for Apparatus, and "*there are other better understood methods*" for Performance.

Communication (4 responses), *Technology* (4 responses) and *Integration* (2 responses) are the same barriers described in the Literature Review.

Validation & IP which are legal issues, *Lack of know-how* which concerns the capacity of engineers and researchers to understand the process of commercialization (i.e. transition from research to market) and *Funding* which is a financial issue, share the fourth place with *Communication* and *Technology*, each with 4 responses.

Finally, *New technology* which regard the lack of divulgation of microfluidics and *Work force* which concern the lack of specialized workforce, were both mention 3 times. *Others* constitutes the other 5 responses which didn't fit in any category.

The detailed list of the *submitted barriers to the diffusion of microfluidics* and respective group division can be found in the *Appendices* Section.

There are no significant difference in the responses of *publishing groups* regarding this section's topic (Appendix 8).

Barriers to the Diffusion of Microfluidics

The first barrier is *Communication* (7.15), followed by *Technology* (6.62). After came *Standards and Integration* (6.15), and last *Focus* (5.85) (Figure 34).

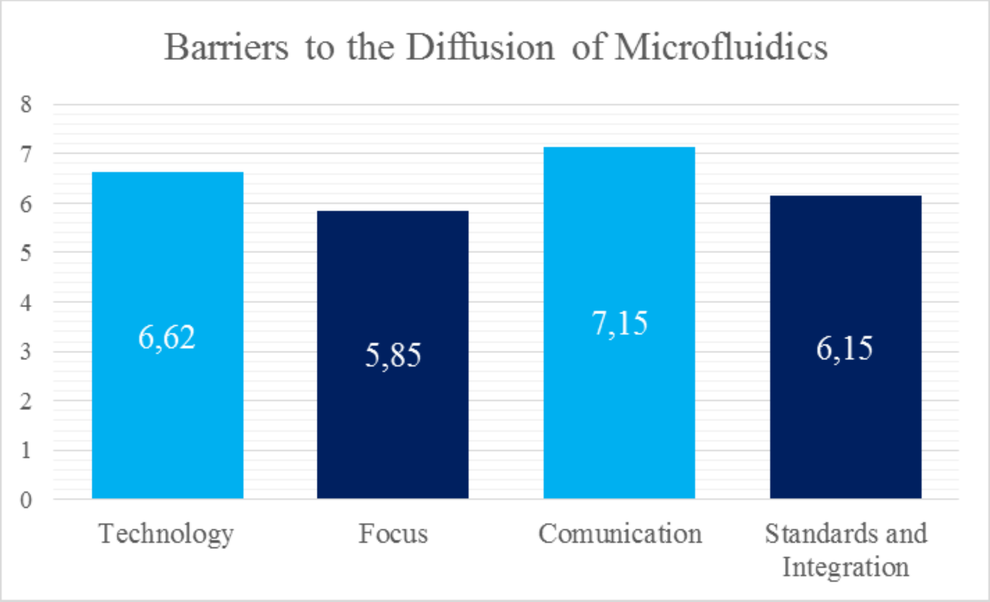


Figure 34 - Barriers to the Diffusion of Microfluidics

As shown in (Figure 35), those who publish ranked: *Communication between Academia and Industry* in first place; second place: *Standards and Integration* tied with *Technology*, and last place: *Focus*.

On the other hand, those who didn't publish ranked: *Technology* in first place; second place: *Communication between Academia and Industry*; third place: *Focus* and last place: *Standards and Integration*.

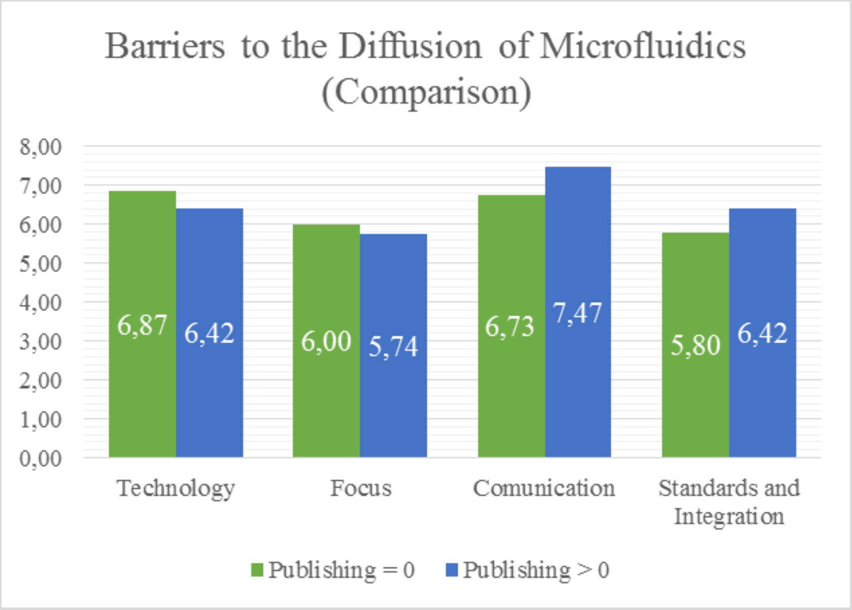


Figure 35 - Barriers to the Diffusion of Microfluidics (Comparison)

Regarding magnitudes, *Communication* (0.74) and *Standards* (0.62) have the largest differences between groups, followed by *Technology* (- 0.45) and *Focus* (- 0.26) (Table 3).

Table 3 - Differences of barriers to the diffusion of microfluidics between publishing groups

	Technology	Focus	Communication	Standards
Differences[2]	- 0,45	- 0,26	0,74	0,62

The larger differences in *Standards and Integration* - also ranked last in those who didn't publish - and *Communication* between groups might be because these problems are more perceptible to those who work directly with microfluidics. Respondents who publish have significantly more work experience and years with microfluidics and this might be the reason why *Standards and Integration* and *Communication* are more pressing problems, thus are more relevant to this group and so their ranking and magnitude (Figure 35) are higher.

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[2] $Difference = \text{"Publishing>0"} - \text{"}Publishing = 0\text{"}$

5. Discussion

Microfluidic Platform, Standard and Integration

The characteristics attributed to a microfluidic platform: “a set of intuitively combinable modules which perform basic operations”, and the following prediction of the benefits brought by the platform: “collaboration”, “less loss of work” and “no need to start from scratch” are characteristics” analogous to those habitually credited to the dominant design.

Furthermore, the considerations” by (Zengerle & Ducrée, 2007) that a microfluidic platform would “unleash: “switch from a device oriented to a system oriented approach” and “a flexible and cost efficient design research model” strongly resembles the paradigm shift associated with the entrance into the transitional phase (second stage) of the Utterback Model.

Therefore, the prediction of benefits and paradigm shifts of what it would be like to find a microfluidic platform suggest that the microfluidics community is yet to find its dominant design, and it also locates microfluidics in the fluidic phase (first stage) of Utterback – before the emergence of the dominant design.

Additionally, the following solution of integration and standardization, which are characteristic of transitional phase and consonant with the path after the emergence of dominant design, suggested by (Volpatti & Yetisen, 2014) as a solution, also implies that microfluidics is still seeking these solutions and has yet not benefited from them, which confirms the conviction that microfluidics is in the fluid phase of the Utterback, and the equivalent of the early stages of the technology S-Curve.

As so, by the reasons mentioned it’s possible to withdraw that: microfluidics is in the Utterback Fluidic Phase (first stage); there’s still no dominant design; the solution of standardization and integration to microfluidics to become a more commercialized technology are major consequences of finding the dominant design, which suggest microfluidics needs a dominant design; there’s a wish to reap the benefits characteristic of the transitional (second) stage of Utterback model; microfluidics is located in the early stage of the S-Curve, before the dominant design emergence, and in which innovation mainly relies on R&D.

Lack of Communication between Academia and Industry

The solutions purposed by Lee (Blow, 2009), and (Whitesides, 2013), to improve the manufacturing communication in order to improve the commercialization of microfluidics is, by other words, an incentive to increase the growth rate of process innovation. The increasing growth of process innovation precludes the entrance into the transitional phase of the Utterback model, where the process innovation overtakes product innovation. A better relation with manufacturers incentivizes a more defined workflow and an increase in product output, which are also characteristic of the transitional phase. Therefore, for these reasons microfluidics is once more pinpointed to the fluid phase of Utterback looking to breakthrough to the transitional phase.

Besides, to have a higher manufacturing fosters the implementation of standards and integration, previously suggested. Also, the survey data supports that manufacturing is a problem: "manufacture" was the most mention barrier (14 out of 66) when survey respondents were asked to think of barrier to microfluidics commercialization, without any previous mentions of the ones found in the Literature Review. As so, by the reasons mentioned it's possible to withdraw that: microfluidics is in the fluid phase of Utterback; microfluidics needs to increase its process innovation; the microfluidic community (survey respondents) spotted manufacturing as the biggest suggested barrier.

Technology for Technology Sake

Technology for Technology's sake detected as a problem implies that microfluidics is in a product diversification paradigm – a lot of different products and a variety of designs - which is characteristic of the fluid phase (first stage) of Utterback, and corresponding to the early stages of the S-Curve where innovation mainly relies on R&D.

Additionally, during an informal interview, PhD's Professor Hugo Águas and Rui Igreja from Faculdade de Ciências e Tecnologia (FCT) revealed hesitancy in committing to an answer when asked about what field of microfluidics would grow faster until 2020. Their answer: "A new innovation tomorrow can change everything" reinforces, once more, the conviction that microfluidics is on the early stages of the S-Curve, and corresponding to the Utterback fluidic phase, before the dominant design, when there's a high degree of experimentation and of uncertainty.

The following solution: to consider function first, it's conceptualized as a market pull strategy. As so, this suggestion takes as a given the current mindset of the microfluidic community to be technology push oriented, which is a typical mindset of emerging technologies. As so, by the reasons mentioned it's possible to withdraw that: microfluidics is in the early stages of the S-Curve, and corresponding fluid phase of Utterback model; microfluidics is an emerging technology; microfluidics has a high degree of uncertainty; that the current mindset is "technology push" oriented, but has to become a "market pull" one.

Lack of Focus

Researchers tend to be lured by disparate opportunities, instead of focusing in one particular application and developing the appropriate device, they tend to switch depending what where is the latest new innovation. Moreover, because academia rewards innovative new devices, researchers don't have any incentive to break this paradigm. This shows a product diversification mindset, again focused on technology oriented strategy.

The suggested solution of a focused product developed are similar to the concept of strategy: of defining proper workflows and to purposefully decide what is the institution seeking. This suggests once more that microfluidics still doesn't have any guidelines, or rules, which is characteristic of the fluid stage of Utterback.

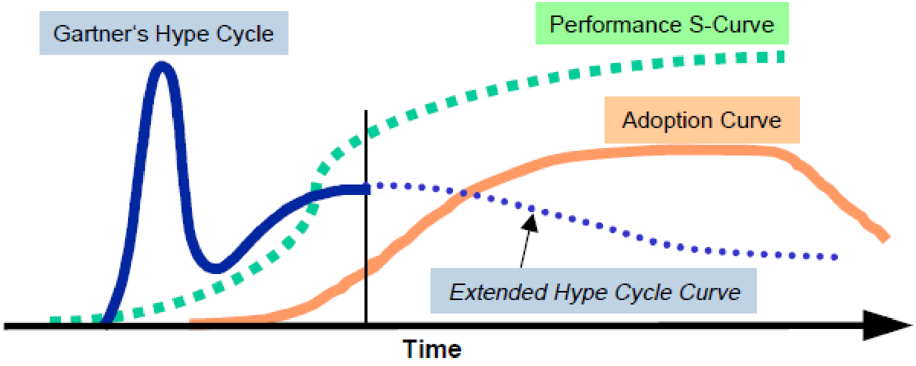

Figure 36 - Gartner's Hype Cycle, Performance S-Curve and Adoption Curve (Linden & Fenn, 2003).

In (Figure 36) it's possible to compare that the early stages of the S-Curve, which is where microfluidics is located, corresponds to the stages between: after the exit of the *Peak of inflated expectations* and before the *Plateau of productivity* on the Gartner's Hype Cycle. It turns out that this is aligned with where the survey respondents locate microfluids: *Slope of enlightenment*.

Additionally, the results from the *barriers suggested* in the online survey indicate performance (8) and apparatus (11), after manufacture, were the next two most mentioned barriers, which implies, correspondingly, that microfluidics can't outperform the competing technology already in the market, and that a lot of issues are related with technical apparatus.

Besides these facts, Hugo Águas referred the same concern: "There are still technologies in the market that can do a better job than microfluidics". Since through the S-Curve (Figure 37) it's possible to see that a new technology overtakes an existing one – technology discontinuity - when the new technology is further from the early stages of the S-Curve, it's possible to pinpoint microfluidics before the second stage of the S-Curve, and so, just as it happen with the micro-waves and floppy disks in the beginning (Foster, 1986), microfluidics has still to meet customer standards, which confirms that microfluidics is still in its early stages of innovation.

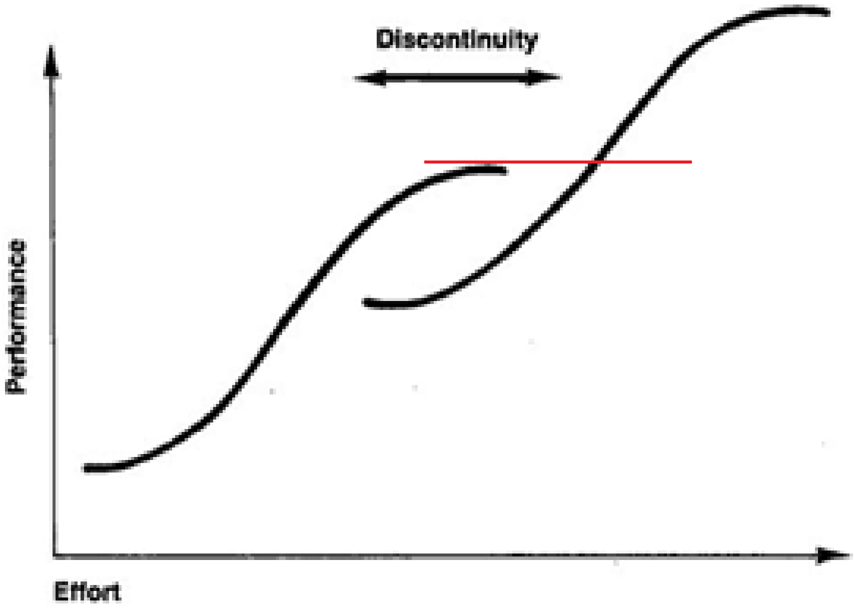

Figure 37 - S-Curves and technological discontinuity, adapted from: (Foster, 1986).

6. Conclusions, Limitations and Future Research

6.1. Conclusions

Microfluidics is located in the *early stages* of the Technology S-Curve, correspondent to the *fluid phase* of Utterback Model and to the *trough of disillusionment* on the Gartner's Hype Cycle. It's possible to conclude that microfluidics is an emerging technology still on the early stages of innovation. Microfluidics has still to find the dominant design, which will serve as a catalyzer towards standardization and integration.

To be aware of the barriers detect and analyzed in this dissertation is the first step towards overcoming them. Subsequently, the implementation of rigorous quality control processes will help increasing the collaboration between researchers, and improve the effort to success ratio of the microfluidics community in general, which will undoubtedly advance microfluidics in the right direction for the dominant design. Furthermore, improving the communication between academia and industry (e.g. manufacturers) will provide deeper insights of the customer needs and expectations, which will be crucial to design the right solutions to compete in the market. This will also aid in breaking the technology for technology's sake (product diversification) paradigm, and foster the implementation of standards. Likewise, a "market pull" oriented mindset is imperative if microfluidics wants to break this paradigm and reach commercial success. To keep research aligned with functionality will provide a better chance at meeting customer needs and maintaining focus – something that the microfluidic community is in high need. Moreover, it's perceptible how squared and out of synch are the efforts of the microfluidic community – both inside the research environment and also with the communication between research and industry. Researchers should increase their focus in delivering a tangible functional product with a precise application. And in the meantime, they should reflect how much energy they will put into publishing, consulting to commercial partners, or going for patent protection. Microfluidics potentialities are more likely to be realized by starting with one successful product. The eagerness to demonstrate the wide range of powerful possibilities, or to run multiple projects, is counterproductive to microfluidics success.

Despite the fact that there's a high degree of uncertainty characteristic of early stages of innovation, Point-of-care (POC), Pharmaceutical and life science research, Clinical & veterinary diagnostics, and arguably Analytical Devices, are the fields which will drive the biggest growth of microfluidics until 2020. As so, the microfluidic community will have a higher likelihood to have success if they invest in these areas.

All the above problems, and respective suggested solutions, are interrelated, meaning that allocating efforts to overcome one of them will improve the likelihood of in the future to conquer alternative ones. Thus, a new paradigm in the microfluidics can be set in motion by anyone who has a cooperative market oriented mindset and is willing to take the initiative. Moreover, to tackle this barriers with devotion and patient will be crucial and will also improve the rate of innovation of microfluidics, provide a better foundation to overtake existing technologies and empower microfluidics to have a greater impact in our lives, and in the world.

6.2. Limitations of the Study and Future Research

It wasn’t possible to compare the survey responses from academia against industry due to the imbalance of industry respondents.

Legal issues such as: intellectual property, patent validation and licenses, and Funding/Investing conditions remain to be explored, as they can be a topic of further research which can be clarifying to the research community about what are investors seeking and afraid of, and how can legal issues be avoided, or more easily surpassed, in order to bring microfluidics to market

Due to time constraints, the data collection period was short (five days) which didn’t provide appropriate conditions for collecting a good sample. The following problems may have been originated from this issue: small number of respondents (34 responses), most of the respondents are Portuguese (88.2%) and from *Academia* (82%).

Due to spatial (number of words) and time constraints (2 months) a decision had to be made about which frameworks to include into this dissertation. Since the aim of this study is to understand the roadblocks perceived by the microfluidic community through managerial frameworks lenses, especially technology ones, such tools as: Porter Five Forces and the Adoption Model had to be left out, as its relevance didn’t brought more clarity than the ones used in this dissertation. Nevertheless, future research can be carried in market research and market dynamics in order to provide a deeper understanding, and undercover several leverage points where the microfluidic community can use to its advantage.

Regarding technology, microfluidics is a very broad technology because it's an enabling technology. As so, it is very difficult to cover every aspect of microfluidic world and this dissertation may have left, or simplified, some aspect of this technology. Further research can be more specific in such promising fields as: point-of-care and life sciences.

From a scientific perspective, the drivers found to drive the growth of microfluidics can be increasingly explored with a managerial perspective, meaning that understanding which technology capabilities are already well understood and could be brought together to create a functional product can improve the likelihood of microfluidics to find commercial success.

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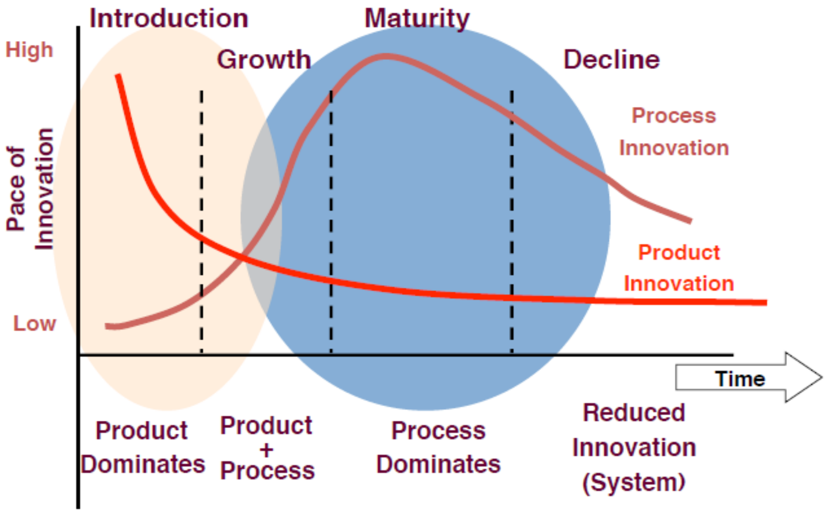
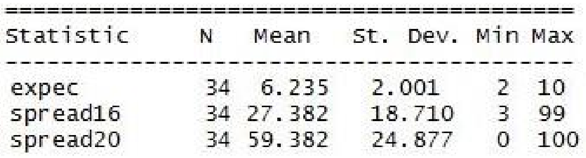
Appendices



Appendix 1 - Process and Product development



```
==========================================
Statistic     N    Mean    St. Dev. Min Max
------------------------------------------
 expec         34   6.235    2.001    2  10
 spread16      34  27.382   18.710    3  99
 spread20      34  59.382   24.877    0  100
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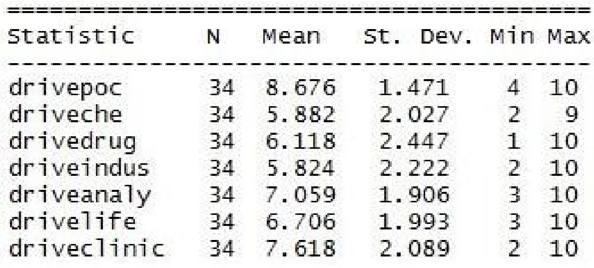
Appendix 2 - Expectations of microfluidics and Spread from 16 to 20



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==========================================
Statistic     N    Mean    St. Dev.  Min Max
------------------------------------------
drivepoc      34   8.676    1.471    4   10
driveche      34   5.882    2.027    2    9
drivedrug     34   6.118    2.447    1   10
driveindus    34   5.824    2.222    2   10
driveanaly    34   7.059    1.906    3   10
drivelife     34   6.706    1.993    3   10
driveclinic   34   7.618    2.089    2   10
```
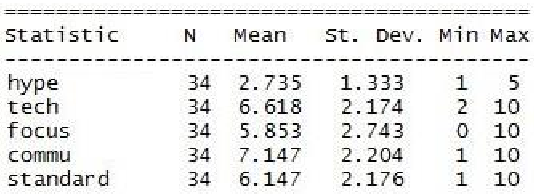
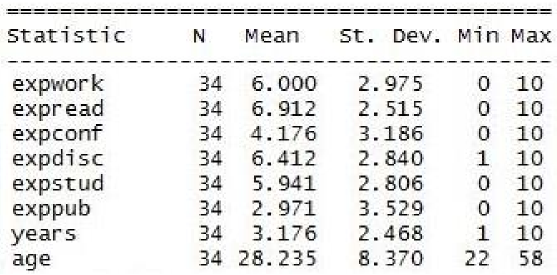

Appendix 3- Drivers



```
==========================================
Statistic      N   Mean    St. Dev.  Min Max
------------------------------------------
hype          34   2.735    1.333     1   5
tech          34   6.618    2.174     2  10
focus         34   5.853    2.743     0  10
commu         34   7.147    2.204     1  10
standard      34   6.147    2.176     1  10
```

Appendix 4 - Hype Cycle and Barriers

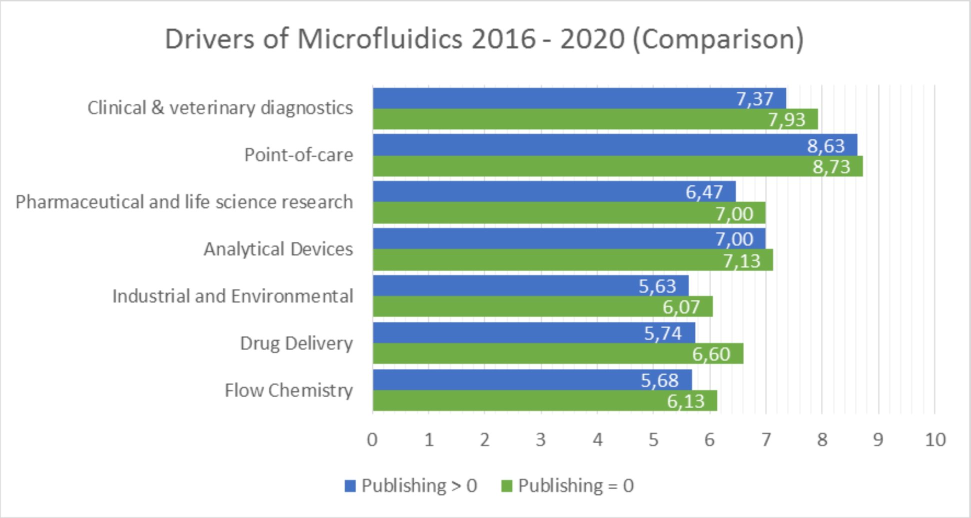


```
=========================================
Statistic      N   Mean   St. Dev. Min Max
-----------------------------------------
 expwork      34  6.000    2.975    0  10
 expread      34  6.912    2.515    0  10
 expconf      34  4.176    3.186    0  10
 expdisc      34  6.412    2.840    1  10
 expstud      34  5.941    2.806    0  10
 exppub       34  2.971    3.529    0  10
 years        34  3.176    2.468    1  10
 age          34 28.235    8.370   22  58
```

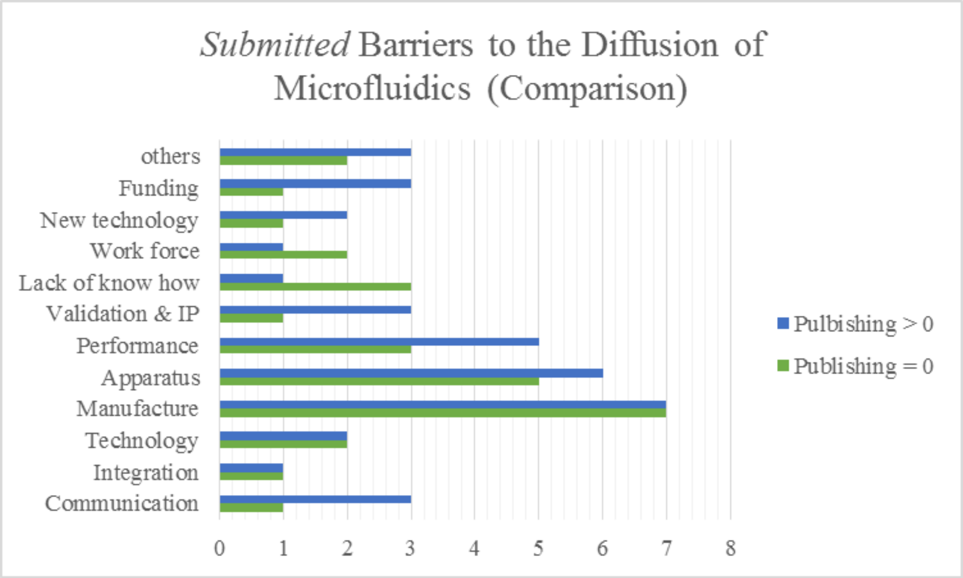
Appendix 5 - Area of experience, Years of Experience and Age

Portuguese	30
Indian	1
British	1
Italian	1
American	1

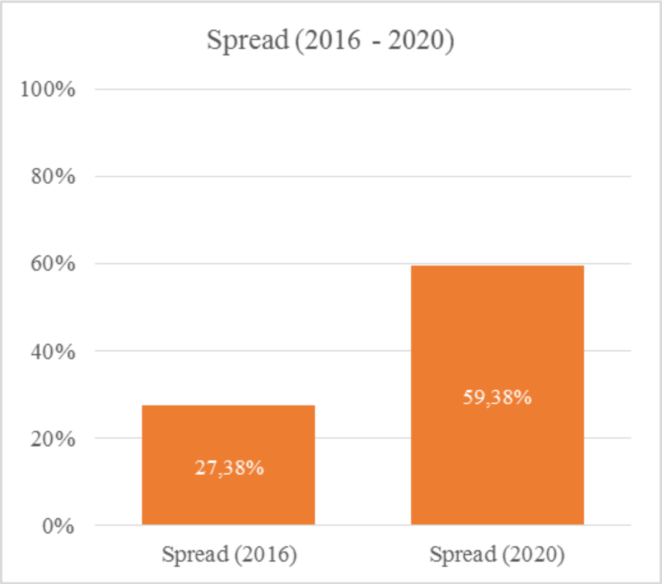
Appendix 6 - Nationality of respondents



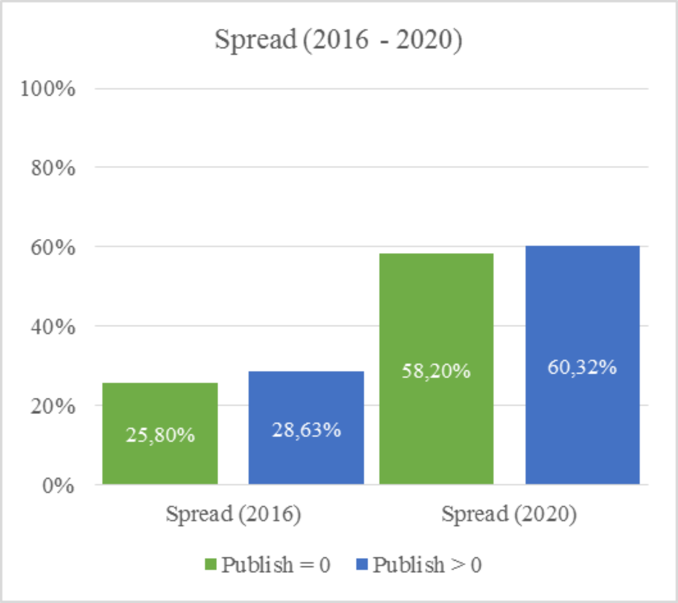
Appendix 7 - Drivers of Microfluidics 2016 - 2020 (Comparison)



Appendix 8 - Submitted Barriers to the Diffusion of Microfluidics (Comparison)



Appendix 9 - Spread from 2016 to 2020



Appendix 10 - Spread from 2016 to 2020 comparison.

Online Questionnaire

Dear participant,

Thank you for taking the time to help me with my Master thesis about "Diffusion of Microfluidics from Research to Market".

This questionnaire shouldn't take much longer than 5 minutes.

Your data will be analyzed anonymously.

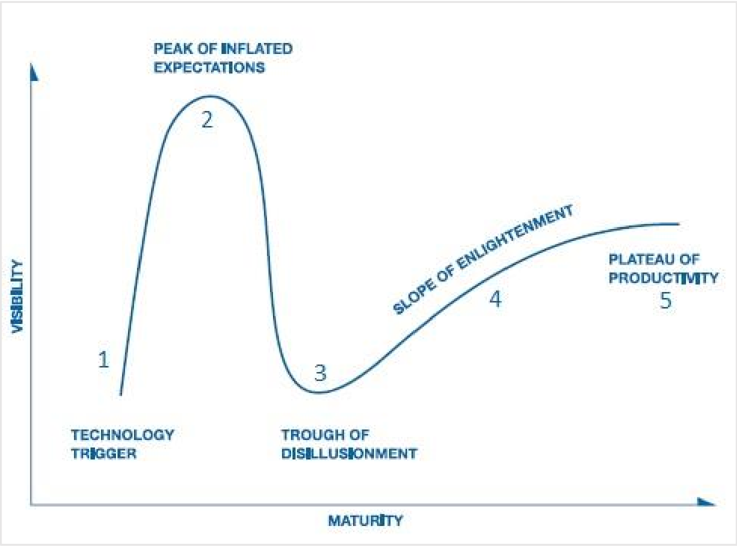
Thanks for your collaboration!

Gonçalo Salgado

Section 1

This section will be about the microfluidics market.

1. How well do you think microfluidics has fulfilled its expectation? *From (0-10)*
2. How much would you say microfluidics is spread in the market: *From (0% to 100%)*
   - Today (2016)
   - In 2020
3. In your opinion how much will these fields drive the growth of microfluidics until 2020? *From (0-10)*
   - Point of Care Diagnostics
   - Flow Chemistry
   - Drug Delivery
   - Industrial & Environment
   - Analytical Devices
   - Life Sciences Research
   - Clinical & Veterinary Diagnostics
4. Looking at this graph where would you locate the current state of microfluidics? *(1,2,3,4 or 5)*



Section 2

This section will be about the barriers that slow down the diffusion of microfluidics from research (academia/university/research institutes) to market.

"... few microfluidic technologies have made the leap to fully functioning integrated devices that provide real clinical value." (Chin, Linder, & Sia, 2012)

5. Can you think of 1 to 3 barriers that slow down the diffusion of microfluidics from research (academia/university/research institutes) to market?
   - Example 1: *fill*
   - Example 2: *fill*
   - Example 3: *fill*

6. In your opinion how much do these barriers slow down the diffusion of microfluidics from research (academia/university/research institute) to market: *(each from 0 to 10)*

Technology for Technology's Sake (not oriented towards functionality)

It's very common in academia that researchers heedlessly focus in building novel devices with state-of-the-art technology, yet disregard their practicality and therefore fail to solve real word problems (Whitesides, 2013).

Lack of Focus (lack of strategy)

"Academics are doing the fundamental development," says Lee, "but they tend to be random and not focused" (Blow, 2009)

Lack of Communication between Academia/Research Institutes and Industry

A discussion has now started concerning the widening gap between what is developing in academia and the needs and the actions in industry (Blow, 2009).

Lack of Standards, Integration and Dominant Design

Past research has focused on the invention of individual lab-on-a-chip (LOC) components (...) issues with standardization preclude the possibility of easily stitching together these innovative components to form functional, fully integrated device (Volpatti & Yetisen, 2014).

7. If you can think of other barriers worth mentioning please write them below. Otherwise, click next.

Section 3

Almost done! This last section is about your relation with microfluidics.

8. What's you role title? *(choose one)*
   - Researcher
   - Industry Engineer
   - Master Student
   - PhD
   - Other
9. If you picked "Other", please specify. Otherwise, click next.
10. Rate your source of expertise in microfluidics *(each from 0 to 10)*
    - Work experience
    - Published Literature
    - Reading academic literature/articles
    - Conference/Workshop/Seminars
    - Discussion with other researchers
    - BSc/MSc or PhD studies
11. How long have you been associated (studying/discussing/working) with microfluidics? *(from 0 to 15 years)*
12. What university/company/institution are you currently working in?
13. Introduce your Age and Nationality