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Mestrado em Economia da Inovação e do Empreendedorismo

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LIST OF ABBREVIATIONS

COP - **C**ommunities **o**f **P**ractice

DWT – **D**ry **W**eigh**t**

EC - **E**xperience **C**urve

EU – **E**uropean **U**nion

FPFT – **F**lat **P**anel **F**low **T**hrough

GW – **G**reen**W**all Technology

KM – **K**nowledge **M**anagement

LC – **L**earning **C**urve

LD – **L**earning-by-**d**oing mechanism

LI – **L**earning-by-**i**nteracting mechanism

LR – **L**earning **R**ate

LS – **L**earning-by-**s**earching mechanism

LU – **L**earning-by-**u**sing mechanism

MPS – **M**icroalgae **P**roduction **S**ystem

NGCC - **N**atural **G**as **C**ombined **C**ycle

OECD – **O**rganisation of **E**conomic **C**ooperation and **D**evelopment

PBR – **P**hoto**b**io**r**eactor

QS - **Q**uorum **S**ensing

R&D – **R**esearch and **D**evelopment

SME – **S**mall and **M**edium **E**nterprise

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A APRENDIZAGEM TECNOLÓGICA NOS SISTEMAS DE PRODUÇÃO DE MICROALGAS: A CURVA DA EXPERIÊNCIA E OS MECANISMOS DE APRENDIZAGEM REVISITADOS

Victória del Pino Álvarez

RESUMO

No contexto mundial actual, caracterizado por crescentes e constantes mudanças nos mercados e nas tecnologias, as empresas para serem competitivas, eficientes e lucrativas, devem estar preparadas para acompanhar a rápida metamorfose em curso. Os processos de inovação, de aprendizagem e de acumulação de experiência, são considerados cruciais para sustentar a sua competitividade. O conceito de "curva da experiência" integra, de uma forma simples, estes processos, uma vez que à medida que as organizações vão melhorando o seu desempenho em determinada tarefa, tornam-se, naturalmente, mais eficientes na sua execução. Portanto, quanto mais as organizações "aprendem", maior facilidade detêm para desempenhar as actividades a que se propõem, podendo ter estas um cariz inovador. Por outro lado, esta melhoria na eficiência reflecte-se em ganhos de produtividade e na redução dos custos de produção.

Apesar de existir já uma extensa investigação, desenvolvida em vários sectores, demonstrando que a acumulação de experiência leva a melhorias nas *perfomances*, o nosso trabalho preenche parte de um vazio, em termos de conhecimento, focalizando-se nos aspectos relacionados com a curva da experiência e com a aprendizagem de um determinado tipo de biotecnologia, designada genericamente por "sistemas de produção de microalgas" (SPM).

As microalgas são microorganismos fotossintéticos, que para a sua divisão e crescimento necessitam de luz, nutrientes e dióxido de carbono. O potencial biotecnológico das microalgas tem crescido rapidamente, nos últimos anos, principalmente devido às suas inúmeras aplicações comerciais. As microalgas podem ser tanto vendidas como alimento para consumo humano, como utilizadas na obtenção de compostos naturais de alto valor introduzidos em formulações de produtos cosméticos e nutracêuticos, ou até para a sequestração de carbono, o aproveitamento energético em biocombustíveis e o tratamento de efluentes líquidos e gasosos. Nesse sentido, os SPM são uma das mais biotecnologias mais promissoras da actualidade.

As particulariedades dos processos de aprendizagem e de acumulação de experiência são introduzidos, desde o ponto de vista da gestão do conhecimento, na revisão bibliográfica. O nosso estudo define o conceito de curva da experiência, relata a sua evolução histórica e apresenta exemplos da sua aplicação. Alguns exemplos retratam as aplicações incorrectas das curvas de aprendizagem, sobretudo no que respeita à sua capacidade de previsão de custos tecnológicos futuros. A curva da experiência deve ser usada com precaução, uma vez que, e por exemplo, não possibilita a antevisão de descontinuidades tecnológicas.

Neste trabalho sintetizaram-se as diferentes perspectivas, os avanços e tendências tecnológicas, e os futuros desafios deste sector biotecnológico. Para melhor compreensão da complexidade tecnológica dos SPM, estes foram caracterizados de uma forma genérica, mas técnica. É ainda apresentada uma comparação técnico-económica entre os sistemas abertos e fechados, que integram os SPM.

Na tentativa de compreender o processo de aprendizagem tecnológica, que está na base do desenvolvimento e operação dos diferentes SPM, recorreu-se a um caso de estudo, como metodologia central da investigação. O caso de estudo é uma empresa pioneira portuguesa, Necton S.A., dedicada, desde 1997, à produção de microalgas. A Necton instalou e operou vários tipos de SPM, desde sistemas abertos, como é o caso da tecnologia de *raceways*, a sistemas fechados como os fotobioreactores.

Os dados secundários da nossa investigação foram extraídos de vários relatórios de produção e outros registos e de entrevistas semi-estruturadas com os trabalhadores da empresa relacionados com as actividades produtivas. Os dados recolhidos foram utilizados em duas metodologias distintas. A primeira metodologia permitiu aplicar o modelo da curva da experiência para quantificar a evolução da relação dos custos unitários de produção com a quantidade de biomassa microalgal produzida. Através da logaritmização destas duas variáveis, foi possível calcular o rácio de progresso e a taxa de aprendizagem, que caracterizam o processo de aprendizagem tecnológica de cada SPM. A segunda metodologia visava a determinação dos efeitos da aprendizagem tecnológica no ciclo de vida de cada SPM, fazendo uso dos dados recolhidos durante as entrevistas.

Os resultados obtidos, ao longo desta investigação, confirmaram que:

i) as condições ambientais, como a amplitude térmica diária, a temperatura média mensal, a irradiação e o número de horas de sol a que estão expostas as culturas, afectam a produtividade dos SPM. A produção de microalgas está sujeita à sazonalidade, da mesma forma que outro tipo de culturas de plantas. As alterações tecnológicas necessárias para atenuar os impactos dos factores ambientais na produtividade devem ser consideradas para a melhoria do desempenho dos SPM.

ii) os SPM estudados (fotobioreactores do tipo "flat panel flow through" e fotobioreactores tubulares) seguem curvas da experiência com rácios de progresso e taxas de aprendizagem diferentes. Os rácios de progresso determinados enquadram-se na gama de valores, relativos a tecnologias ambientais e a empresas de manufactura, que foram encontrados na literatura.

iii) os diferentes mecanismos de aprendizagem contribuem, de forma semelhante, em cada ciclo de vida das tecnologias estudadas, pese aos diferentes graus de complexidade tecnológica dos SPM;

iv) o contributo do mecanismo de aprendizagem *leaning-by-doing* é mais relevante nos estágios de crescimento, sendo que o mecanismo *learning-by-using*

adquire maior relevância nas fases de maturidade tecnológica dos SPM. O mecanismo de aprendizagem *learning-by-searching* é activado em determinadas situações, nas quais seja necessário resolver limitações de ordem técnico-científica, recorrendo para tal, a actividades de investigação e desenvolvimento.

A escassez de informação relativa aos sistemas abertos, que estiveram em operação na empresa Necton, obrigou a recorrer a dados recolhidos na literatura acerca deste mesmo tipo de SPM. Apesar disso, os dados foram insuficientes, para chegar a uma conclusão clara quanto à existência de curvas da experiência, de comportamento diferente, entre os sistemas abertos e os sistemas fechados. Apenas se pôde concluir que existem diferenças entre os dois tipos de sistemas, no que se designou por melhoria na produção (*production improvement*), ou seja, cada tipo de sistema apresenta um aumento na produção, relativamente ao ano anterior, melhoria essa que parece ser específica a cada sistema.

No decurso da nossa investigação surgiram novas questões que poderão vir a ser desenvolvidas em trabalhos futuros, abrindo novas linhas de investigação na interface entre as áreas científica e económica, mas sobretudo no âmbito da gestão do conhecimento. Um dos maiores desafios, lançado neste trabalho, é tentar compreender se é possível promover os diferentes mecanismos de aprendizagem tecnológica, dentro da organização, para que os custos unitários de produção mínimos sejam atingidos com maior brevidade, proporcionando uma oportunidade para a introdução de inovações e "percorrendo", desta forma, novas curvas da experiência.

Palavras-chave: curva da experiência, curva de aprendizagem, mecanismos de aprendizagem, microalgas.

TECHNOLOGICAL LEARNING IN MICROALGAE PRODUCTION SYSTEMS: REVISITING THE EXPERIENCE CURVE AND THE LEARNING MECHANISMS

Victória del Pino Álvarez

ABSTRACT

Facing the world scenario, businesses are striving for efficiency and profitability. The processes of innovation, learning, and experience accumulation are, indeed, thought to be crucial for sustaining competitiveness of businesses. The experience curve concept integrates those processes, as it is based on the premise that the more often a task is performed, the lower will be the cost of doing it.

Although extensive research has shown that cumulative experience leads to performance improvement, across numerous sectors, our work fills part of the existing knowledge gap by focusing on experience curve and learning aspects of the modern biotechnology of Microalgae Production Systems (MPS). Microalgae are one of the most exciting future-oriented business areas of modern biotechnologies, which have turned into an important global industry, with a diversified field of applications.

The particularities of learning and experience accumulation processes were introduced in our work. Our study also addressed some of the applications and misapplications of the experience curve concept. We also reported on some of the perspectives and advances of the MPS, the general technical description of the MPS, the technological trends, as well as the future challenges. The research methodology is based on the case-study of Necton S.A., a pioneer Portuguese firm, dedicated, since 1997, to microalgae cultivation. Therefore, in an attempt to understand the technical complexity of microalgal biotechnology, the learning process, underlying the technological development, was studied through different research questions. Data was, mainly, collected from production records provided and from a set of interviews, conducted with the company workers. The results confirm that: i) the different MPS studied follow an experience curve, with progress ratios which are in between the ones determined for manufacturing firms and energy technologies; ii) the learning mechanisms play a similar role through the technologies life-cycle, although the MPS studied are different in technological complexity; iii) learning-by-doing is more relevant in early technology stages, learning-by-using appears to be fundamental in the maturity stage, and learning-by-searching is critical to solve particular technical constraints.

Keywords: experience curve, learning curve, learning mechanisms, microalgae.

Chapter 1 Introduction

For the last two hundred years, neoclassical economics has only recognised two factors of production: labour and capital. Knowledge, productivity, education, and intellectual capital were all regarded as exogenous factors. The New Growth Theory, based on the work of economist Paul Romer (Romer, 1986; Romer, 1990) and others, have attempted to deal with the causes of long-term growth. Knowledge as an endogenous variable became of great concern and one of the most driven goals of present economic analysis (Romer, 1990).

Building upon the research of economists such as Joseph Schumpeter (Schumpeter, 1947) Robert Solow (Solow, 1957) and others, Romer proposed a major input to the neoclassical model by considering technology as an intrinsic part of the economic system and knowledge as the third production factor in leading economies (Romer, 1986; Romer, 1990). Other scholars, such as Adam Smith and Karl Marx, have also dealt with knowledge creation, division, utilisation and appropriation, as major factor of growth (Smith, 1776; Marx, 1954).

Important developments in the economics of knowledge received contributions of Herbert Simon, Friedrich Hayek, Kenneth Arrow, and Fritz Machlup. Hayek (1945) studied the problems resulting from mass dissemination of knowledge and the impossibility of transferring knowledge to a central planning agency. Later on, Arrow (1962) provided foundational work in many other areas of economics, including the endogenous growth theory and the economics of information. In the early 80´s, Simon (1982) studied the role of memorisation in the learning process, being considered a precursor of the economics of information technology. In 1984, Machlup researched the mechanisms of skills acquisition, the transfer of knowledge, and the economic theory of choices and expectations in situations of uncertainty and incomplete information.

Literature on knowledge has evolved significantly since the pioneering works of Paul Romer, becoming multi-faceted. Theories of knowledge acquisition suggest that organizations facing similar changes vary in their capacity to learn due to cognitive (Senge, 1990), interpersonal (Argyris and Schon, 1978), structural (Duncan and Weiss, 1979), or managerial (Dutton and Thomas, 1984) factors, and even fail to learn (Hirsch, 1952). In general terms, researchers have all come to a general consensus that, when pursuing a development goal, embodying knowledge should be a priority task in modern organisations.

Thus, it is not surprising that, more recently, management literature has been focused on the management of organisational knowledge including the intangible dimensions of the organisation (Von Krogh *et al.*, 2001), and has been conducted within the frameworks provided by economic theories[1]. Therefore, there is now a clearer understanding of the nature of knowledge (relationships between data, information and knowledge; between tacit and explicit knowledge; between individual and organization knowledge; between types of thinking), and of the dynamics of knowledge (knowledge acquisition and learning mechanisms, knowledge conversion, knowledge dissemination and knowledge application) in organisational contexts.

As Lundvall (1995) remarked, contemporary capitalism has reached the stage at which knowledge is the most strategic resource, and learning the most important process. Firms are characterised by Rothschild (2004) as "organised intelligence", and organisational learning, over the course of time, is currently identified as the primary catalyst of economic evolution. Moreover, Teece (2000) mentioned that

[1] Economics theories such as the resource-based view, the competence-based view, cognitive frameworks theory, the capability perspective, or dominant logics.

business success depends on the organisation's ability to create, use, and develop its knowledge-based assets.

Eventually, knowledge accumulation in firms should lead to cost reductions and rising revenues, and from a micro-economic perspective, and assuming the positive contribution of firms for the dynamics of socio-economic change (Schumpeter, 1947), the economic evolution is a process of continuous cumulative learning (Rothschild, 2004).

The cumulative learning can be quantitatively captured in a so-called 'learning curve' (LC). The LC concept is based on the empirical observation that the costs of a product fall by a constant proportion with every doubling of cumulative production. Nowadays, the dominant stream of literature of the knowledge management (KM) science assumes that these cost reductions reflect, not only the benefits from learning-by-doing, but also the benefits derived from other types of learning mechanisms, such as learning-by-using, learning-by-searching, learning-by-interacting, and more recently learning-by-learning and learning-by-expanding. All the learning mechanisms play a different, thus relevant, role in the learning organisation, and their effects are collectively reflected in the experience accumulation. The concept 'experience curve' (EC) is based on the intuitive idea that the time required to perform a task decreases as a worker gains experience (BCG, 1974).

Few concepts in management and economics have drawn more empirical attention than the EC. Embodying knowledge in workers, or learners, and embodying knowledge in assets (services or goods), through technology, or more elaborated processes, is costly in time and resources. Therefore, from a managerial perspective, benefits arise whenever the two functionalities are fully assumed. The most cited example in the management literature is the production of aircrafts published in the *Journal of Aeronautical Sciences,* as part of an article entitled "Factors Affecting the Cost of Airplanes" (Wright, 1936). The author's pioneer findings showed that as the number of aircraft produced in sequence increased, the direct labour input per airplane decreased, in a regular pattern, that could be estimated mathematically (Wright, 1936).

Facing the world scenario, businesses are striving for efficiency and profitability. Furthermore, when knowledge and experience stocks complement other asset stocks, imitation by other firms is more difficult and superior performance can be expected (Nelson and Winter, 1982). Additionally, knowledge and experience are to be managed as strategic variables, and KM can positively affect the process performance by sharing experience and getting better at performing value-creating tasks.

The strategic importance of knowledge stocks, and how to manage them, is undeniable. However, if a firm does not have the scale and/or does not rapidly learn how to produce with lower costs, it will not be able to produce below market price, what may mean, stepping into the market. This will result in the firm having to compensate initial losses with posterior returns. Moreover, there is no guarantee that the initial price will be valid in the future, bringing up uncertainty on the expected returns.

One could argue that "riding down"[2] the EC will bring short-term profits while accumulating experience by producing the same old product, but this simplistic vision masks the forcefulness of innovation and knowledge accumulation. In fact, firms need to be focused on re-enforcing their own competencies, not only to embody as much experience and knowledge as possible to achieve a rapid unitary cost reduction in the same product, but if possible, transferring this to new challenging outputs for the permanent changing consumer preferences. After all, the market decides the final form of the production function through an intense and interactive process of innovation. The learning associated with innovative activities is not a purely individual phenomena, for the increasing complexity of innovation it is required a collective and interactive process. Several researchers have even looked at consumers as co-creators of products and value (Prahalad,

[2] The expression "riding down" was borrowed from Jakob and Madlener (2004).

2004), as co-innovators (Von Hippel and Katz, 2002), and as 'prosumers'[3] who both produce and consume (Xie *et. al*, 2007).

Indeed, innovation is highly influenced by vertical cooperation, not only with consumers, but also with suppliers and customers, especially in low-tech firms where the development of new products or processes often takes into account new demands and market changes (Vaz and Nijkamp, 2009). Companies that are better able to utilise information and knowledge can make decisions faster and closer to the point of action, overcome internal and external barriers, provide more opportunities to innovate, reduce product development time and enhance customer relationships (Hackett, 2000).

Firms learn differently, depending on several endogenous and exogenous factors and time-dependent stages, and through distinctive learning mechanisms. Theoretically, if knowledge can be managed (Alavi and Leidner, 2001; Chen and Chen, 2006), experience and knowledge accumulation could be accelerated via KM through differentiated learning mechanisms promotion, improving the pace of innovative activities. If innovation is rapidly endogenised, the firm is ready and prepared to shorten the innovative lag-phase and launch another innovation.

But in this complex process, the idea of learning as a driver of cost reduction still remains very attractive. Learners (or workers) become better at doing what they do over time, leading to efficiency increases and permanent cost reductions, at a profit business level. The implications of both "practice makes perfect" and "performance improves with experience" effects have held up remarkably well over time (Pisano *et al*., 2001), and are reflected on the EC concept.

[3] The term 'prosumer' is a late 20th century concept that combines some of the common characteristics of a producer and a consumer, and is generally applied to situations where consumers are considered to have reached a level of sophistication and such a strong working knowledge, that the consumer can effectively dictate the production or re-design of goods and services. More information about the 'prosumer' concept can be found elsewhere (Prosumer Studies Working Group at http://www.bsos.umd.edu/socy/prosumer/about.html).

Goals of the study

Understanding the processes that facilitate organisational learning, and how these processes might be better managed, are of central importance for industrial managers. The general aim of this work is to comprehend to which extent the EC concept can be used as a managerial tool, and how learning takes place in technological learning, in order to improve business performance and indirectly enhance innovation in firms.

Methodology

In our work, the case-study approach was chosen as the main research methodology. The case-study is related to a particular biotechnology, the Microalgae Production Systems (MPS) that have been installed and in operation in the company Necton – Companhia Portuguesa de Culturas Marinhas S.A. (Necton, hereinafter), a pioneering Portuguese company.

Several reasons justify this choice: i) microalgae are one of the most exciting future-oriented business areas of modern biotechnologies (Richmond, 2000; Wijffels, 2007); ii) their steady growth during the past two decades, has turned microalgae in an important global industry, with a diversified field of applications (Carlsson *et. al*, 2007); iii) microalgae are not a well-studied group from a biotechnological point-of-view (Olaizola, 2003), and even less from the KM perspective.

The present case-study is unique in the sense that it is the first to examine the EC of MPS, and provides a promising contribution to what, will hopefully evolve into long-term research in a transversal field of linking technological processes to economic and management sciences.

In an attempt to understand the technical complexity of microalgal biotechnology, the learning process, underlying the technology development, was studied through different these research questions:

H1: MPS of the case-study follows an experience curve

H2: Closed and open MPS follow similar experience curves.

H2: Learning mechanisms play different roles across the MPS life-cycle.

In our work, we proposed that secondary data is obtained from two different research strands: qualitative, through semi-structured interviews, firm records and other research-related documents; quantitative, collecting information from different databases and bibliographic references. Two different methodologies were presented to study whether the EC concept can be applied to the MPS and the role of each learning mechanism in technological development within each MPS.

1.1 Brief theoretical background

The object of KM is to analyse knowledge as an economic asset. However, the definition and scope of such a discipline is surely not a consensual issue. It depends on the conception of knowledge and information, and it is easily mingled with other disciplines, such as the economics of knowledge, the economics of research, the economics of innovation, and the economics of information.

Essentially, knowledge empowers its possessors with the capacity for intellectual and physical action, providing them with cognitive capability. Information is in the mind of individuals and takes the shape of structured and formatted data that remains passive and inert, used by those with the knowledge needed to interpret and process them (Foray, 2006). The use of both, knowledge and information, promotes, even further, the capacity to learn and act.

The temptation to presuppose a rigid hierarchy from data to information to knowledge does not survive scientific scrutiny. Rather, knowledge is 'personalised' information related to facts, procedures, concepts, interpretations, ideas, observations, and judgements (Alavi and Leidner, 2001)[4].

Understanding relationships between data, information and knowledge should precede the comprehension of how organisations dynamically create knowledge and how organisational learning mechanisms usually take place. Some definitions should be clarified, before deepening into our work.

There are two types of knowledge: explicit knowledge and tacit knowledge. Nonaka, Toyama and Konno (2000) provided both definitions. "Explicit knowledge can be expressed in formal and systematic language and shared in the form of data, scientific formulae, specifications, manuals and such like. It is possible to be processed, transmitted and stored. Tacit knowledge is highly personal, hard to formalise and communicate to others, and is rooted in action,

[4] Alavi and Leidner (2001) reviewed conceptual foundations of knowledge related with KM and KM systems.

procedures, routines, commitment, ideals, values and emotions, subjective insights, intuitions and hunches". In 1995, Nonaka and Takeuchi proposed a learning model in which knowledge creation is a spiralling process of interactions, between tacit and explicit knowledge, where new knowledge is created[5]. Many other works have emerged since then, strongly based on this spiral model. Chen and Chen (2006) have reviewed the history of knowledge conversion over the past decade. In general terms, knowledge is created through interactions, between tacit and explicit knowledge, as mentioned above, rather than from tacit or explicit knowledge.

In our work, the acquisition of knowledge is termed learning. There are, however, several strands of the learning literature, which highlight different aspects and ways of learning in an organisation. For instance, there is a clear distinction between a technical and a social strand in the learning literature. On one hand, the technical strand takes the view that learning is a matter of processing, interpreting and responding to quantitative and qualitative information, which is generally explicit and in the public domain (Argyris and Schon, 1978). On the other hand, the social strand focuses attention on the importance of cultural and socialisation processes (Senge, 1990; Lave and Wenger, 1991; Nonaka and Takeuchi, 1995).

[5] Nonaka and Takeuchi's influential book "The Knowledge-Creating Company", presented to corporations and organisations in 1995, proposed a spiral model and four modes of knowledge conversion, termed SECI process by the authors, to understand how an organisation creates knowledge through the interactions between explicit knowledge and tacit knowledge in a "knowledge conversion". The model of knowledge creation consisted of three elements: (i) the SECI process, the process of knowledge creation through conversion between tacit and explicit knowledge; (ii) "Ba", the shared context for knowledge creation; and (iii) knowledge assets - the inputs, outputs, and moderator of the knowledge-creating process. The three elements of knowledge creation have to interact with each other to form the knowledge spiral that creates knowledge.

The SECI process is based in four modes of knowledge conversion: (1) Socialisation (from tacit knowledge to tacit knowledge); (2) Externalisation (from tacit knowledge to explicit knowledge); (3) Combination (from explicit knowledge to explicit knowledge); and (4) Internalisation (from explicit knowledge to tacit knowledge).

1.2 Learning organisation and learning mechanisms

Within this work, the focus will be on all the learning activities in an organisation that produce knowledge, not only the formal research activities that are traditionally more accounted for in the learning processes. There is little consensus among researchers about what learning is, and no theory of learning includes all the activities involved in human learning. Recently, Foray (2006) has even claimed that economists have created a "comfortable world" in which only some agents, institutions, and sectors are specialised in the production of knowledge, excluding a large proportion of activities, learning mechanisms and agents from the economics of knowledge.

In fact, particularly in firms, knowledge production has become a vital source of sustainable and competitive advantage, which is in the basis of economic growth and productivity increase. Therefore, the KM science has lately established a set of new organisational practices, which seems to be of wide relevance in the economics of knowledge (Foray, 2007), and has turned KM into 'a must' from the managerial perspective.

KM deals with any intentionally set of practices designed to optimise the production, distribution and use of knowledge. Ramalho and Sarmento (2004) evidenced the complexity and importance of managing knowledge and the skills and competencies of a knowledge manager.

Learning, and subsequently knowledge production, is created within a social context, where people are the real agents, able to act upon the structures and systems of which they are a part (Senge, 1990). According to Senge (1990), learning organisations are "organisations where people continually expand their capacity to create the results they truly desire, where new and expansive patterns of thinking are nurtured, where collective aspiration is set free, and where people are continually learning to see the whole together"[6].

Senge also defines two types of thinking: adaptative and generative. Generative thinking cannot be sustained in an organisation where event thinking predominates. A conceptual framework of systemic thinking is required to acquire the ability of discovering the structural causes of behaviour. For a learning organisation, adaptive learning should go together with generative learning to promote the "learning that enhances our capacity to create" (Senge, 1990).

The learning organisation has a basic rationale. In situations of rapid change, only those organisations that are flexible, adaptive and productive will excel. For this to happen, Senge (1990) argues that organisations need to "discover how to tap people's commitment and capacity to learn at all levels".

Adopting, as a point of departure, the anthropological framing of Bateson (1973), learning is a multi-level activity. Bateson (1973) structured learning in three levels: i) first-order learning is confined learning, in which facts or skills are defined by the context; ii) second-order learning takes the learner outside of a restricted framework, enabling connections and comparisons to be made, encompassing both the objective material and subjective factors; iii) third-order learning involves discovering the ability to doubt on the validity of previous perceptions, taking a meta-view both of the content process, and being constructivist and reflective.

The distinction between first-order and second-order types of learning is also addressed by Dutton and Thomas (1984). No works, or at least almost none,

[6] In 1990, Peter Senge wrote the seminal book "The Fifth Discipline: The Art and Practice of The Learning Organization". Briefly summarising the book content, Senge claims that the dimension that distinguishes learning from more traditional organisations is the mastery of certain basic disciplines or 'component technologies'. Those basic disciplines are systems thinking, personal mastery, mental models, building shared vision, and team learning.

besides anthropological, sociological and psychological ones, were found regarding third-order learning mechanisms.

Adler and Clark (1991) argued that the first-order learning is a process based on repetition and on an incremental development of expertise. Therefore, via learning-by-doing, new knowledge fuels productivity directly. Learning-by-doing is a form of learning that takes place at the manufacturing and/or utilisation stage, after the product has been designed (Foray, 2006). This learning mechanism is a result of a direct involvement in the productive process that will lead to many kinds of productivity improvements, often individually small, but cumulatively very large (Foray, 2006).

Some of the learning created by gaining experience can be of second-order, transforming the goals of the process, by explicit managerial actions, into technological changes that augment capabilities. Besides learning-by-doing, four fundamental learning mechanisms were identified: learning-by-using (Rosenberg, 1982); learning-by-interacting (Lundvall, 1992); learning-by-searching (Boulding, 1985; Johnson, 1992); and, more recently, learning-by-expanding (Schaeffer, 2004). Different approaches have been developed to further conceptualise knowledge acquisition (*see Table 1*).

Table 1 – Organisational learning mechanisms.

Learning Mechanism > Bibliographic References	**Brief Description**
Learning-by-doing > (Arrow, 1962)	Learning from experience in production processes. Know-how produced by experience can be regarded as tacit knowledge, residing in individuals, organisational routines and manufacturing practices. Also described as first-order learning.
Learning-by-searching > (Boulding, 1985) > (Johnson, 1992)	Knowledge brought forward by R&D. Knowledge more concentrated on "know-why"; knowledge development on general concepts and principles.
Learning-by-using > (Rosenberg, 1982)	Solutions are found in practice and optimised according to experience. Also described as "know-what".
Learning-by-interacting > (Foray & Lundval, 1998)	Knowledge transfer between users, producers, research institutes and policy makers. Knowledge transfer is more intense whenever relevant information is exchanged. Also described as "know-who" knowledge.
Learning-by-learning > (Rotmans and Kemp, 2003)	Primary learning processes improve over time, and more intensively if learning strategies are developed, applied and evaluated. Also described as reflexive learning or second-order learning.
Learning-by- expanding > (Schaeffer, 2004)	If a process/technology is frequently applied, more actors, organisational structures and industrial sectors will become involved in, focused on, dependent on and adapted to the new technology. Also described as "'learning-by-expanding" or "learning-by-network growth" or "learning-by-embedding".

As summarised in Table 1, organisational knowledge can be acquired in different ways, through formal research and work development, or through learning as doers or users. But surprisingly, and even though users intensively influence the innovation process, the learning-by-using mechanism has not been studied enough. Although Rosenberg (1982) has highlighted the critical role of the 'user learning' for several technologies, this field has received little empirical attention.

More recently, the concept of "communities of practice"[7] (COP) has become increasingly influential within the KM literature. COP are "groups of people who share a passion for something that they know how to do and who interact regularly to learn how to do it better" (www.ewenger.com). Intentionally created, COP are currently being used to facilitate knowledge transfer within firms, as the tacit aspects of knowledge are often the most valuable, as they consist of embodied expertise (Ramalho and Sarmento, 2004). Furthermore, presently, codified knowledge is losing part of its strength as a source of competitive advantage, and tacit knowledge is reinforcing its significance as a mean of adapting to new requirements and therefore, spatial proximity to sources of relevant knowledge creation is becoming central (Vaz and Nijkamp, 2009).

1.3 Learning and experience curves

Initially, LC models were developed from the basic premise that individuals and organisations acquire knowledge by doing work. More recently, it has been proposed that organisations learn by using, interacting, searching and expanding. Thus, through different learning mechanisms, organisations and individuals develop relatively permanent changes in behaviour, accumulating experience. As more products are produced by a manufacturer, the cost per unit of the product often decreases at a determined rate. This phenomenon is represented by an exponential curve, also known as the EC.

The organization gains a competitive advantage when it converts the cost reductions into productivity gains. However, the trickiest attribute of experience

[7] The COP concept was originally developed by Lave and Wenger (1991) in a study of situated learning.

accumulation is its strategic importance, due to the fact that experience cannot be traded.

The literature on experience curves provides benchmarks for the progress ratio from other fields of technology (IEA, 2000). Nevertheless, among the extensive body of research on LC, two seminal studies are to be cited, starting with Wright (1936). This author introduced a quantitative model to describe the time savings (and associated cost reductions) achieved in manufacturing aircraft. Wright found that the time required to assemble an aircraft, decreased with increasing production levels[8]. The relationship was well-predicted by an equation of the form:

$$y = C.x^{-b} \tag{1}$$

where C equals the costs (hours) to manufacture the first unit, x depicts the cumulative number of units produced, y is the cost (hours) required to produce unit number x, and b gives the slope for the improvement in costs (hours) in producing the units. On a log–log scale, equation (1) plots as a straight line with slope $-b$ (*Figure 1*).

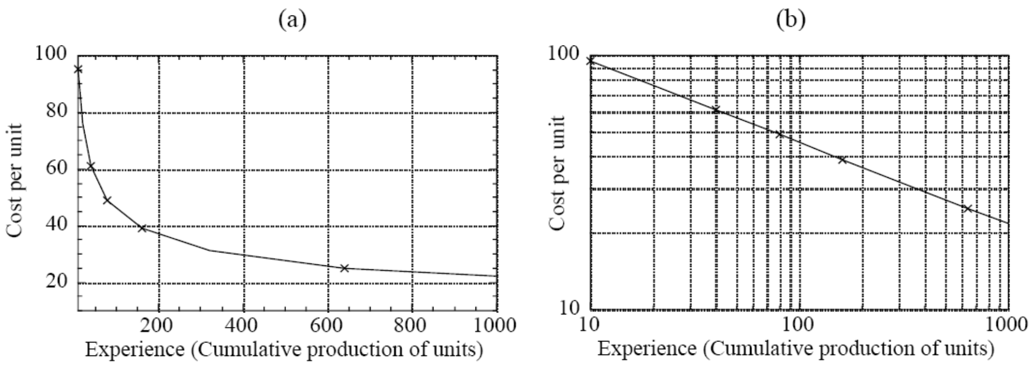


Figure 1 – A LC on (a) linear and (b) log-log scale (Neij *et al.*, 2003).

[8] Even before Wright´s work, in the nineteenth century, the German psychologist Hermann Ebbinghaus, described a phenomenon similar to LC, but focused on the time required to memorize nonsense syllables.

The Progress Ratio (PR) is defined in Eq. (2). Wright coined the term ‘‘progress ratio’’ to describe the ratio of current cost to initial cost after a doubling of production. For example, a PR of 0,80 meant that costs decreased by 20% for each doubling of cumulative production.

$$PR = 2^{-b} \tag{2}$$

The current theory and practice, surrounding LC, are based upon three conclusions: 1. the time required to perform a task decreases as the task is repeated; 2. the amount of improvement decreases as more units are produced; 3. the rate of improvement has sufficient consistency to allow its use as a prediction tool. In this study, Wright concluded that consistency in improvement has been found to exist in the form of a constant percentage reduction in time required over successively doubled quantities of units produced. The constant percentage, by which the costs of doubled quantities decrease, is called the rate of learning. The Learning Rate (LR) represents the proportional cost savings made for a doubling of cumulative output as presented in Eq. (3).

$$LR = 1 - PR \tag{3}$$

Wright’s work was related to learning within a factory and his curves for inputs to the factory process became known as LC (IEA, 2000). Wright’s LC equation was subsequently found to describe the decline in production costs for a wide range of manufacturing activities remarkably well (e.g., Dutton and Thomas, 1984).

Almost 3 decades after, Kenneth Arrow published, in 1962, another relevant work with the same framework of Wright´s LC. Arrow proposed a model based on the concept of “learning-by-doing”, with conceptual foundations on the psychological meaning of learning, and formalised an endogenous growth theory of the changes

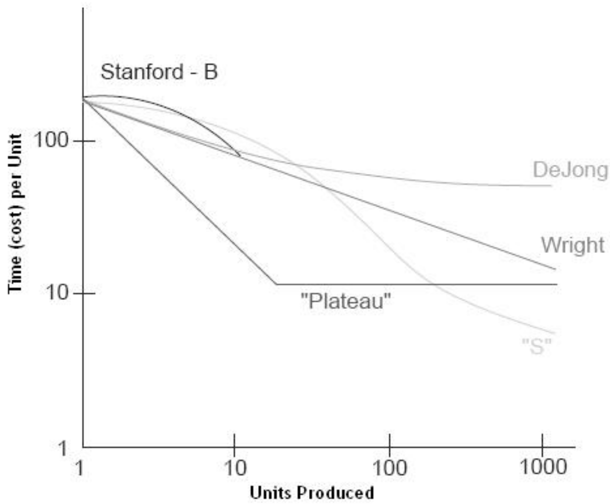
[10] The booklet deals with the EC techniques and value engineering problems to state a problem in terms of specific figures and give a sample solution using these figures. The solutions are directed toward obtaining the total savings and the average savings per unit for some given quantity as the result of a value engineering change made at some point in production.

in knowledge. Arrow formalised the LC model that explained technical change as a function of learning derived from the accumulation of experiences in production. As learning was only due to experience, learning could only take place through the attempt to solve a problem, and during the activity itself. As a consequence, Arrow concluded that learning associated with repetition was subjected to sharply diminishing returns. More recently, other learning mechanisms were studied, in order to comprehend the increasing performances and support the argument that learners have to be stimulated by situations that steadily evolve, rather than repeating activities.

In the late 1960s, Bruce Henderson**,** of the Boston Consulting Group (BCG), extended the LC and began to emphasise the implications of the EC for firm strategy. It was applied to the total cost of a product, thereby including other learning mechanisms, such as research, development and demonstration and economies of scale, and other cost factors (e.g., cost of capital, marketing, overhead) (Van Sark, 2008). Based on empirical observations, the BCG´s study found that the "costs appear to go down on value added at about 20 to 30% every time total product experience doubles for the industry as a whole, as well as for individual producers" (BCG, 1974).

The term EC was first applied in 1966 and was selected to distinguish the phenomenon from the LC effect. The development of this concept was furthered in the 1970's by BCG, which marketed it as a strategic marketing instrument. Statements such as "The EC effect can be observed and measured in any business, any industry, any cost element, anywhere. Most of the history of insight into the EC effect and its significance is still to be written", as can be read on a reprinted version (BCG, 1973).

Since Wright, LC have been applied to monitor and evaluate worker performances. Different models of univariate and multivariate curves have been developed. These models are constituted by different mathematical functions and the complexity of shapes of the curves, which represent the models, are closely related with the intricacy of the production process. Among the univariate LC, the best-diffused models are the potential (*see Figure 2*), exponential and hyperbolic (Anzanello and Fogliatto, 2007).



Model of Wright

$$y = C.x^{-b}$$

Model of "Plateau"

$$y = B + C.x^{-b}$$

Model of Stanford-B

$$y = C(x + B)^{-b}$$

Model of Dejong

$$y = C\left[M + (1 - M).x^{-b}\right]$$

Model "S-curve"

$$y = C\left[M + (1 - M)(x + B)^{-b}\right]$$

Figure 2 - Potential models of EC in linear scale, adapted from Anzanello and Fogliatto, 2007.

As learning is often equated with experience, the terms LC, EC, "progress curve", and "learning-by-doing curve" are frequently used interchangeably. Generally, the term EC is more of a macro-concept, while the term LC is a micro-concept. The term LC refers to the phenomenon that unit production costs typically decrease over time, and the LC effects are considered restricted to learning effects of the workers (learners). In contrast, the EC effects comprise learning effects of the whole firms and entire industries, such as learning trough research and learning trough scale-production and up-scaling of individual products (IEA, 2000). On the other hand, the term EC relates to the total production, or the total output of any function, such as manufacturing (Conley, 1970), marketing, distribution, or even aggregating entire industries, rather than single plants (Dutton and Thomas, 1984). Essentially, the EC generalises the labour productivity LC, to include all the costs necessary to research, develop, produce and market a given product, and according to BCG´s work it may be more influenced by technological inputs.

The popularity of the EC reached a peak in the mid 1970s (Papineau, 2006), with BCG´s strategic marketing tool based on EC effects. By that time, firms were recommended to expand in order to avoid competitor's entrance and maintain advantage. Some of these strategies failed because firms did not consider the effect of knowledge diffusion (Lieberman, 1987). Following this, the EC concept underwent a decrease in credibility.

1.3.1 Applications and misapplications of LC and EC

An extensive number of empirical studies have documented the link between cumulative experience (e.g., cumulative production volume, cumulative production time) and some measure of operational performance improvement (e.g., cost reduction, yield improvement, productivity improvement) in a variety of industrial settings, providing an empirical basis for the concept of learning-by-doing.

The LC model has been studied in many industries: airframes (Wright, 1936; Alchian, 1963), machine tools (Hirsch, 1952), metal products (Dudley, 1972), power plants (Zimmerman, 1982; Joskow and Rozanski, 1979), chemical processing (Lieberman, 1984), shipbuilding (Argote *et al.*, 1990), semiconductors (Webbink, 1977), photovoltaics (Harmon, 2000), combined cycle gas turbine (Claeson Colpier and Cornland, 2002), fuel cells (Tsuchiya and Kobayashi, 2002), ethanol production (Goldemberg, 1996), or carbon sequestration technologies (Riahi *et al*., 2002; Rubin, 2006).

The document entitled "Value Engineering and experience curve predictions" is a curious booklet produced by the Procurement and Production Directorate of the

United States Army Missile Command (Kelley, 1965) with general procedure guidelines. The booklet illustrates situations in which EC techniques may be applied as an aid in analysing a "Value Engineering Change Proposal"[10].

There is no natural law requiring production costs to follow an EC (Junginger, 2005). However, this phenomenon has been observed empirically numerous times. Dutton and Thomas (1984) have analysed over 100 EC for manufacturing firms and found PR ranging between 0,6 and 1,0, with a mean of 0,8. McDonald and Schrattenholzer (2001) have collected data for energy technologies (26 data sets) and found a distribution of PR also ranging between 0,6 and 1,0, but with a slightly higher mean, of 0,84.

1.3.1.1 Competitiveness of new and innovative products and processes: forecast of costs

Schumpeter (1947) identified patterns in the ways that technologies are invented, improved, and diffused into society. Other studies have described the complexity of the innovation process in which uncertainty is inherent, knowledge flows across sectors are important, and lags can be long (Nemet, 2006). Possibly, because of such characteristics, theoretical work on innovation provides only a limited set of methods with which to predict changes in technology, therefore the LC appears to be an exception (Nemet, 2006).

Several definitions of innovation can be found in the literature (e.g. Utterback, 1994; Frascati Manual, 2002; Oslo Manual, 2005). Nevertheless, almost all definitions include the concepts of novelty, commercialisation and/or implementation. In other words, if an idea has not been developed and transformed into a product, process or service, or it has not been commercialised, it should be classified as an innovation.

The Oslo Manual (2005) refers to innovation as "the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations". This definition is well suited to the scope of this work. Moreover, the national Portuguese Standard NP 4456:2007, regarding the Management of Research, Development and Innovation, has adopted this definition (IPQ, 2007).

The way innovative technologies develop and diffuse is characterised by various stages, from invention to widespread implementation (Hettinga *et al.,* 2009). Different learning mechanisms play a role in each of these stages. The learning process will lead to technological change and to cost reductions (Neij *et al.,* 2003; Junginger, 2005). Therefore, the EC approach can help to measure and quantify the aggregated effect of technological development and should not be neglected.

A technological discontinuity, also called radical innovation, marks the onset of a new technology. It is "based on a different set of engineering and scientific principles and often opens up whole new markets and potential applications" (Henderson and Clark, 1990). In consequence of the occurrence of a technological discontinuity, the EC can come to an abrupt stop (*see Figure 3*). This event is represented graphically by a curve truncation. Whenever such a phenomenon is identified, a red alert should be displayed in the 'competition monitoring device' of the firm, which means that existing processes become obsolete and the firm should upgrade to remain competitive. The upgrading will mean that the old EC will be replaced by a new one.

An important implication of the EC, related with technological discontinuity, is that increasing accumulated experience in the early stages of a technology will create the possibility of developing a 'dominant design' (BCG, 1972). A 'dominant design' is a technology management concept that identifies key technological designs that become the standard in their market place. Firms will introduce alternative designs until some combination becomes clearly preferred by end-users and widely accepted as an industry standard (Anderson and Tushman, 1990). Eventhough, the EC offers no method to predict discontinuities in the learning rate or the eventual occurrence of a dominant design, it may help at least to identify future barriers that could lead to technological discontinuities, and point out critical R&D areas (Nemet, 2006). A technological discontinuity appears in the form of a double knee. Figure 3 illustrates a step in the EC, indicating a change in the entry point and possibly also in the progress ratio before and after the change (IEA, 2000).

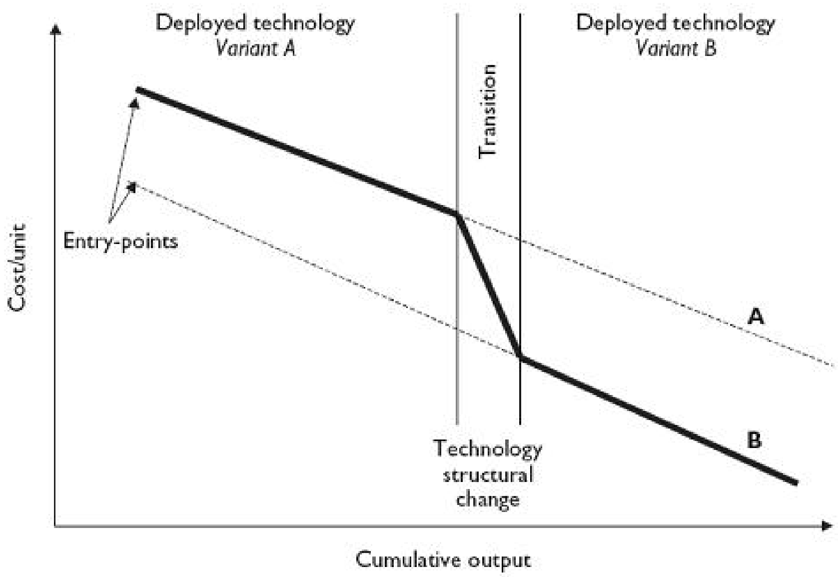


Figure 3 – Technological discontinuity (IEA, 2000).

The 'technology variant A' is deployed, but during the transition period investors realise the advantages of 'technology variant B'. As the two technology variants are assumed to be similar, in the transition period for 'technology variant B', there is experience accumulation from the learning process that occurred during 'technology variant A' deployment (IEA, 2000).

Emerging technologies pass through several stages before they mature, encompassed by different learning mechanisms. Among the different organisational learning mechanisms, in order to achieve an increased market penetration of a technology, learning-by-searching is the most dominant mechanism in the early phase of technology development (Van Sark, 2008). It also often plays an important role at later stages, as well, as the effect of R&D on an industry's capacity to decrease cost is analogous to experience, because it brings dynamism to economies or downward shifts in the cost curve (Papineau, 2006).

In the case of niche-market applications, for instance of new technologies, the learning-by-doing mechanism will ultimately promote innovation in the form of continuous improvement. Foray (2006) claims that, at the micro-economic level, learning-by-doing can be related to innovation and knowledge production. The researcher also points out the fact that learning-by-doing should not be confused with incremental innovation, because while learning-by-doing generates only technological or organisational increments, most incremental innovations are produced only through learning-by-doing mechanisms. After, the initial development phase, whenever technology diffusion takes place it leads to learning-by-interacting, and, from that point on, to the last stage of mass production.

The learning process is a result of the development of increasing skill in production, being therefore a source of innovation that is recognised as a component of the R&D process and receives no direct expenditures (Foray, 2006).

As the process of innovation is inherently uncertain, prospects for future learning with existing technologies do not consider breakthroughs (i.e., through R&D investments) and market developments. One has to be cautious when using EC for innovation forecasting purposes. The simplistic use of industry-wide EC can easily mask the underlying dynamics of the process of innovation. It would be wise only to use EC whenever incremental innovations are inferred as simplification and improvement activities, and avoid using EC for domains where radical innovations may take place.

Another drawback of EC, indirectly pointed out by Peter Senge (1990), is the "core learning dilemma" that confronts organisations – organisations learn best from experience but never directly experience the consequences of many of the organisational strategic decisions.

1.3.1.2 Modelling and policy support decision tools: the EC and LR in the case of energy sector

Newfound interest in EC has arisen in recent years, not only as before, as a production planning or strategic management tool, but more recently with a focus on achieving reliable estimates of technological learning rates as inputs in technology forecasting models used for decision-making for government policies (IEA, 2000; Hettinga *et al.*, 2009; Van den Wall Bake *et al.*, 2009, Weiss *et al.*, 2010). For instance, figure 4 illustrates the use of learning opportunities in the power sector in the European Union (EU).

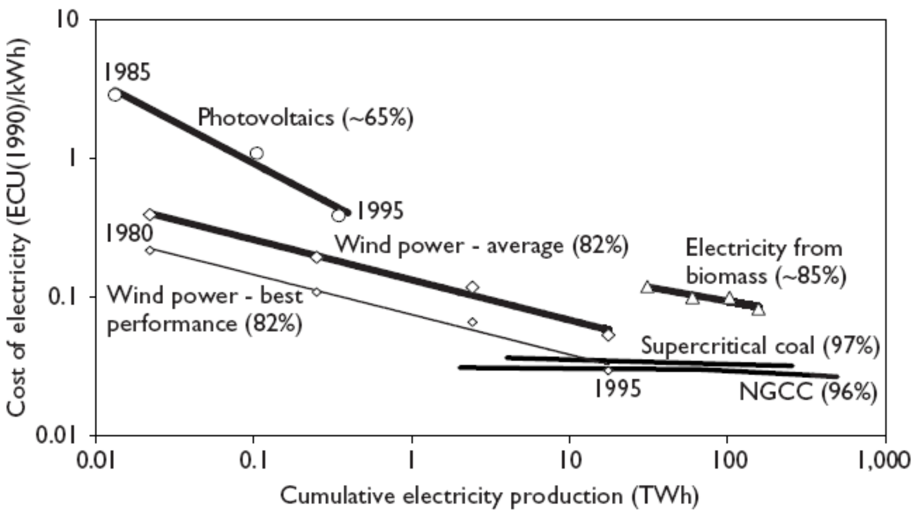


Figure 4 – Cost of electricity, electricity produced and PR from selected electric technologies installed in the EU, from the year 1980 to the year 1995 (IEA, 2000) (NGCC stands for Natural Gas Combined Cycle).

Eventhough, several national energy policies face controversy as electricity customers are paying more for subsidise wind farms, surprisingly, according to IEA (2000), electricity from wind produced at the sites, with best performance, can today compete with electricity produced in coal-fired power plants; photovoltaics and biomass technology require considerable improvements in performance before electricity from these technologies can compete with electricity from fossil fuel technology.

Technological policy decisions should always be supported by reliable estimation and technology cost forecasts. It is no longer plausible to use the EC methodology to estimate cost patterns on the basis of a price proxy. It is obvious that new approaches are needed to attenuate or solve the EC methodology limitations.

Several works have used LC as important tools for technical change modeling and policy making support. Duke and Kammen (1999) provided a method for evaluating the cost effectiveness of public policies to support new technologies. Van der Zwaan and Rabl (2004) have weighted public technology investment against environmental damage costs.

More recently, other works have pointed to the significant uncertainties of key parameters (Wene, 2000). LC must be used with caution, when inadequately applied, as they may lead to inappropriate public policies (Papineau, 2006). Nemet (2006) even stressed the importance of caution when applying EC in early stages of market dynamics for photovoltaic, fuel cell, carbon capture and sequestration technologies. Nevertheless, it is important to keep in mind that LC are a heuristic measure, without a solid theoretical basis.

Other studies indicate that learning from experience only weakly explains reductions in technology costs. For example, Nemet (2006) quantified the sources of cost reductions in photovoltaic technology and concludes that plant size, module efficiency and silicon cost are the most important factors of cost, being minimally affected by experience.

EC provides an useful analytical tool for assessing the historical and expected future performance of technologies in markets. However, for public policies development is still widely under-utilised, even though it could help to shape energy, environmental, climate change, and other policies (Jakob and Madlener, 2003). A good example of this application is the Green Econometrics Research (Davies, 2007) which attempted to develop a 'what-if' scenario for the solar energy market by comparing energy costs for different EC and market growth rates, using data from the Department of Energy of the USA (*see Figure 5*).

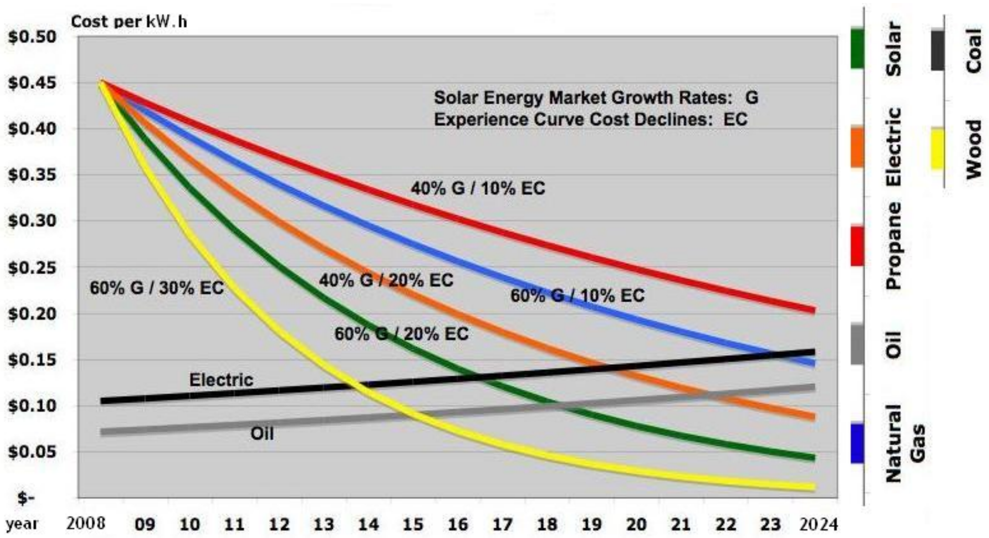


Figure 5 – Energy costs for different EC and market growth rates, adapted from Davies, 2007.

Figure 5 depicts that the most optimistic scenario of market growth of 60% and EC of 30%, suggests that it would take until 2014 before solar energy price equals to the price of electric energy. Davies (2007) also claims that increased funding into solar energy research and higher energy prices would shorten the time to reach price parity between energies.

Another EC application, rarely addressed, consists of promoting learning spillovers as a diffusion policy, learning gains and first mover advantage (Schwoon, 2006). In a working paper on fuel cells vehicles, Schwoon (2006) shows that high LR, long planning horizons of the producers and high learning spillovers have a positive impact on the technology diffusion. In addition, Clark and co-workers (2006) identified three sources of technological change, such as research and development (R&D), learning-by-doing, and spillovers, that are particularly relevant to the process of technological change. Moreover, Nemet (2006) concludes, in a study where sources of cost reduction in photovoltaics are quantified, that learning derived from experience is small compared to those of expected future demand, risk management, R&D, and knowledge spillovers.

1.3.1.3 Support decision tool at the firm's level: EC cross-comparisons

Despite an extensive body of research, especially on the effects of EC on business strategy, few studies have paid attention to firm-level and organisational-level differences in slopes of LC. Therefore, unstudied comparisons between LC across independent organizations in the same industry remain to be conducted (Pisano *et al.*, 2001).

An interesting exception is the work on early U.S. rayon production (Jarmin, 1994), where a different relationship was identified between cumulative experience and performance improvement across producers, having found differences in the abilities of rayon producers to benefit from their own cumulative production experience.

Only few studies have established the possibility that LC can vary across plants or organisational sub-units within the same company. Hayes and Clark (1986) have concluded that these differences were not explained by product or technology differences. There is the underlying suggestion that organisational learning effect, in addition to experience effects, contributes to performance improvement.

Considering BCG´s perspective (1968), the cycle for a viable product has four phases (*Figure 6*):

- **"Development phase"**, where the initial producer sets prices below cost to establish the market.

- **"Price Umbrella phase"**, where the producer as market leader may maintain prices over the higher cost producers that are entering the market. In effect, the producer is already cashing in on his development by trading future market share for current profits. Under the Price Umbrella, the new producers will learn and thereby reduce their cost, and the typical PR for this phase is 90% or more.

- **"Shakeout phase"** inevitably occurs when producers become low-cost producers and the difference between the price and the cost for these producers becomes larger and larger. PR typically will be around 60% for this phase, but there are considerable variations around this value.

- **"Stability phase"**, where prices stabilise around an EC with the same PR as the cost curve, leading to a fixed cost/price ratio.

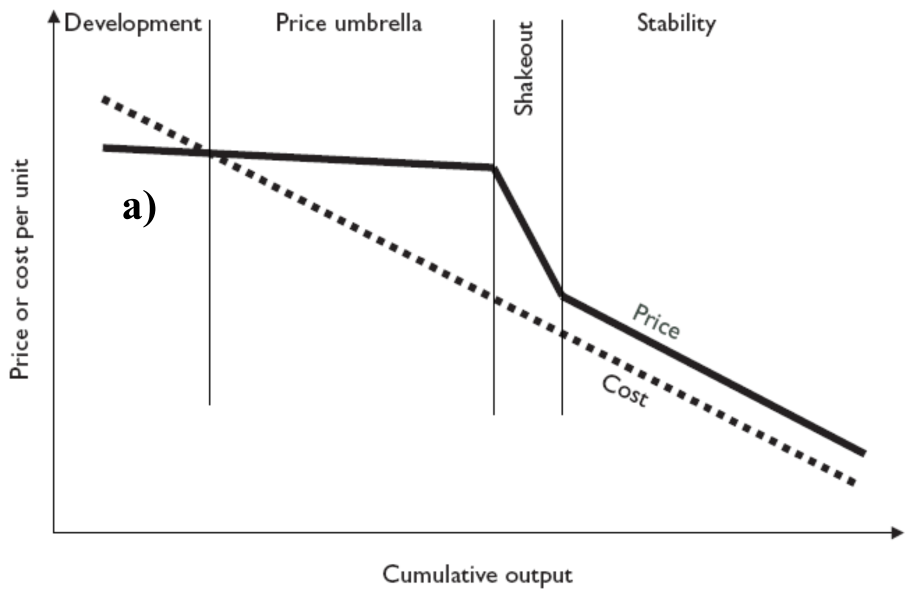


Figure 6 - Price-cost cycle for the market introduction of a new product based on BCG, 1968.

More recently, Morrison (2008) went one step further with the EC applications, arguing that the "anticipation of future cost reduction that accrues as production experience is gained, suggests setting prices aggressively, even below cost of manufacturing, early in a product life cycle in order to build market share" (*see a) in Figure 6*).

The BCG´s four-phase cycle, and related models, should be used with caution in our globalised economical framework, and imperfect economy, due to different phenomena. On one hand, the technological structural change, which can be depicted in the cost EC, is difficult to measure, thus tempting the analyst to use the price curve as an indicator for technology structural change. On the other hand, innovative processes that occur and rapidly diffuse worldwide can easily affect technological structural change. Therefore, the cost EC modelling should include a 'calm down factor', in order to avoid excessive optimistic scenarios. Finally, the market structural change, which can be observed in the price EC, will have no effect over the cost curve (IEA, 2000), so that the behaviour of the cost curves will never accurately be predicted by the price EC.

Chapter 2 Materials and methods

It has generally been assumed that the EC concept can be used with prudence as a managerial tool to improve business performance and enhance innovation in firms. Even though the EC is based on data of past performances, if the underlying learning mechanisms present in experience accumulation are identified, KM can be put in practice for future improvements. In this context, the present work is a preliminary attempt to understand to which extent EC may be used for KM purposes, through the case study of the technology of microalgae production.

A research strategy was developed, aiming towards a better appreciation of the interrelated aspects of learning and experience build-up in a technology-based firm. In this work, the case-study approach was chosen as the main methodology of research, as it provides an in-depth investigation of underlying principles of learning and experience accumulation during the technology instalment and development in a business environment.

In our work, secondary data are obtained from two different research strands:

- Qualitative data, trough semi-structured interviews, firm records and other research-related documents;
- Quantitative data collected from databases and bibliographic references.

Following data collection, the information gathered was processed with two different methodologies, one regarding EC and the other focused on the learning mechanisms involved in the technology development. Table 2 summarises the sources for secondary data collection, and the generalised scheme of our research strategy is shown in Figure 7.

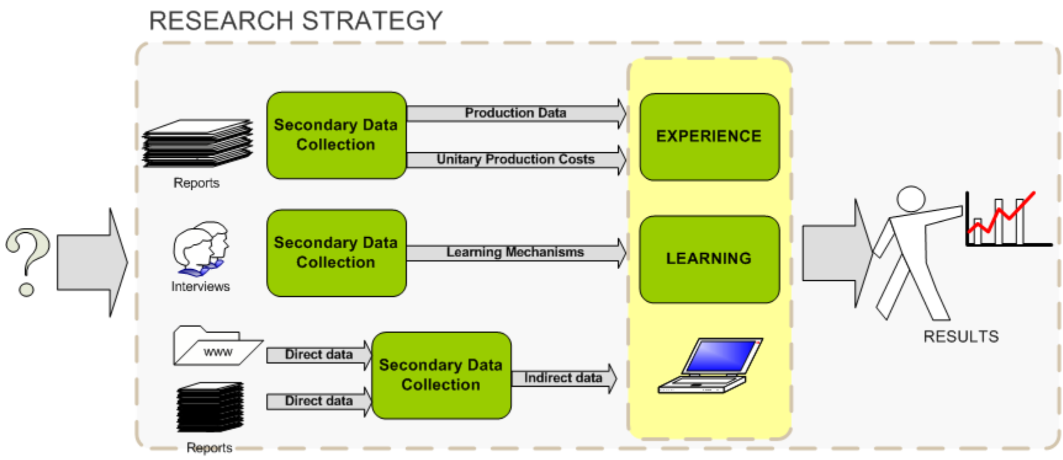


Figure 7 – Research Strategy.

Table 2 – Sources of secondary data.

Sources of secondary data	
Semi-structured interviews with technical staff related with production and laboratory activities	Learning Mechanisms
Necton's 'Annual Production Reports' 2000 - 2008	Production per month Productivity per month
'Boletim do Trabalho e Emprego' (http://bte.gep.mtss.gov.pt/)	Wages of Technical Staff
Meteored (http://clima.meteored.com)	Max., Min. & Average Temperatures
Meteored (http://clima.meteored.com)	Rainy Days
Tu tiempo Network (www.tutiempo.net)	Sun hours
European Solar Irradiation Database (http://re.jrc.ec.europa.eu/pvgis/solres/solres.htm)	Irradiation

2.1 Case-study selection

Projections for 2009 estimated that products and services developed worldwide by blue biotechnologies[11] account for 2,6 billion Euros per year, with a market growth rate of 3,8% (SAER, 2009)[12]. Marine biotechnology falls within the scope of blue biotechnology, and aims to develop methods for producing novel products extracted from or originating within marine organisms. These products can contribute to human healthcare, food and feed industries, and to the energy industry.

Among the marine organisms, microalgae are an untapped resource. Even though processes that use microalgae are not novel, surprisingly few microalgae are produced for commercial purposes. There is currently a niche market for several microalgal products, such as carotenoids and omega-3 fatty acids. Microalgae are

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[11] The influential Organisation of Economic Cooperation and Development (OECD) provided, in 2001, a working definition for biotechnology: "biotechnology is the application of scientific and engineering principles to the processing of materials by biological agents to provide goods and services" (OECD, 2001). There are four main subfields of biotech that can be represented by colours: white, green, red, and blue. White (or grey) biotech is a metonym for health application. Red biotech is for industrial application. Green stands for agriculture and environmental uses, and the blue subfield is for aquatic uses.

[12] There are four main subfields of biotech that can be represented by colours: white, green, red, and blue. White (or grey) biotech is a metonym for industrial application. Red biotech is for industrial application. Green stands for agriculture and environmental uses, and blue subfield is for aquatic uses.

The blue biotechnology market is expected to grow rapidly for several reasons, but specially due to the fact that 80% of living organisms are to be found in aquatic ecosystems (SAER, 2009). Therefore, the pace of discovery of new species and products through marine bioprospecting, potentially useful to pharmacology, is thought to be higher for marine organisms than for terrestrial organisms. Traditionally only 1 out of 10.000 to 20.000 molecules extracted from terrestrial microorganisms, plants or animals finally reached the market (EU, 2006). However, marine organisms present a better opportunity for encountering successful candidates in view of the large biodiversity, lack of current knowledge and extreme environments (EU, 2006). Approximately 15.000 natural marine products have been screened, and out of these, currently there are 45 marine derived natural products tested to be used as medical drugs in preclinical and clinical trials; and two of them have been developed into registered drugs (Wijffels, 2007).

now also receiving renewed attention because of their potential as a source of biofuels (Stephens *et al.*, 2010).

The success of commercial large-scale production of microalgae depends on many factors, and one of these is the development of cost effective large-scale culture systems for the microalgae. The development of such systems has been, and continues to be, a gradual process (Borowitzka, 1999).

Almost all the industrial processes are designed to produce large amounts of products, moving towards mass production. For larger scale production of microalgal products, such as those required for the production of bulk chemicals or biofuels, major developments in science and technology will have to be achieved. However, the commercial success of microalgal bioproducts and processes not only depends on relevant scientific and technological development, but also on a supportive regulatory framework. Recently, a few countries, such as the U.S.A., United Kingdom and Japan, have made a strong effort in R&D activities regarding blue biotech. Over the last few years, the Portuguese biotechnology sector has experienced an important and significant increase in the number of companies created. Presently, there are over 40 biotechnology start-up companies in Portugal, most of which were created between 2001 and 2006 (APBIO, 2006). While all four subfields have contributed with a number of valuable processes, green biotech is probably the most widely used, while blue biotech is still relatively rare. This generalisation is confirmed by recent statistics relating to Portuguese biotech companies (APBIO, 2006). Even though Portugal has a vast ocean shoreline, surprisingly few companies have emerged dedicated to marine biotechnology, and only one company in Portugal produces microalgae (Necton).

Besides the required R&D efforts, there is also a significant need in the techno-economical domain to study, comprehend and try to reduce production costs. The reduction of production costs may, in this case, as well as in others, expand the potential industrial use of microalgae. Thus, the EC is tool potentially worthy of application to the MPS.

Necton is based in the Ria Formosa Natural Park, in the Southern Portuguese Algarve region. Established in 1997, the microalgae production unit began to operate as a pilot plant settled in the saltpans.

In general terms, microalgae cultivation implies a succession of dilution and concentration processes. A good quality of inocula is accomplished in the laboratory under very controlled conditions, to avoid contaminations and optimise biochemical composition of microalgae. After growing the inocula indoors, it is possible to scale-up to photobioreactors (PBR), and slowly adapt the microalgae to outdoors conditions. Necton uses a semi-continuous cultivation system with an ‘on-line set point’ of pH and temperature control, which regulates carbon dioxide supply and the refrigeration of cultures, respectively. This automated control allows the maintenance of excellent growing conditions according to the microalgae species. Biomass is harvested daily through a controlled centrifugation process, which promotes an optimal microalgae culture growth. Microalgal cultures are controlled daily for nutrients, growth parameters, contaminations and biochemical quality.

The microalgal biomass is sold primarily to the aquaculture market, but also for the cosmetic industry. Aiming to solve hatchery managers constraints related to in-house microalgae production crashes, Necton developed a set of specialised microalgae concentrates. The company commercialises the ‘PhytoBloom’ product range, based on an improved strain of *Nannochloropsis oculata* and is presented as a frozen paste, a liquid formula or a freeze-dried powder (*see Figure 8*). This product range mainly targets aquaculture fish hatcheries, R&D institutions and fish feed producers.

a) b) c)

Figure 8 – Products commercialised by Necton for the aquaculture market: a) PhytoBloom ice - microalgal biomass in frozen state; b) Phytobloom Green Formula – live microalgae in a liquid formulation; c) PhytoBloom prof – freeze-dried microalgal biomass.

At present, Necton is using the 4^{th} generation of MPS. The first technology to be designed and implemented in Necton´s facilities, even before the company was established, was an open raceway to produce *Dunaliella salina*, a microalgal strain that produces natural betacarotene. At that moment, the market constraints and the low productivity of this type of system dictated a slow abandonment of the technology, being replaced by a closed system technology, designated as "flat panel flow through" PBR (FPFT - PBR).

Since the year 2000, the company has been operating 5 FPFT – PBR, with a total cultivation volume of 13.000 litres. In 2006 the 3^{rd} generation of PBR was built, which consisted of a tubular PBR with a cultivation volume of 3.200 litres. The design of the tubular PBR was aimed at solving one important restraint of the FPFT-PBR technology related to cleaning and maintenance. Both types of PBR are strategically positioned and designed to favour optimal sun-light exposure, in order to guarantee maximum productivity.

The technological *portfolio* of Necton was enlarged in 2007 with the installation of 'GreenWall' technology (GW). The GW is a closed system that consists of a 700 litre plastic bag where the culture is grown; mixing is accomplished by bubbling air into the culture.

After more than a decade of microalgae production experience know-how, several technologies were tested in Necton´s production site, such as raceways, closed PBR, and even 700 litre GW.

Necton is perhaps the only company in the world that has tested so many different MPS, ranging from closed to open systems (*see Figure 9*), and produces a wide range of microalgal species[14].

[14] A collection of more than 15 strains, both marine and freshwater species, are maintained and ready to be scaled up. In Necton´s MPS it is possible to grow *Nannochloropsis*, *Tetraselmis*, *Phaeodactylum*, *Porphyridium*, *Chlorella*, *Haematococcus pluvialis* and *Porphyridium cruentum*, among others.

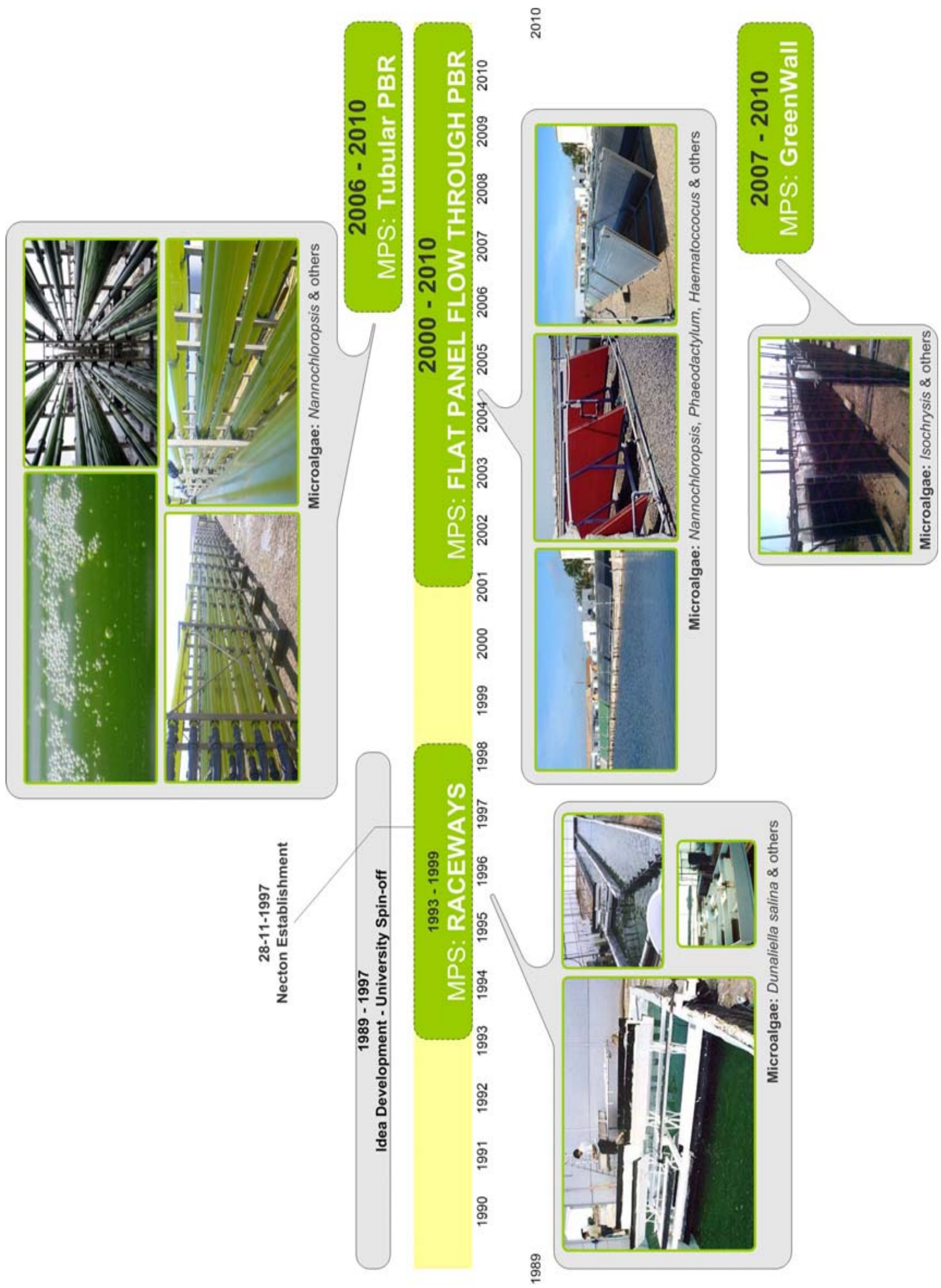


Figure 9 – Technological *portfolio* of Necton.

The technical details and extended description of MPS will be introduced in Chapter 3.

2.2 Research questions and working hypotheses

In the present study, the term ‘technology performance’ corresponds to the total biomass produced, due to the fact that this is the main result arising of the company’s activity. In order to understand the evolutionary process of technological learning within the firm´s context, it was fundamental to understand how the firm has learnt year over year to produce biomass. Consequently, two research questions immediately arose. The first focused on the EC phenomenon, and on how it occurred in the case-study, as the outcome of integration of all the learning processes. The second question aimed to explore the variation between different types of technologies for MPS, and if technological differences globally influenced the EC.

Companies that have the capability to learn will lead the market. Currently, it is not enough to have learning-by-doing capabilities, and therefore the third question brought up more specific uncertainties, related with what learning mechanisms, besides learning-by-doing, have taken place along technological experiencing, and to what extent they have affected the organisational learning and technological performance.

From the main research questions, three working hypotheses were therefore addressed:

H1: MPS of the case-study follows an experience curve

H2: Closed and open MPS follow similar experience curves.

H2: Learning mechanisms play different roles across the MPS life-cycle.

2.3 Data Collection

The company Necton provided several documents, such as 'Annual Production Reports' and other records, that gathered information about daily production, monthly production and productivity accomplished, since the year of 2000, when the several FPFT PBR were installed. During the year 2006, the tubular PBR was installed and started to be in operation, which entailed, for the purpose of this study, the detachment of data, in a daily basis, from the year 2006 to the year 2008, from the records of total biomass produced within total installed capacity biomass into two different data sets, regarding each type of technology. Data regarding biomass produced per year could then be used in the 'Methodology for experience curve determination' for both MPS.

The MPS of the case-study are installed outdoors, and use sun-light as source of energy. Therefore, there are several parameters related with environmental conditions that can alter microalgae growth rates, with subsequent implications in technology performance. Even though they are difficult to control, for an accurate analysis those parameters must be known. A set of environmental data was collected and processed, including minimum temperature and maximum temperature, sun-hours, rainy days and irradiation (*see Appendix A*). Environmental data, especially those related with photobiology, largely affect technology performance, and have been reviewed in detail elsewhere (Pulz, 1992; Pulz and Scheibenbogen, 1998; Tredici and Zitelli, 1998; Molina Grima, *et al.*, 1999; Tredici, 2010).

First-hand data was extracted from semi-structured interviews conducted with technical staff from Necton. The set of interviews was conducted with direct personnel, namely those workers that were directly involved with technology design and redesign, technology on-site implementation, and production activities. The size of the sample was 5 workers. Each interview lasted approximately for 2 hours, allowing questions to be brought up during the interview. A framework of themes was explored, all related with how each collaborator had experienced technological discontinuities, organisational changes and which learning activities were more present in each phase of the different technologies implementation.

The final semi-structured interview guideline is presented in Appendix B. Because the interview script was semi-structured, the number of questions asked was not constant along the interviews, and discussions varied depending on responses from workers. In addition, as interviewees had to make use of memory, some graphical representations and diagrams were shown to grant an event contextualisation. Qualitative analysis was used to estimate the contribution of each learning mechanism in the technology life-cycle, and how workers experienced performance increase. The data obtained in the interviews were applied in our 'Methodology for learning effects determination'.

2.4 Research methodologies

In order to test the working hypotheses, two methodologies were combined together.

2.4.1 Methodology for EC determination

The EC model, expressed in equation (1), in a natural log-log scale, can be presented as:

$$\ln(y) = C + b.\ln(x) \tag{4}$$

Considering that x stands for cumulative units produced (CUP), and that y corresponds to the unitary cost (UC):

$$y = UC = \sum_1^n \frac{PC}{TB} \tag{5}$$

where *PC* is the production cost (approximated by labour) in the year n, and *TB* is the total amount of biomass produced in the year n. Therefore, equation (4) can be expressed as follows:

$$\ln(\sum_1^n \frac{PC}{TB}) = C + b.\ln(CUP) \qquad (6)$$

Labour costs were determined considering a technical team of 4 workers, with different time allocations to production activities, herein expressed in percentage of time: business unit manager (20%); plant manager (100%); maintenance technician (100%); laboratory technician (100%). Wages used in this study are referred in (BTE, 2007) as a minimum wage of each worker category. The information regarding TB was extracted from the 'Annual Production Reports' provided by Necton.

A regression analysis was performed over equation (6), providing the EC and the quantification of PR and LR for each type of technology (FPFT PBR and tubular PBR).

Production data, regarding open systems, was taken from the literature (Vonshak, 1997; Sánchez *et. al*, 2003), but unitary production costs were not found. Regardless of this fact, production improvement was determined for closed and open systems.

2.4.2 Methodology for learning effects determination

Based on Adler and Clark´s work (1991), the present methodology aims to understand which learning mechanisms were, or were not at all, experienced by workers, and at what point they took place in each MPS life-cycle. The technologies to be studied are the ones that were installed in the past, or are currently still in operation in Necton: raceways, FPFT PBR, tubular PBR, and GW. To pursue with our research purpose, four variables were measured:

• **Learning-by-doing (LD)** is the contribution of learning-by-doing mechanism to the MPS performance experienced by workers, measured as percentage of time dedicated by workers to production activities, such as every-day production routines and practices.

• **Learning-by-using (LU)** is the contribution of learning-by-using mechanism to the MPS performance experienced by workers, measured as percentage of time dedicated by workers to production and product design changes, production optimisation, either running experiments or learning new specifications, and process evaluation and reengineering.

• **Learning-by-searching (LS)** is the contribution of learning-by-searching mechanism to the MPS performance experienced by workers, measured as percentage of time dedicated by workers to researching, searching and lab activities.

• **Learning-by-interacting (LI)** is the contribution of learning-by-interacting mechanism to the MPS performance experienced by workers, measured as percentage of time dedicated to knowledge transfer with suppliers, clients, R&D and commercial partners.

During the interview, workers were asked to contextualise each learning mechanism along each MPS life-cycle, with some facts observed in the production records and other documents provided by Necton.

Although there are two other learning mechanisms identified, as summarised in Chapter 1, ‘learning-by-learning’ and ‘learning-by-expanding’. These were not included in our study, due to their complexity and difficulty to be measured.

Chapter 3 MPS: perspectives and advances

Microalgae are microscopic organisms found in both marine and freshwater environments. They are classified into divisions based on various properties, such as pigmentation, chemical nature of photosynthetic storage product, organisation of photosynthetic membranes, and other morphological features. The three most important classes of microalgae, in terms of abundance, are diatoms (*Bacillariophyceae*), green algae (*Chlorophyceae*), and golden algae (*Chrysophyceae*). The cyanobacteria (*Cyanophyceae*) are also referred to as microalgae.

Microalgae reproduce mainly by cell division, so that they can exponentially multiply if optimal conditions are provided. Microalgae grow very quickly compared to terrestrial crops. They commonly double in size every 24 hours. During the peak growth phase, some microalgae can double every 3,5 hours (Chisti, 2007).

Blue-green microalgae, such as *Nostoc*, *Spirulina*, and *Aphanizomenon,* are edible and have been used as a nutrient for many centuries in Asia, Africa and Mexico (Olaizola, 2003). The first traceable use of microalgae by humans dates back 2000 years to the Chinese, who used *Nostoc* to survive during famine (Spolaore *et al*. 2006). From 1890 to 1990, most microalgae were grown for human consumption, and *Spirulina* was even believed to offer a solution to world hunger and malnutrition. Table 3 summarises historic data from algal biotechnology.

Table 3 - Algal biotechnology historical data, adapted from Borowitzka, 1995, and Borowitzka, 1999.

1860s	Alfred Nobel invented dynamite, using diatomaceous earth (diatomite), which consists of the fossil silica cell walls of diatoms, to stabilise and absorb nitroglycerine into a portable stick.
1890	The first unialgal cultures with *Chlorella vulgaris* were developed by the Dutch microbiologist Martinus Beijerinck.
1919	Cultures of *Chlorella vulgaris* used for studying plant physiology.
1940s	Microalgae started to become more important as live feeds in aquaculture (shellfish or fish farming), along with the zootechnical development of aquaculture techniques.
1948	R&D mass culture of microalgae began at Stanford (U.S.A.), Essen (Germany) and Tokyo. Applied algology developed rapidly, extending into Israel and Italy, aiming to produce protein and fat as a nutrition source.
	At that time, the idea of using microalgae for wastewater treatment was launched and the systematic examination of algae for biologically active substances, particularly antibiotics, began.
1953	First edition of the "Algae Culture from Laboratory to Pilot Plant", written by John Burlew, from the Carnegie Institution of Washington.
Early 1960s	Commercial large-scale culture of *Chlorella* in Japan and Taiwan as a novel health food commodity.
	In the U.S.A., the interest to use microalgae as photosynthetic gas exchangers for long term space travel emerged.
Early 1970s	The first large-scale commercial harvesting and culturing facility of *Spirulina* was established in Mexico, at Lake Texcoco, by Sosa Texcoco S.A.
1977	Establishment of commercial *Spirulina* plant in Thailand, by Dai Nippon Ink and Chemicals Inc..
1978	The energy crises triggered considerations about using microalgal biomass as renewable fuels and fertilizers. An environmental technology from the USA aimed at improving the quality of wastewater through microalgae and the subsequent fermentation of the resulting biomass to methane was developed (Pulz and Scheibenbogen, 1998; Spolaore *et al*. 2006). Furthermore, a $25 million USD program (Aquatic Species Program, ASP) was set up by Jimmy Carter´s Administration to investigate high-oil types of algae that could be grown for biodiesel production.
Early 1980s	Kawaguchi (1980) reports 46 large-scale factories in Asia, producing more than 1.000 kg of microalgae (mainly *Chlorella*) per month.
Mid 1980s	Establishment of commercial production of *Dunaliella salina* as a source of β-carotene by Western Biotechnology Ltd and Betatene Ltd. in Australia. At this point, the production of *Dunaliella salina* became the third major microalgae industry.
	Establishment of other commercial *Dunaliella salina* plants in Israel and U.S.A..
	Establishment of large-scale production of cyanobacteria in India.

In the 1990s, several developments were made in the microalgae field. Mass production was achieved for the new microalgae *Haematococcus pluvialis*, as several plants began large-scale production in the U.S.A. and India. The already commercialised species, such as *Chlorella* and *Spirulina*, reached consumption and production peaks. Indeed, Lee (1997) reports that 2.000 tons of *Chlorella* were traded in Japan alone and Pulz and Gross (2004) estimate that in 1999, about 3.500 tons of *Spirulina* biomass were produced.

But even today the microalgal market is dominated by *Spirulina*[15] (Pulz and Gross, 2004). This has been confirmed by extensive research conducted within this work, using different information sources such as on-line company and product directories. From the 194 microalgae producing companies, 65% produce *Spirulina.*

Microalgae are an untapped resource, with more than 100.000 species (Carlsson *et al.*, 2007), of which fewer than 15 are in commercial production. From an extensive search in the EUR-Lex database (http://eur-lex.europa.eu), we found that besides the most common microalgae, such as *Spirulina* and *Chlorella*, presently only *Odontella aurita* can be used as a food ingredient in the EU. Other microalgal extracts have also been approved as novel food ingredients, like extracts from *Schizochytrium* sp., *Haematococcus pluvialis*, and *Ulkenia* sp.

[15] There are several reasons for this commercial success. *Spirulina* is well-know due to its high protein content, nutritive value, and not the least, because it is easy to grow!

Microalgae are one of nature's richest raw materials in vitamins, proteins and other nutrients (*see Table 4*).

Table 4 – Products from microalgae (Barbosa, 2003).

Product		**Applications**
Biomass	Biomass	Health & Functional Food, Feed Additive, Aquaculture, Soil conditioner
Colouring substances & antioxidants	Xantophyls (astaxanthin and canthaxanthin), Lutein, β – carotene, Vitamins C & E	Food Additive, Feed Additive, Cosmetics
Fatty acids	Arachidonic acid, Eicosapenatenoic acid, Docosahexaenoic acid, γ-linolenic acid, Linolenic acid	Food Additive
Enzymes	Superoxidade dismutase, Phosphoglycerate kinase, Luciferase and Luciferin, Restriction Enzymes	Health Food, Research, Medicine
Polymers	Polysaccharides, Starch, Poly-β-hydroxybutyric acid	Food Additive, Cosmetics, Medicine
Special Products	Peptides, Toxins & Isotopes, Aminoacids, Sterols	Research, Medicine

Current commercial applications are limited to processes for high added value compounds or algae used in food and cosmetics. It is estimated that 5.000 tons of algal biomass are produced per year (Pulz and Gross, 2004). Over the years, the algal biotechnology companies have brought a number of products to market, ranging from aquaculture feed to specialty chemicals. The commercial value of products synthesised by microalgae can vary significantly, from 50 to 15.000 Euros per quilogram (Rosenberg, 2008).

Currently, the development of biofuels is a priority of the industry, as microalgae contain the right kind of oil for producing biodiesel. Microalgal biomass contains three main components: carbohydrates, proteins, and lipids/natural oils. The bulk of the natural oil made by microalgae is, mostly, in the form of tricylglycerols. The oil content of microalgae usually ranges between 20 percent and 50 percent (dry weight), while some strains can reach as high as 80 percent (Spolaore *et al.*, 2006).

Pursuing to obtain the 'green gold', in the last 10 years, many new commercial companies, and consequently new production technologies, have been created, to exploit microalgae for biofuel production and/or carbon dioxide sequestration. The idea of using microalgae as a source of fuel is not new, but has been given greater credibility recently because of the escalating price of petroleum and, more significantly, the emerging concern about global warming (Chisti, 2007). Inclusively, some existing microalgae companies have identified a business opportunity in the bioenergy field and shifted their business models to consultancy services, technology design or to join big R&D projects related with renewable energies and biorefinery concepts (*see Table 5*).

Table 5 - R&D projects focusing on biofuels from microalgae, adapted from Beneman, 2008.

R&D Project	Description
Aquatic Species Program (ASP), USA 1980 1996	- Biodiesel from algae grown in ponds and PBR. - Run by the National Renewable Energy Laboratory. - Funded by Jimmy Carter´s Administration with $25 million U.S. dollars. - Achievements: PBRs too costly.
U.C. Berkeley, USA 50s – 60s	- Methane from algae grown in ponds.
NEDO-RITE, Japan 1990 -2000	- CO_2 abatement with PBR. - Funded with 250 million U.S. dollars. - Achievements: total failure.
Some small projects, Worldwide 2000 – Present	- Explosion in R&D teams. - More than 100 projects or companies dedicated to producing biofuels from microalgae, mostly in PBR.

3.1 General description of microalgae production process

Most microalgae are obligate photoautotrophs, depending strictly on the generation of photosynthetically derived energy. Other microalgae are heterotrophs, and therefore rely on glucose or other carbon sources for carbon metabolism and energy. Some algae can also grow mixotrophically, being able to switch from photoautotrophic to heterotrophic growth.

Cultivating heterotroph microalgae involves the production in the dark using organic substrates as the source of energy and carbon. Such a fermentation is performed in closed tanks, very similar to fermentors, in which the conditions can be controlled. *Crypthecodinium sp.* and *Schizochytrium sp.* are heterotrophic microalgae, and both are known for their capacity to produce docosahexaenoic acid (DHA). Tthe study of this type of MPS is out of the scope of the present work.

The photosynthetic mechanism of microalgae is similar to plants, but, due to a simple cellular structure and the fact that microalgae are submerged in an aqueous environment, where they have efficient access to water, carbon dioxide and other nutrients, they are generally more efficient in converting solar energy into biomass (*see Figure 10*).

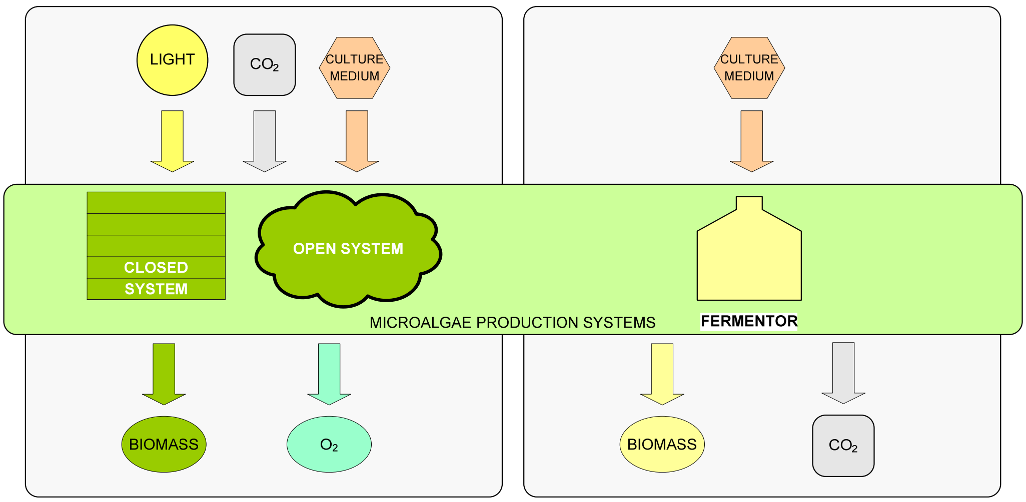


Figure 10 – Representation of MPS for photoautotrophic and heterotrophic microalgae.

Microalgae Production Systems

Photoautotrophic microalgae grow very quickly under optimal conditions compared to terrestrial crops. MPS are often operated in a continuous mode, i.e. fresh feed (containing nutrients that include nitrogen, phosphorus and inorganic salts) is added, carbon dioxide is injected or bubbled, while the biomass from the culture broth is harvested and oxygen released to the atmosphere. Photoautotrophic microalgae can be cultivated in either open or closed systems.

Open systems can be divided into natural waters (lakes, lagoons, ponds) and artificial ponds or containers, built in different ways (*see Table 6)*.

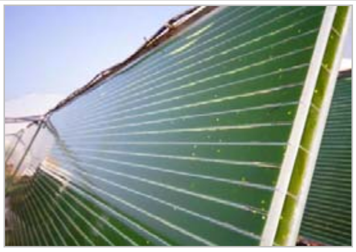
Table 6 – Open microalgae production systems.

Microalgae Productions Systems	**Type of MPS**	**Examples of running facilities**		
		Microalgae	**Company / Organisation**	**Country**
Open ponds	**> Třeboň-type cascade**	*Chlorella*	Lab. of Algal Research	Czech Republic
		  Source: www.youtube.com		
	> Circular	*Chlorella*	Sun Chlorella	Japan
		  Source: www.sunchlorella.com		
	> Raceways	*Dunaliella* and *Haematococcus*	Cyanotech	U.S.A.
		  Source: www.cyanotech.com		
Lakes & lagoons		*Dunaliella* salina	Cognis Germany	Australia
		  Source: www.cognis.com		

Despite a great deal of variability in shape, the most common technical designs for open pond systems are raceways cultivators driven by paddle wheels, typically operating at water depths of 15–20 cm (Pulz, 2001). Eventhough raceways are the most generalised configuration, it is worth noting that the biggest microalgae production farms are lakes, with over 250 hectares, and are located at the Hutt Lagoon, in Australia.

Pulz (2001) classified closed systems for microalgal mass culture in three configurations: (1) tubular systems, (2) flattened, plate-type systems, and (3) ultrathin immobilized systems (*see Table 7*).

Table 7 – Closed microalgae productions systems.

Microalgae Production Systems	Type of MPS	Examples of running facilities	Microalgae Production Systems	Type of MPS
Photobioreactor	**> Tubular**	Production of *Haematococcus*	Algatech	Israel
	  Source: www.algatech.com			
	> Flattened, plate-type	Production of several microalgae	Necton S.A.	Portugal
	  Source: Necton S.A.			
	> Ultrathin immobilized system	Device for wastewater treatment using microalgae	Hong Kong University	China
	 Source: www.ust.hk			

Harvesting, drying and packaging

The broad phylogenic microalgae diversity is a source of wide chemical varieties with different applications and trading goods. The majority of the microalgae-derived products (extracts) currently produced are used for health foods and pharmaceutics manufacturing, as well as for the aquaculture sector and animal feed industry. After microalgae cultivation, biomass is harvested, processed and/or dried (*Figure 11*). The microalgal biomass and extracts are usually marketed as tablets, capsules, and liquids.

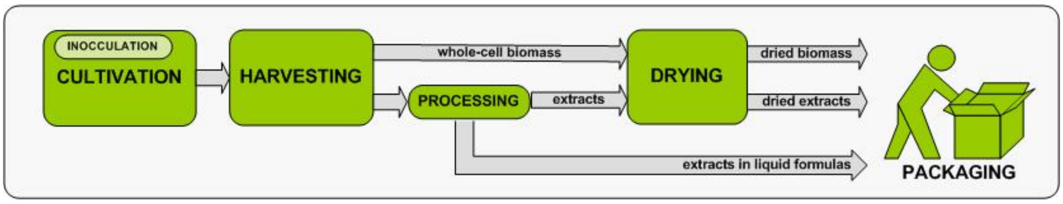


Figure 11 – The microalgae production process, from cultivation to product packaging.

In most MPS we have found a relatively low biomass concentration, due to limited light penetration and the small size of microalgal cells. Inevitably, costs and energy consumption for biomass harvesting are a significant concern, that needs to be properly addressed.

There are different harvesting (or separation) technologies, including chemical flocculation, biological flocculation, filtration, centrifugation, and ultrasonic aggregation, that have been used for microalgal biomass harvesting.

Chemical and biological flocculation are processes known for their low operating costs, but at the same time require long processing periods, with an eminent risk of bioreactive product decomposition. On the other hand, filtration, centrifugation, and ultrasonic flocculation are more efficient, but also have a higher cost (Li *et al.*, 2008).

The selection of an appropriate drying technology depends on the species of microalgae, the final product desired, the value of the target product, and the biomass concentration (Uduman *et. al*, 2010). Algal properties, such as a large cell size and the capability of the microalgae to autoflocculate, can simplify the dewatering process. Microalgae for whole-cell aquaculture feed or whole-cell dietary supplements applications can be sold as a bulk powder. Drying is accomplished using either freeze-drying or spray-drying.

Generally speaking, microalgae typically grown in open systems, such as *Spirulina* and *Chlorella*, have lower market prices. Both microalgae are used as whole-cell dietary supplements, and marketed in tablets or capsules. Prior to final compression or encapsulation, microalgae are spray-dried.

Other microalgae, with higher market prices, are normally sold as a freeze-dried bulk powder. Freeze-drying of biological biomasses produces stable powders, almost without biochemical degradation and cell disintegration. The majority of these products are freeze-dried from simple aqueous solutions. As freeze-drying is still an expensive process, when compared to spray-drying, for that reason freeze-dried bulk powders are sold at higher prices.

Biomass drying for further processing (lipid or bioactive extraction; thermochemical processing) is another step that needs to be taken into consideration. Sun drying is an ancient and probably the cheapest drying method. However, this method takes a long time, requires large drying surfaces, and risks the loss of some bioreactive products (Li *et al.*, 2008).

Another low-cost drying technology is low-pressure shelf drying. However, it is also very inefficient. More effective but costly drying technologies have been investigated for drying microalgae: drum drying, spray-drying, fluidized bed drying, freeze drying, and refractance window dehydration technologies.

Molina Grima and co-workers (2003) discussed the economics and options for microalgal biomass recovery, and concluded that for commercial recovery of high-value products, centrifugation appears to be the preferred method for recovering biomass from broth. In the case of fragile microalgae, microfiltration stands as a suitable alternative.

More recently, Uduman *et al.* (2010) claim that microalgae dewatering is a major obstruction to industrial-scale processing of microalgae, as the dilute nature of harvested microalgal cultures creates a significant operational cost during dewatering, and there is no superior method of dewatering microalgae. Efficient techniques, that may result in a greater algal biomass, may have drawbacks, such as a high capital cost or high energy consumption.

3.2 Technological discontinuities and dominant designs

The technological evolution of open ponds or raceways has not been characterised by noticeable design changes. The innovations have been in an incremental way, and focused on small technical details such as pumping, paddle configurations or isolation materials.

Open systems present a low technological complexity, in contrast with closed systems. Apart from the previously mentioned closed systems, commercial companies for microalgal products have developed many new technical systems for biomass production, which might be considered as technological discontinuities, as all technologies disrupted the concept behind the open systems technologies.

The concepts of technological discontinuity and dominant design were introduced in Chapter 1. In Figure 12, it is possible to find a technological track record of radical innovations in MPS during the last two decades. Some technologies are quite original, such as biocoil and dome, and present a different set of engineering and scientific principles that characterise a technological discontinuity.

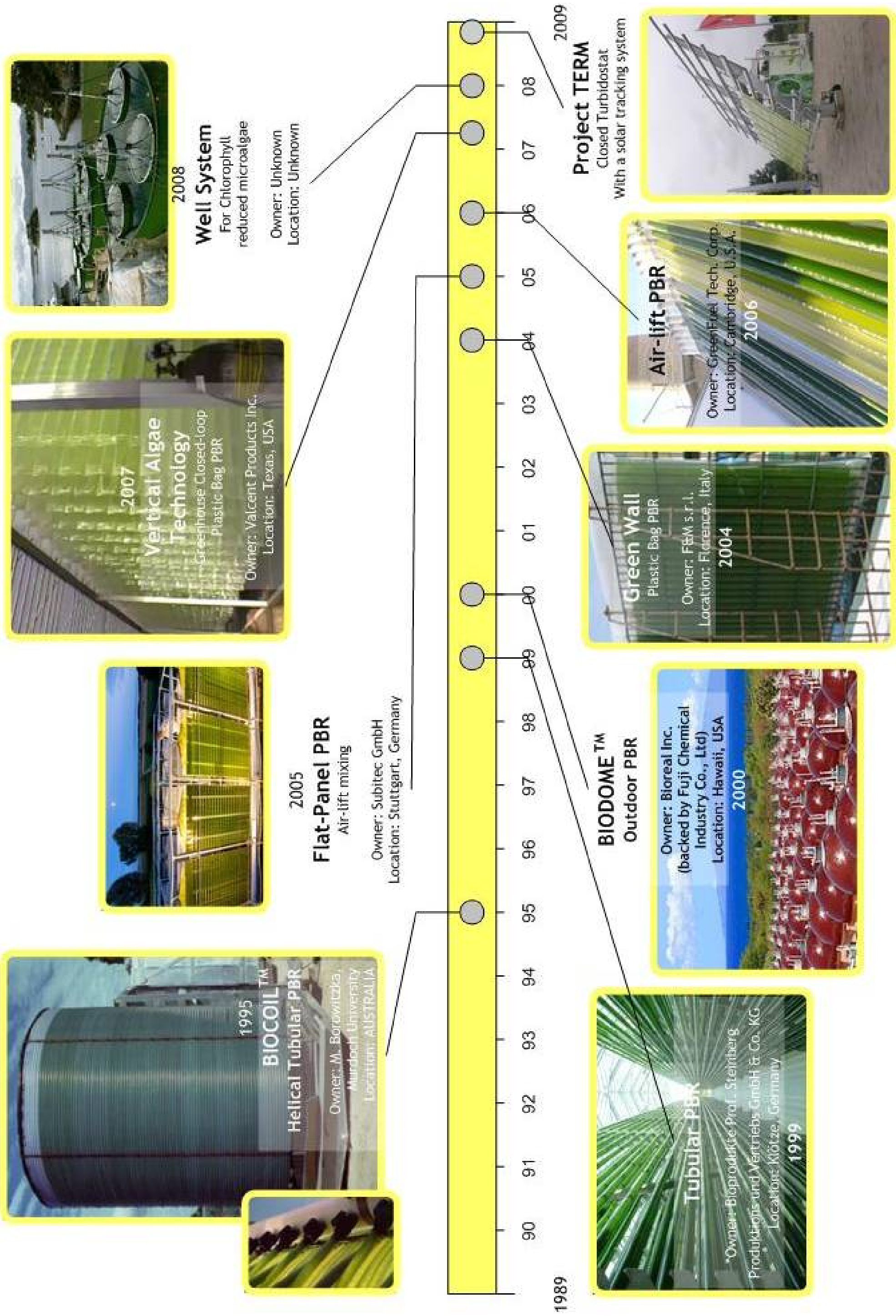


Figure 12 – Technology discontinuities of MPS.

If attention is paid to the technological discontinuities shown in Figure 12, it is clear that technological innovation in MPS has not followed a clear pattern, possibly because biotechnology has a higher degree of complexity than other types of MPS.

The last two decades were quite active from an innovation point-of-view. The technological developments have been, and still are, driven by a clear objective of better controlling cultivation conditions. Nowadays, many of these technologies have been abandoned. In fact, tubular PBR is now the dominant design for closed systems, as almost all microalgae producing companies use this type of technology. Vertical arrangements of horizontal running tubes or plates seem to be preferred for reasons of light distribution and appropriate flow (Pulz, 2001).

The potential of microalgal biotechnology with the existing MPS is tremendous, but to date applications have fallen short of expectations, and many commercial companies, with significant investments, have failed. The large ponds and PBR, that should demonstrate such cost reductions, have not yet been constructed, or have failed commercially and technically soon after start-up (Tredici, 1998). More recently, Beneman (2008) described four commercial failures. In 1989, the 1 ha PBR production unit in Spain was shut down, after two weeks of operation. Another example is the company Algatech, in Israel, which installed 1 ha of *Haematococcus pluvialis* growth for astaxanthin production, and is only sporadically in operation. The third example is a commercial photobioreactor unit in Germany for *Chlorella* production, that also went broke. The last example of non-viable systems was a commercial covered greenhouse pond system for *Spirulina* production in China.

Most of these cases failed due to errors in process design and over-estimations for both closed and open system, predominantly due to many of the assumptions on yield and costs being extremely optimistic (Beneman, 2008). Therefore, learning from the mistakes of others is a starting point for more advanced KM strategies. It is of great utility for future newcomers and policy development in marine biotechnology to take into consideration the basic requirements for further technology development.

3.3 Basic requirements for technological development

In order to improve the future economies of microalgal cultivation, regardless of the type of application, some issues should be taken into consideration with plant design. General factors to be considered include the biology of the microalga, the cost of land, labour, energy, water, nutrients, climate (if the culture is outdoors) and the type of final product (Borowitzka, 1992).

Nevertheless, selecting a suitable geographic region for project unit construction is a significant decision step to be taken before process design. Therefore, prior to any techno-economical analysis, there are basic requirements that should be included in the analysis to avoid unnecessary costs after the installation is running, or at worst a complete project failure:

- An abundant source of fresh and/or marine water will reduce costs with culture medium production;

- Microalgae are photoautrophic and light is a limiting growth factor. Microalgae absorb light differently and light absorption is a wavelength dependent phenomena. The culture should be exposed to a sufficient amount of light energy for efficient biomass production. The magnitude of solar radiation is dependent on the geographical position on Earth and the climatological conditions at that position (Janssen, 2002);

- For open-culture systems, one should choose areas with low pluviosity and temperate weather, as these systems take advantage of natural sunlight and are totally subject to the vagaries of weather, unless some form of shading system is utilised;

- Refrigeration systems, such as spraying water on PBR or immersing tubes in cooling baths, functioning as heat exchangers, are required to control temperature in tubular PBR;

- In PBR a degasification reservoir should be included, as oxygen must be removed to prevent inhibition of photosynthesis and photo-oxidative damage;

- Biofouling causes light intensity reduction and increases contamination crashes, but cleaning procedures may cause abrasion and limit PBR life-time;

- The number of species that can be grown in open ponds and raceways is limited, thus reducing plant production flexibility.

3.4 Techno-economical comparison between open systems and closed systems

From a technological point-of-view, there are major drawbacks to open systems, that in the end cause low productivity rates, such as significant evaporative losses, diffusion of CO_2 to the atmosphere, contaminations, light limitation, and the need for large production areas. In opposition to open systems, closed systems present some fundamental technological benefits, such as, reduced contamination risks, no CO_2 losses, reproducible cultivation conditions, controllable hydrodynamics and temperature, and flexible technical design (Pulz, 1992).

From the economical perspective, the most cost-effective way to farm microalgae is in open systems that present lower biomass production, investment and operational costs (*Table 8*), but higher harvesting costs than closed systems, due to low biomass concentration and better control over species and conditions.

Literature review revealed different orders of magnitude for production costs: i) Tredici and co-workers (1998) claimed a “relatively low cost” of 50 US$.m^{-2} for a PBR system; ii) estimates for the production costs of algal biomass in PBR ranged from 30 to 70 US$.kg^{-1}(Moore, 2001; Molina Grima *et al.*, 2003; Olaizola, 2003); iii) Chisti (2007) projects a cost of 2.85 US$.kg^{-1} for PBRs, based on the assumption that economies of scale will reduce costs significantly.

Table 8 – Techno-economical comparison between open systems and closed systems, adapted from several authors (Vonshak, 1997; Moore, 2001; Pulz, 2001; Olaizola, 2003; Molina Grima *et al.*, 2003; Chisti, 2007). Chisti (2007) used for estimation a 100 ton raceways biomass production facility with 8 units of 978 m^2/pond (pond dimension: 12 m wide, 82 m long, 0,30 m depth) and a 100 ton PBR biomass production facility with 6 units of 132 parallel tubes/unit (tube dimension: 80 m long, 0,06 m of diameter).

Parameters or issues		**Open systems**	**Closed systems**
Technical	**Temperature**	Highly variable	Cooling often required
	pH	Hardly controlled /specie specific	Controlled and specie specific
	Oxygen concentration	Low	Gas exchange devices required
	Biomass conc. broth [g.l^{-1}]	0.1 - 0.5 (low)	2 - 8 (high)
	CO_2 consumption [ton]	183,33	183,33
	Shear	Low	High
	Required space [m^2]	7.828 (high)	5.681 (low)
	Production flexibility	Low	High
	Cleaning	No issue	Required
	Water losses	Very high	Low
	CO_2 losses	High	Low
	Process control and reproducibility	Limited	Possible
	Startup [weeks]	6 – 8	2 – 4
Quality-related	**Contamination risk**	High	Low
	Biomass quality	Variable	Reproducible
Others	**Weather dependence**	High (light intensity, temperature, rainfall)	Medium (light intensity, cooling required)

Parameters or issues	**Open systems**	**Closed systems**
Biomass production cost [$.kg^{-1}]	3,80 – 11,00	2,85 – 70,00
Capital costs	High	Very high
Operating costs	Low (paddle wheel, CO_2 addition)	Very high (CO_2 addition, pH-control, oxygen removal, cooling, cleaning, maintenance)
Harvesting cost	High, species dependent	Low

Among closed systems, the dominant design is the tubular configuration, but the scalability of this MPS has generated some contradictory positions: i) Molina Grima and co-workers (1999) claimed that “of the many types of PBR proposed for closed monoculture, tubular devices are amongst the more scaleable and suited to large-scale production"; ii) Ogbonna and Tanaka (1997) find that tubular PBR do not work well in large-scale production, as dissolved oxygen levels easily increase, leading to oxygen poisoning, since photoinhibition results from the excess light exposure, because the surface-to-volume ratio is lower, causing poor light absorption. Length of tubes is another matter of concern for tubular PBR. As the length of the tubes gets larger, the time for microalgae exposure to light increases. Hence, increasing the absorption of available carbon dioxide and increasing photosynthesis rates.

3.5 Future challenges

Microalgal biotechnology has evolved as a significant manufacturing tool for products like pigments, fatty acids and polymers, but most of these items are still products for specific applications and sectors. Current development projects, including those focused on biofuels, indicate that microalgal biotechnological processes and products may soon approach the market place in a radical different way. The recent, and hopefully future, achievements in different fields will boost microalgae to compete with other raw materials of chemical or agricultural origins.

Besides the basic requirements for MPS development, the different operating strategies (Enes and Saraiva, 1996), and the techno-economical limitations of each type of technology, the technological progress is continuously challenged. Table 9 summarises our perspective about future challenges of the microalgal biotechnology sector. An example of an interesting challenge would be to accomplish the extraction of compounds from microalgae without cell disintegration. Hejazi and Wijffels (2004) have actually proposed and tested the process "milking of microalgae" for the microalgae *Dunaliella salina*, to achieve a selective extraction of β-carotene from microalgae. Another example would be to use the concepts of cell-to-cell communication, discovered and described over 30 years ago for two marine bacterial species. Quorum sensing (QS) is a phenomenon where microorganisms communicate and coordinate their behaviour by the accumulation of signalling molecules, and quorum quenching can be considered the opposite mechanism, where inhibition of QS signalling molecules occurs by degradation enzymes. A similar process probably exists in microalgae, as for example in Necton it was observed that in the case of microalgae *Nannochloropsis*, when it reaches a certain cellular concentration, no contaminations seem to occur.

Table 9 – Future challenges in microalgal biotechnology sector.

Technological and knowledge challenges in	
Materials	• Development of materials with selective porosity (for instance, to inlet of CO_2 and to outlet of O_2).
Separations techniques	• Usage of nanoparticles to separate cells from culture medium.
Extraction techniques	• Milking the microalgae for high value compounds extraction. • Development of more economic and ecological solvents than the ones currently used in industry.
Energy exploitation	• Development of photons capture processes. The photobiology of microalgae is quite complex: on one hand, excess of light damages cells, but on the other hand, loosing photons can be considered an energy waste. • Reduction of energy used to created turbulent hydrodynamics.
Cultivation systems	• Development of new production systems (for instance, offshore cultivation of microalgae).
Species selection and genetic modification	• Enhancement of biomass productivity and/or of a particular product, without loosing stability. • Inducing heterotrophy in microalgae. • Nucleic acids reduction, as high nucleic acid content is an important factor limiting the nutritional and toxicological value of microalgae.
Policultures	• Mixed cultures of microalgae.
Quorum sensing and quorum quenching	• Control communication between cells to synchronize multiplication and fight contaminations.
Market and business models challenges	
Feed market	• Acceptance of microalgal biomass as feed for animals.
Health food market	• Acceptance of microalgae as edible biomass, no longer needing application to “Novel food ingredient”.
Strategic shifts	• Specialisation of companies, that once produced components for other industries, in MPS application.
Biorefinery concept	• Integration of biomass conversion processes and equipments to produce fuels, power, and chemicals from biomass.

Chapter 4 Results and discussion

Learning from microalgae

Observing, analysing and reengineering the MPS, in order to apply knowledge and experience accumulation in technological adaptations, is constantly required for microalgal growth optimisation. Therefore, the deeper the knowledge is, and the broader the experience, the better technologies will work out. For that reason, Necton is an interesting case-study, as it has been producing microalgae, in a large-scale, since the year 2000.

For the purpose of the present study, only one biotechnological perspective was explored, regarding the fact that MPS technological performances are largely affected by environmental parameters. In order to understand how environmental factors may have affected the biomass productivity, some parameters were studied. The environmental parameters analysed, from the year 2003 to the year 2008, were pluviosity (measured in mm), total number of hours that cultures are exposed to sunlight, irradiation of the production site (measured in $Wh.m^{-2}.day^{-1}$), the quantity of rainy days, thermic amplitude (measured in ºC), average monthly temperature, average maximum and minimum temperatures (measured in ºC).

Data, regarding environmental parameters, is compiled in Appendix A. In Table 10 are summarised the minimum and maximum values observed of each parameter, as well as the month and year of the observation.

Table 10 – Ranges of the different environmental parameters.

	Parameter Range			
Environmental parameter	**Minimum Value**	**Month / Year**	**Maximum Value**	**Month / Year**
Pluviosity (mm)	0,0	several	193,8	Nov / 2006
Sun-hour (#)s	8,0	Dec / 2004	14,7	Jun / 2007
Rainy days (#)s	0,0	several	18,0	Oct / 2003
Irradiation (Wh.m^{-2}.day^{-1})	2.124,0	January	7.507,0	July
Thermic amplitude (ºC)	6,9	Oct / 2006	11,1	Jul /2007 and Jul / 2008
Average Monthly Temperature (ºC)	10,5	Jan / 2005 and Feb /2005	25,6	Aug / 2005
Average Maximum Temperature (ºC)	14,6	Jan / 2006	31,1	Jul / 2006
Average Minimum Temperature (ºC)	5,5	Feb / 2005	21,0	Aug / 2003

Monthly biomass productivities per year and average productivity per month of operation of the FPFT PBR[16] are represented in Figures 13 and 14.

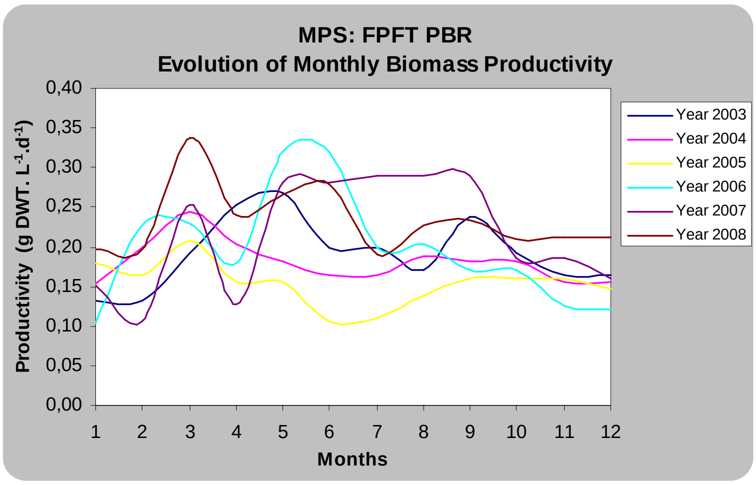


Figure 13 – Representation of monthly evolution of biomass productivity on FPFT PBR (2000-2008). DWT stands for dry weight.

[16] Eventhough a similar treatment was applied to data regarding tubular PBR, and as results are identical to the ones obtained from the operation of FPFT PBR, for that reason they were deliberately excluded from our work.

The graphical representation of the monthly productivity, along each production year, shows that, from March to September, biomass productivities are higher, and that, from October to February, they appear to be lower. From Table 10, it is possible to identify that the months with more irradiation, more sun-hours, less thermic amplitude, and higher minimum and maximum temperatures, are those that provided better conditions for growing microalgae. Once again, this general behaviour may be an evidence of the contribution of several environmental factors for the biomass productivity.

The best productivity, achieved during the analysed data, was in the year of 2008, during the month of March, with 0,34 g $DWT.L^{-1}.d^{-1}$. On the other hand, the worst productivity was found to have occurred in the month of January of the year 2006, with a monthly productivity of 0,10 g $DWT.L^{-1}.d^{-1}$.

If we pay attention to Figure 14, we may conclude something similar, the month that presents lower productivities is January, and the months with higher productivities are March and May.

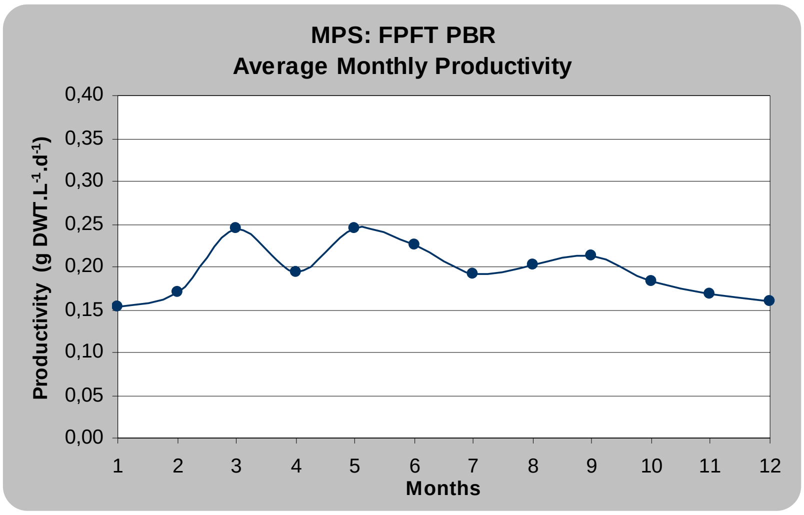


Figure 14 - Representation of average biomass productivity per month on FPFT PBR (2000-2008). DWT stands for dry weight.

This analysis would not be complete, without understanding which environmental factors contribute more to the biomass productivity. A multivariate regression was applied to environmental data, using the Least Square Regression Model available as a curve fitting routine of Excel Program 2003, in order to understand how the environmental factors are correlated with biomass productivity. The equation that returned the best fit, from several combinations tested, was found to be the one that correlated four explanatory variables (thermic amplitude, average monthly temperature, irradiation and number of sun-hours) with productivity. The resulting equation is expressed in (7):

$$BP = 0{,}7215 - 00{,}0235.Sun - 0{,}0063.Irra + 0{,}0001.AverT - 0{,}0463.TA \qquad (7)$$

Where *BP* corresponds to biomass productivity, *Sun* to number of sun-hours, *AverT* is the average monthly temperature, *Irra* is the irradiation of the production site, and *TA* is the thermic amplitude registered. The curve fit has a reasonable coefficient of determination (R^2) of 0,78. Therefore, it is possible to conclude that the biomass productivity depends of those environmental factors. The regression model application is compiled in Appendix E.

In general terms, microalgae grow better when temperatures are around their optimal temperature (25ºC), when the thermic amplitude between night and day is as low as possible, and when cells are optimally exposed to light, without being affected by photoinhibition or scarceness of light. Some authors have claimed that, in all cases, the key issue for success in biotechnological solutions for optimum growth, besides the creation of turbulent regimes in cultures, is light (Tredici, 1999; Tredici, 2010). Therefore, and eventhough the correlation between environmental parameters with the variable *BP* was expected, it would be worth exploring another mathematical tools. The purpose of this approach is to determine whether it is possible to predict more accurately the biomass productivity, including not only the environmental factors, but, if possible, to estimate the contribution to the productivity of the daily operation procedures, optimised trough learning and knowledge accumulation.

If we consider again the example of the month of March, that provided the conditions to achieve the best productivity registered. The most relevant environmental conditions do not significantly vary from one year to the other on the month of March. As a matter a fact, the number of sun-hours vary from 11,9 to 12,0, the irradiation is practically the same, the thermic amplitude ranges from 7,3 to 10,3, and the average month temperature vary from 14,3 to 15,3 ºC. Therefore, it is possible to assume that the learning effects, embodied in the everyday production routines, result in productivity gains (*Figure 15*).

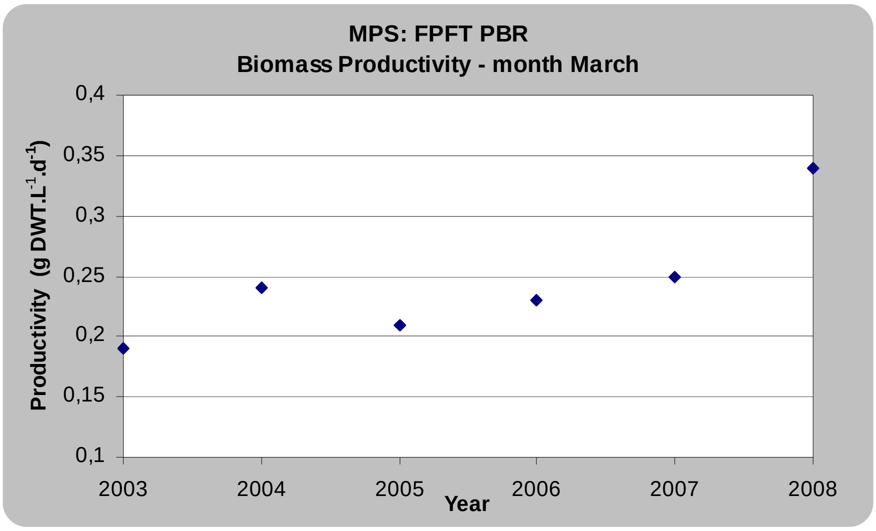


Figure 15 - Representation of biomass productivity per year on the month of March in the MPS FPFT PBR (2000-2008). DWT stands for dry weight.

The MPS configuration of Necton allows us to establish a set-point for controlling the temperature, activating coolers (water sprinklers) whenever temperature increases over 25ºC, and inactivating them when the culture temperature is bellow 25ºC**.** The results obtained demonstrate that just as cultures are cooled down, whenever temperature rises above 25ºC, one might in the future consider the possibility of having a heating system that warms culture in wintertime, in order to maximise technology performance, thus producing more biomass. Another technological improvement would aim to increase the numbers of hours of exposure to light, using artificial lamps during winter, or even during the night, to enhance the photosynthetic processes.

For closed PBR placed outdoors, controlling the environmental conditions may be technologically difficult. Indeed, microalgae production managers are farmers, and microalgae cultivation is affected by environmental parameters as much as crop cultivation is.

The biomass produced highly depends of market demand. As Necton mainly provides biomass for the aquaculture sector, it is possible to see that the demand cycle is overlapped with the microalgae production cycle (*Figure 16*). Hatcheries need microalgal biomass for growing their fish, from the month of October to the month of May; therefore, the production of microalgae decreases after May, and slowly increases again to supply the customers, around October.

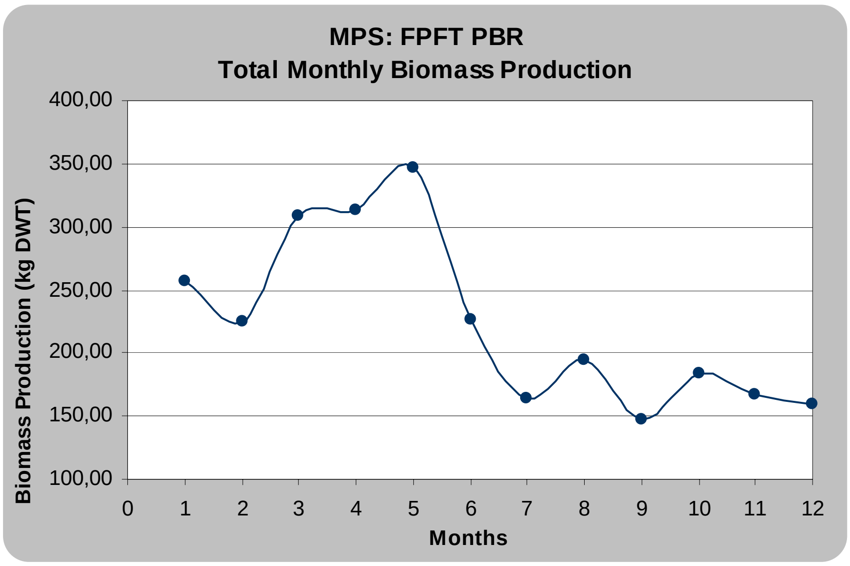


Figure 16 - Representation of total biomass produced per month on FPFT PBR (2000-2008).

Learning from producing

From the literature review, many different positions stand against EC, claiming that costs, if not managed, will obviously tend to rise. In our case-study, it was evident that experience effects have been achieved in the daily operation of the different MPS in Necton´s production site, resulting from a concerted effort by all those involved in production activities, and experience gained by workers.

From our data analysis, regarding total biomass produced along the operation of FPFT, a production shortfall was detected in the year of 2005, pointing out an interruption in the learning process. The MPS performance severely decreased, around 60%, from performance achieved on the year of 2004 (*Figure 17*).

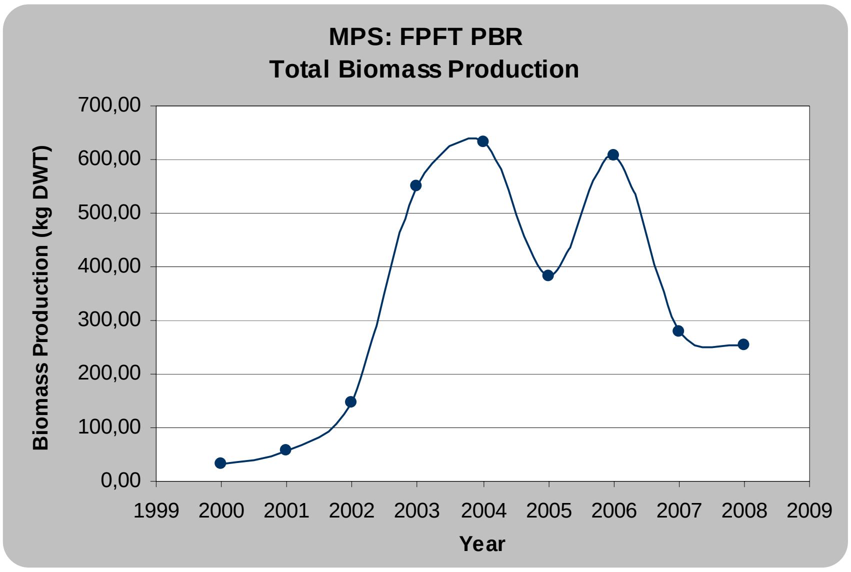


Figure 17 – Biomass production in FPFT (2000-2008). DWT stands for dry weight.

The reason for this event was not clear in production records, and consequently was brought up along the interviews. Apparently, the production manager was on a leave for several months, and therefore production routines and practices were significantly altered. Therefore, the experience gained through years of production seems to be somewhat retained by key staff people. Moreover, knowledge and experience accumulation seems to rely in individuals, and not really possessed by the organisation. Obviously, that this issue would be worth to studying from a KM point-of-view, as modern organisations should embody knowledge, in order to promote inner knowledge fluxes between workers within the organisation, never depending so much on knowledge of individuals.

Experience curve of Microalgae Production Systems

Data regarding biomass produced in FPFT and tubular PBR were applied for the EC determination. The curve of 'unitary cost vs cumulative units produced' for the technology FPFT PBR clearly follows an EC. As cumulative units produced increase, the unitary cost of producing them declines. As a result, the experience accumulated over 8 years of industrial production in the technology FPFT is reflected in Figure 18.

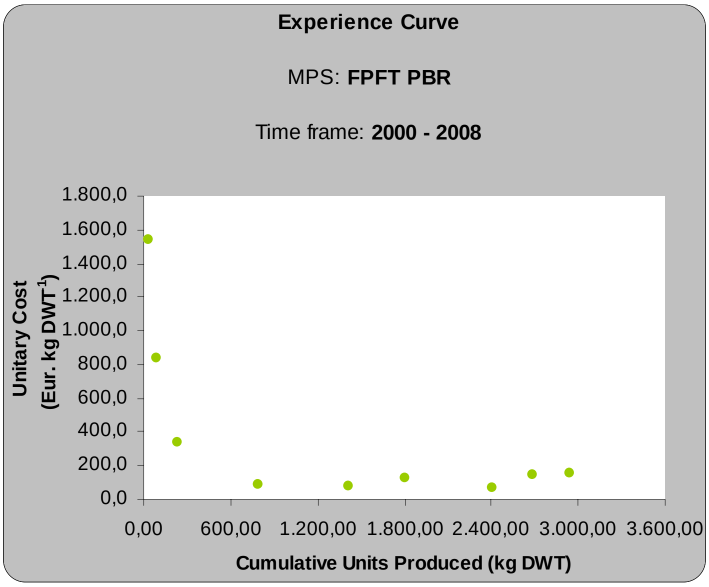


Figure 18 – Experience curve of FPFT PBR (2000-2008). DWT stands for dry weight.

From Figure 18, it is possible to observe that unitary costs appear be at their minimum, and the production capacity of the production plant appears to have reached its maximum.

Since the operation period is shorter for the case of the tubular PBR, was only in operation from year 2006 to the year 2008 the curve does not show the same behaviour of the observed in the EC of the FPFT PBR (*Figure 19*).

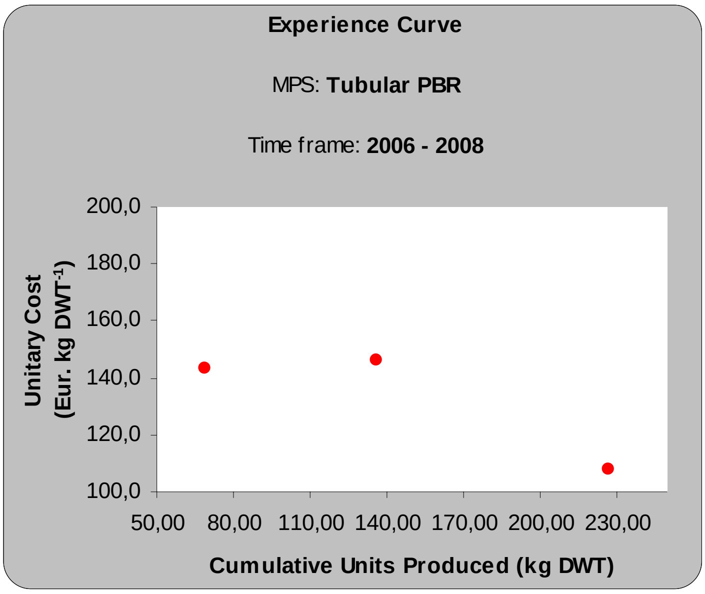


Figure 19 – Experience curve of tubular PBR (2006 - 2008). DWT stands for dry weight.

All data regarding the FPFT (*Figure 20*) and tubular PBR (*Figure 21*) were logarithmised and they are represented in a log-log scale graph.

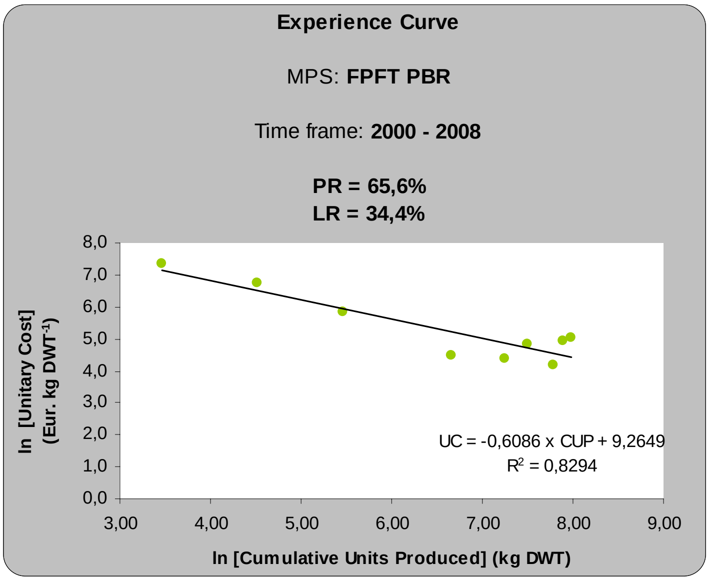


Figure 20 – Experience curve in a log-log scale of FPFT PBR (2000-2008). DWT stands for dry weight.

As data provided from Necton were obtained in a real-context situation, and EC should be a representation of the real behaviours, no data were considered as outliers, what caused a reasonable coefficient of determination (R^2) of 0,83.

The overall PR value is 65,6 %, while LR is 34,4%. This PR means that costs decreased by 34,4% for each doubling of cumulative production. Considering that MPS is a biotechnological system that naturally embodies biological and environmental factors that are difficult to control, PR score lies in between the ones determined for manufacturing firms (Dutton and Thomas, 1984) and energy technologies (McDonald and Schrattenholzer, 2001) that range from 60% to 100%.

A trend may be identified in the operation period [2000 – 2004] is selected: the PR is much higher in the initial technology life-cycle, showing a PR of 94,3%, with very good curve fit (R^2 = 0,98). These results show a very important fact that is that the initial difficulty of learning something and, to an extent, how much there is to learn after the initial familiarity, and that experience accumulation is still in its beginning. The reasons for the early phase of commercial deployment presenting relatively low learning rates are typically linked to shortfalls in performance and or reliability that result from insufficient experience for scale-up and from new problems that arise during full-scale and operation. This observation was also identified elsewhere (Yeh *et al.*, 2009).

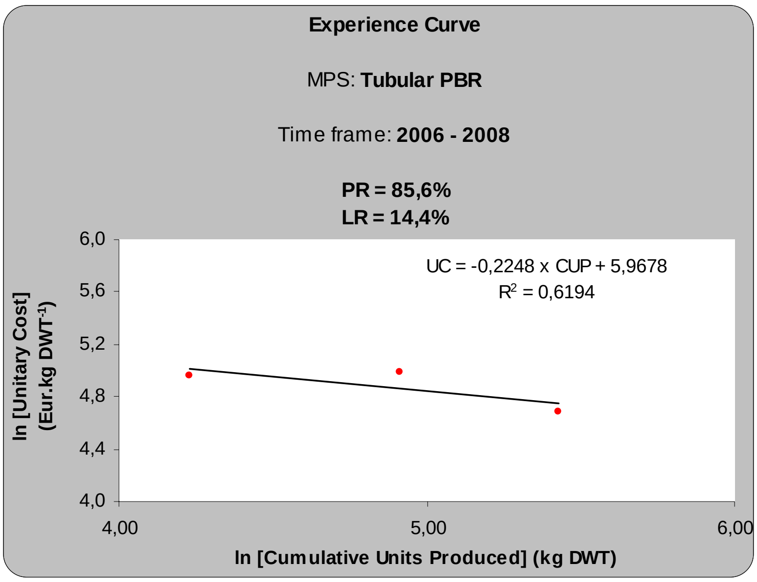


Figure 21 – Experience curve in a log-log scale of tubular PBR (2006-2008). DWT stands for dry weight.

The overall PR of the tubular PBR value is 85,6 %, while LR is 14,4%. This PR means that costs decreased by 85,6% for each doubling of cumulative production. As the tubular PBR was installed few years after the FPFT PBR, the technological learning happened faster, benefitting from the past learning and experience accumulated.

Both EC of MPS were determined using the labour costs for calculating unitary production costs. The resulting curves could be termed as pseudo-EC as they reflect only the costs that mainly contributed to production costs. Based on the interviews and some records, it was possible to detect that, and in the case of MPS: a) the major variable cost is the supply of carbon dioxide to the culture; b) major fixed costs are labour costs, approximately 80% of all fixed costs. If all the costs, both fixed and variable, were provided, the behaviour of the curve would be identical, but plotted in the y-axis with higher unitary costs. As PR are calculated using the slope of the log-log curve, the slope would be the same if unitary costs were higher.

Eventhough there is no natural law requiring production costs to follow an EC (Junjinger, 2005), it has been observed with experimental data that the performance of MPS increased substantially as producer gained experience with technology. Moreover, when new production technologies are implemented in the same production site, as the tubular PBR was built 6 years after the FPFT begun to be operated, the PR value is higher, revealing a process of experience accumulation that provided an improvement of performance when the subsequent technology was implemented (*Table 11*). In other words, the MPS of the case study do follow an EC.

Table 11 – PR and LR of FPFT and tubular PBRs.

Closed System			
FPFT PBR		**Tubular PBR**	
Progress ratio (%)	**65,6**	**Progress ratio (%)**	**85,6**
Learning rate (%)	**34,4**	**Learning rate (%)**	**14,4**

A drawback pointed out by several authors (IEA, 2000; Van Saark, 2008) is related to the fact that the effects of learning and scale are often overlapped in the EC, which complicates the analysis of technology development and the determination of the advantages of the experience accumulation. Luckily, in the case-study presented, scale-up has not taken place. Therefore, the EC is the result of the combined effect of different learning mechanisms in the integral learning process.

Experience curve: open and closed MPS

As pointed out in Chapter 3, within the multitude of technical solutions for microalgal cultivation, one can basically distinguish between open systems and closed systems. Even though both types of technology aim to produce microalgae, the techno-economical framework of each technology is so different that one inevitably raises the question if the EC of each type of system can be similar.

The production available data (Vonshak, 1997; Sánchez *et al.*, 2003), regarding open systems, and data extracted from Necton´s production reports, reveal different rates of learning. Data was plotted in a linear scale graph, showing temporal evolution of the total biomass production per installed capacity (TP) of open systems and closed systems (*Figure 22*).

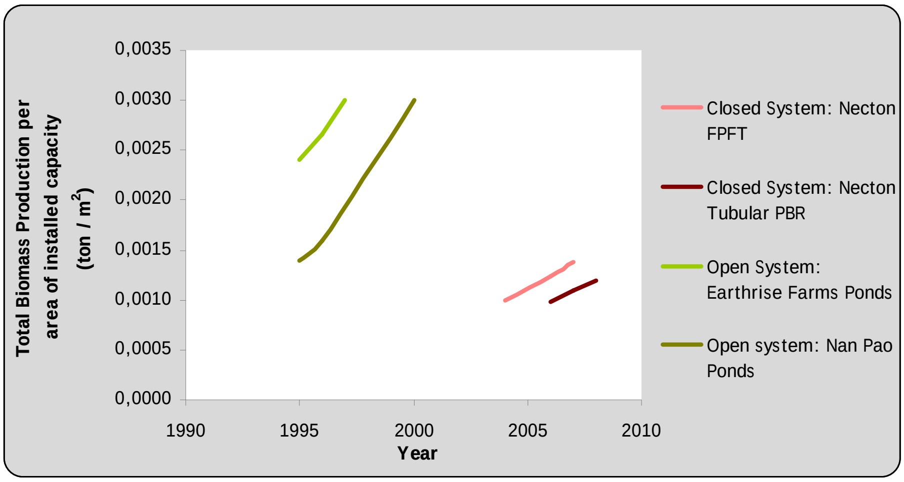


Figure 22 – Production improvement of open systems and closed systems.

Despite data scarceness, a learning process underlies all curves. In all cases, companies managed to increase production along time with the same installed capacity. Besides this fact, the production improvement ($\frac{\Delta TP}{\Delta t}$) was found to be the same among technologies belonging to the same production system, and higher in the case of 'open systems' (*Table 12*).

Table 12 – Production improvement of open systems and closed systems.

Production Improvement			
Open System		**Closed System**	
Earthrise Farms Ponds	$\frac{\Delta TP}{\Delta t} = 0{,}0003$ Equation: TP = 0,0003 x t – 0,5961 $R^2 = 0{,}9959$	**Necton FPFT**	$\frac{\Delta TP}{\Delta t} = 0{,}0001$ Equation: TP = 0,0001 x t – 0,2566 $R^2 = 0{,}9962$
Nan Pao Ponds	$\frac{\Delta TP}{\Delta t} = 0{,}0003$ Equation: TP = 0,0003 x t – 0,6542 $R^2 = 0{,}9944$	**Necton Tubular**	$\frac{\Delta TP}{\Delta t} = 0{,}0001$ Equation: TP = 0,0001 x t – 0,2116 $R^2 = 0{,}9989$

One fact may have conditioned these results. Pond production is a closed production system that has been used extensively since the 70´s. Therefore, pond production is a more mature technology, in comparison with closed systems, showing production improvements greater than those belonging to the closed systems. Another possible explanation would be that open systems are generally simpler in terms of configuration, operability and maintenance, and learning with the technology might be easier in the initial phase than with we closed systems. Nevertheless, more data regarding intermediate technology phases would be needed to support both reasonings.

Advances in installed technology, measuring methods and process redesign might have contributed to sustained improvements in biomass production. If only production costs were known, an EC could be drawn, and it would be possible to confirm what appears to happen, i.e. open and closed MPS do not follow similar curves, as production improvements are different.

Learning effects in MPS

Technology development is characterised by various stages, from invention to implementation. In each of these stages, different learning mechanisms play a role that lead to technological change and result in cost reductions described elsewhere (Neij *et al*., 2003; Junginger, 2005). Necton is an unique case, in terms of industrial knowledge, as it has undergone different technologies, such as raceways, GW, FPFT and tubular PBR.

The learning effects were considered to be those that led to: increased labour efficiency, work specialization and improvements of production methods, through learning-by-doing and learning-by-using; the use of new materials or the introduction of new, more effective production processes, through learning-by-searching mechanism; the improvement of the network interactions between providers, customers, research institutes, industry, end users, policy makers, etc., allowing for the better diffusion of knowledge, through a learning-by-interacting mechanism. Technical staff from Necton was questioned about whether they acknowledged the role of the learning mechanisms in the different life-cycle phases of technologies (growth, maturity, decline).

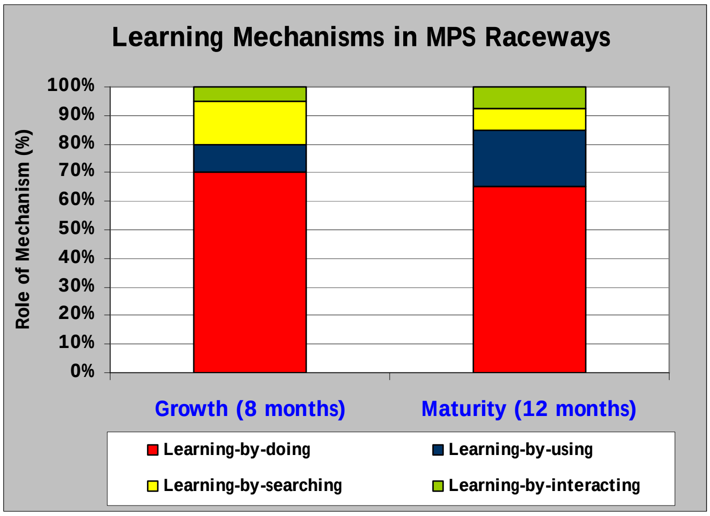


Figure 23 – Role of learning mechanisms in the MPS Raceways.

In the case of the raceways technology (*Figure 23*), there was an abandonment of the technology for market reasons, more than for technological restraints. The interviewees did not consider that the technology life-cycle was closed. The growth phase lasted for 8 months, and the learning mechanism with higher contributions to the learning process was learning-by-doing (70%), followed by learning-by-searching (15 %). The maturity phase had 12 months of duration. The role of learning-by-doing was considered relevant (65%), but the role of learning-by-using substituted learning-by-searching, with 20%, at this stage.

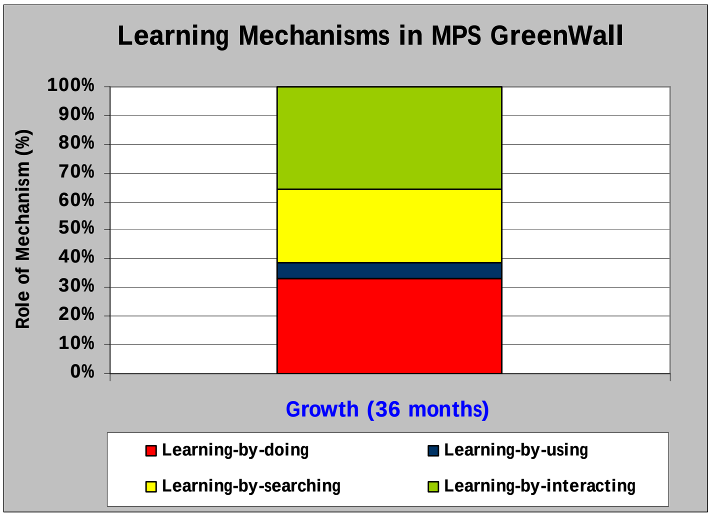


Figure 24 – Role of learning mechanisms in the MPS GreenWall.

In the case of GW technology, it was clear to all technical staff of Necton that this technology is not yet dominated, and is still in its growth phase (*Figure 24*). The learning mechanisms that were identified as being more relevant to the learning process, were learning-by-interacting (36%), learning-by-doing (33%), and learning-by-searching (23%), so that acquiring "know-what", trough the learning-by-using mechanism, played a minor role in its technological development.

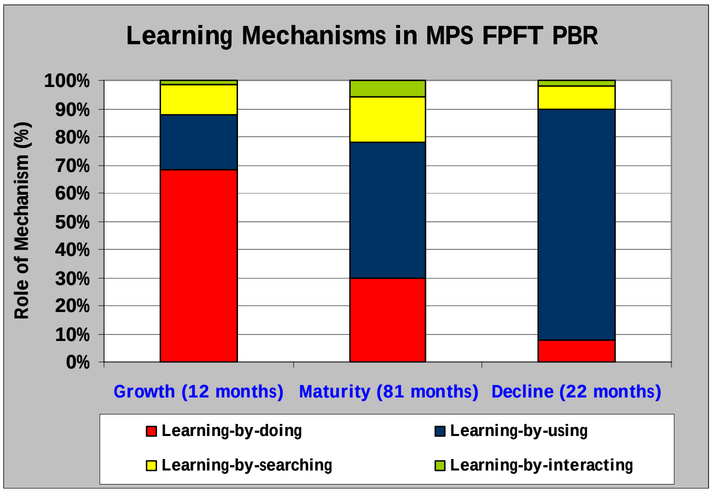


Figure 25 – Role of learning mechanisms in the MPS FPFT PBR.

Figure 25 depicts the overall life-cycle of FPFT PBR MPS. From phase to phase, while the role of learning-by-doing diminishes, starting in 68% and ending in 8%, the role of learning-by-using increases in importance, from 20% to 82%. The growth phase lasted for one year, followed by a long maturity phase of almost eight years. Interviewees acknowledged that technology utilisation is now declining. In the interviewees' opinion, the reasons for this decline are related with an important aspect of technology: cleaning and maintenance are complicated, diminishing the time that PBR are in operation, and, as a result, yearly productivity decreases. This technology will be replaced by tubular PBR, that does not evidence those kinds of operation constraints. This event will generate not only a technology discontinuity in the firm´s technical progress, but also it is clear that a dominant design will arise within the firm's context. This fact is in accordance with the present worldwide trend to use tubular PBR in microalgae cultivation.

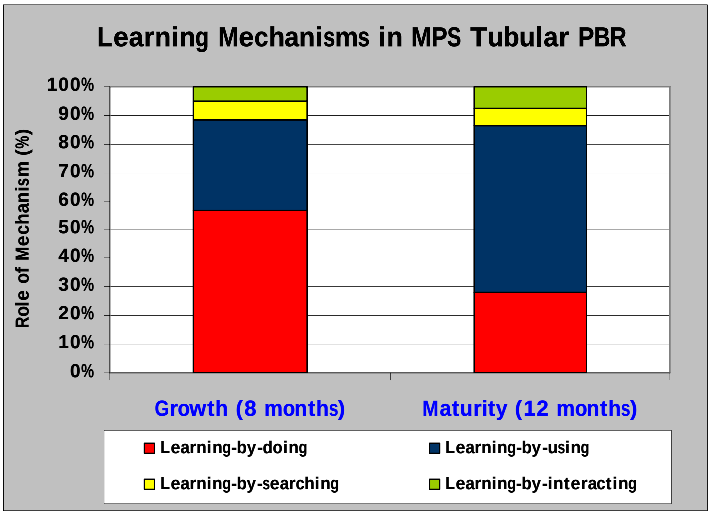


Figure 26 – Role of learning mechanisms in the MPS tubular PBR.

The tubular PBR is the most recently installed technology. The technological development has profited from many years of experience in microalgae production, a fact that is observed in a short life-cycle phase of growth (*Figure 26*). In less than a year, the technology was considered by interviewees as being dominated. Another consequence of knowledge and experience accumulation is that the learning-by-searching role is residual, showing that the learning mechanisms related with more practical aspects of learning, the learning-by-doing and the learning-by-using mechanisms, have played a relevant role in this technology development.

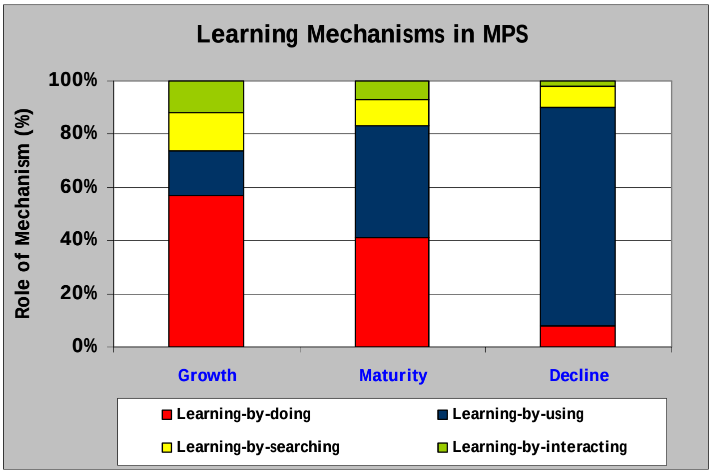


Figure 27 – Role of learning mechanisms in the MPS tubular PBR.

If the contributions of the learning mechanisms, during each technology life-cycle, are integrated in one graphical representation (Figure 27), it is possible to conclude that: i) in the initial growth phase, the most important learning mechanism is learning-by-doing; ii) when the technology reaches maturity, the contribution of the role the learning-by-using surpasses the importance of the learning-by-doing mechanism; iii) in the decline phase, the learning-by-using mechanism is still the most active one.

Chapter 5 Conclusions and future studies

Microalgae are, perhaps, the largest remaining biological resource for the biotechnology industrial sector in the years ahead, but the high cost of microalgae production remains an obstacle for scientific, technical and commercial viability progress. Therefore, the cost-effectiveness of industrial size MPS should deserve full attention by researchers, in a genuine effort to contribute to one of the most important themes for the future of microalgal biotechnology.

Within our work, a case-study research strategy was proposed in order to understand the effects of learning and experience accumulation in technology development. The case-study corresponds to a firm dedicated to microalgae production. Since the year of 1997, Necton has installed, developed and operated several MPS, both open and closed systems with different designs.

Microalgal biotechnology is a complex field with potential outcomes already identified herein, such as pigments, fatty acids, enzymes, or polymers. Through several decades of research, it is clear that the economic viability of microalgal biotechnology depends on being able to take advantage of low-cost, or even free, raw-material sources. For example, CO_2 sequestration from industrial gaseous effluents has been the *leitmotiv* of several R&D projects that aim to integrate this biotechnology on the waste treatment in heavy industries. Another example would be choosing a place for plant installation with nearby marine or freshwater sources. One more example is taking the most of environmental conditions of site location, and because of this, the complexity of this biotechnology also arises from the fact that performance of MPS is highly affected by environmental factors.

The techno-economical comparison between open and closed systems, presented in our work, has not pointed out one preferable technology to cultivate microalgae. The most cost-effective way to cultivate microalgae is in open systems, but only few microalgae may grow in these systems. A better control over microalgae species and growth conditions are reached in closed systems. The dominant design of closed MPS appears to the tubular PBR. The process of finding this design has left behind some interesting technological configurations, such as the biocoil PBR or the dome system, and has been the result of the interplay between technical and market choices.

The Algarve region, at the South of Portugal, where the company is located, provides the highest level of irradiation in Europe, and from the environmental data analysis carried out, the month of May was found to be the one that provided better conditions to cultivate microalgae, with an average productivity of 0,25 $g.L^{-1}.d^{-1}$. On the other hand, January was the worst month for microalgae cultivation, with an average yearly productivity of 0,15 $g.L^{-1}.d^{-1}$. Therefore, and eventhough the control of environmental conditions of closed PBR, that run outdoors, is possible but complex, microalgae production resembles crop cultivation, very much depending on environmental conditions and on farmer's capacity to "learn from microalgae".

In the present work, the underlying definition of technology performance is the quantity of biomass produced. Therefore, whenever a particular situation caused a decrease of biomass produced, it was considered that technology performance was affected. The MPS performance was affected by other factors that are exogenous to technology. Those factors are quite interesting from the KM point-of-view. First, MPS performance was found to be deeply dependent upon the practices and procedures of the production manager. Therefore, knowledge and experience is somehow rooted in individuals, and not in the organisation. The KM challenge for a modern organisation, even for SME, is endeavouring to endogeneise knowledge, trough the codification of tacit unwritten knowledge, as much as possible. Second, MPS performance is clearly affected by market instability, as product demand decreases, production management attempts to lower biomass produced, in order to avoid excessive stocks.

Along the interviews it was possible to confirm that the actual worldwide trend to use tubular PBR in microalgae cultivation is evident. Therefore, the tubular system is also a rising dominant design within the firm context, supported by strong techno-economical foundations, following the worldwide biotechnological trend.

In an attempt to understand technical complexity of microalgal biotechnology, the learning process, underlying technology development, was studied through different research questions: 1. Do the MPS of the case-study follow an experience curve? 2. Do closed and open MPS follow similar experience curves? 3. Do learning mechanisms play different roles across the MPS life-cycle?

In order to answer these questions, two methodologies were applied to the case-study. The first methodology was based on the EC concept, and its application aimed to answer whether or not the MPS followed an EC. The results showed an overall PR of the FPFT PBR of 65,6% and of the tubular PBR of 85,6%. A PR of 34,4% means that costs decreased by 34,4% for each doubling of cumulative production. Both PR obtained are in between the determined PR values for manufacturing firms (Dutton and Thomas, 1984) and for energy technologies (McDonald and Schrattenholzer, 2001), that range from 60 % to 100%. The answer to the first research question is that indeed the MPS follow an EC.

Therefore, several conclusions arise from this finding: a “regular” learning process occurred along technology instalment and operation; the EC found exclusively resulted from the learning effects experienced, as no scale effects occurred during firm’s activity; the learning and experience accumulation from previous technologies installation and daily operation (FPFT PBR) resulted in higher learning in subsequent technologies (tubular PBR). Eventhough the methodology was successfully applied, as progress ratios were determined, in the case of the tubular PBR, the longer the technology is producing, the better the curve fits the EC, and the overall learning process is better understood. Therefore, a technological surveillance should be set and more data from future production records should be incorporated in further studies.

For future research in this field, it would be interesting to know what is the goal, in terms of techno-economic performance of each type of MPS, or in other words, what is the maximum production that managers can aspire, and what is the best PR, and what scenarios may lead to it. These calculations could be pursued using the EC methodology as a cost-forecasting tool. For further work, there are some relevant guidelines that could support safe cost projections. For example, in order to compare costs from the past with current costs, the data has to be corrected for inflation (Junginger, 2005). Another example is related with the sources of data. If production costs are kept confidential, and often only prices are publicly available, prices can be used as a proxy for production costs under the condition that profit margins may assume to represent a fairly constant share of total prices (Junginger, 2005). Alberth (2007) also contributed some relevant considerations about cost analysis: researchers should only consider data from the best commercially viable plants; researchers should use as much data as possible, as the ability to forecast technology costs improves as more data are added; and, finally, researchers should include in the methodology a way of weighting data in such a way that recent data have stronger influence in forecasts.

The MPS were extensively herein described, in terms of technical aspects, operation and harvesting procedures, and even in terms of costs. Generally, MPS are separated in two different technology categories: open systems and closed systems. An effort to comprehend how experience accumulation affected performances was made, despite data scarceness. The production improvement was higher in the case ‘open system’ technologies, perhaps due to the low complexity of open MPS results on a faster learning process and better technology performance. Obviously, this interpretation is an educated guess that should be confirmed. Any attempt to validate this interpretation should consider that data from production records of firms that produce the same microalgae. In the case of open system, the microalgae was *Spirulina* sp., and in the case of closed system the microalgae was *Nannochloropsis* sp.. The comparison of different MPS producing different microalgae species largely contributes to an error, a ‘biological error’, as growing rates of microalgae are different. The analysis should be conducted in a different manner, for example using the microalgae *Haematococcus pluvialis*, which can be produced in open systems and closed systems, or at least comparing microalgae with similar growing rates, which is not the case of the microorganisms used.

As a result, the answer to the second research question is that is not clear whether the EC of open systems and closed systems are similar, but what is observable is that a different learning process underlies both types of MPS, as similar production improvements are observed in technologies of the same category.

The second methodology was set to understand the role of learning mechanisms in the life-cycle of several MPS technologies. Necton has installed and run four types of technologies: raceways, GreenWall, FPFT PBR and tubular PBR. The technical staff of the company was asked whether they have experienced or not the different learning mechanisms (learning-by-doing, learning-by-searching, learning-by-using, learning-by-interacting) during each life-cycle. Therefore, in the end, the results show that the answer to the third research question is that the learning mechanisms played different roles in each life-cycle:

- A general trend that can be identified is that learning-by-doing is more relevant in the phase 'growth' and learning-by-using role has more weight in the 'maturity' and 'decline' phases of technology. These findings are in accordance with literature. First, the learning-by-doing mechanism originates as a by-product of economic activity in general, Kamp *et al.* (2004) claim that this learning mechanism always exists and that producing is sufficient to trigger it. Second, learning-by-using can only be assessed after intensive or prolonged use of the technology, while tasks related with technological optimisation take place (Rosenberg, 1982).

- As learning-by-searching is related to the systematic and organised search for new knowledge, the role of this mechanism became particularly relevant in the 'growth' phase of the raceways and GW technologies, due to the fact that both technologies were the state-of-art when installed. During the interviews, another fact that was mentioned about this type of learning is that whenever new solutions to improve technology performance were based on R&D activities, playing a decisive role.

- The mechanism of learning-by-interacting was fundamental in the case of GW, as Necton closely collaborated with the technology developer. The information required to dominate the technology was tacit and learning occurred during direct face-to-face contacts. Moreover, during the interviews it was also mentioned that the communication between microalgae producers has always been scarce, as there were only few players in the market. Therefore, the role of learning-by-interacting was less noticeable.

It was also possible to conclude that learning-by-doing may not be the only factor underlying the learning process with the firm, and technology development is a reflection of all effects, including the effects of other learning mechanisms, such as learning-by-searching, learning-by-using and learning-by-interacting. In general terms, the role of learning-by-doing is more relevant in initial phases of technology life-cycle, learning-by-using appears in the maturity and decline phases, as it requires a longer utilisation of technology. Learning-by-searching was found to be only relevant when learning-by-doing does not have an immediate and positive effect in the technology performance, in an attempt to find technical and scientific solutions. Learning-by-interacting was quite important in the GW operation, especially with the technology developer. It was also mentioned, during interviews, that as there are few microalgae producers in the market; learning from interacting with other market players is residual. These findings should be confirmed using other commercial plants as additional case-studies. In the future a KM tool could be developed with this sort of information, that could help managers to orientate learning processes towards the acceleration of the rate of learning.

From the KM point-of-view, it would be also important to know how to profit from knowledge diffusion. Not including experience gained outside the investigated system may lead to serious distortions of results (Junginger, 2004). Therefore, learning-by-expanding and learning-by-interacting mechanisms present themselves as important variables, which appear to be quite difficult to introduce in studies. In the same research strand, another useful application of EC, rarely addressed, would be to promote the learning spillovers of marine biotechnology as a diffusion policy, resulting in learning gains that could favour first mover advantages. A long-range strategic framework is needed for microalgal biotechnology and the Mediterranean countries are currently well placed to develop good products for the market, building on its suitable geographic and weather conditions. Portugal is also well positioned to be a successful developer and user of marine biotechnologies.

Our research has raised many questions in need of further investigation regarding the MPS. If a similar study could have been performed on another company that uses similar technologies, would the determined EC and PR of the FPFT and the tubular PBR be alike? The learning mechanisms, which contributed more for the technological progress of each MPS, are different from one technology to the other. The reasons for this finding are not clear: is it because the technologies have different degrees of technological complexity? Or, is it due to the fact that experience accumulation empowers the workers with a capacity to approach, in a different way, the operation of each technology, thus using different learning mechanisms? Or, is it both? Therefore, it is suggested that the association of these factors is investigated in future studies.

Inevitably, the information assorted in so many production reports and other kind of records, provided by Necton, is dense, and consequently a handful of industrial knowledge, regarding microalgal biotechnology, remains to be studied. Despite the interest of these matters for the industrial biotechnology, there are other studies to be conducted, in the KM field, to understand if it is possible to calculate and disaggregate the EC gains in order to create better conditions for increasing EC gains. The possibility to accelerate the technological learning trough KM would mean that the EC would be shortened and the EC gains would be sooner achieved. In a competitive globalised world scenario, the real learning organisations would be flexible enough to ‘ride down’ faster the EC and be ready to shift from one technology to the other. In addition, the hypothesis that the innovative pace of such learning organisations would be faster, should be tested.

The EC is a concept where management, learning and technological development fuse and collide. How should such areas better combine during the development of a technology in an organisation? Moreover, if there is a difference between smaller and bigger organisations, how is this differentiation reflected in such interactions?

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Appendix A – Environmental data

Table A.1 – Pluviosity data.

	Pluviosity per year (mm)						
Months	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**Average**
January	38,8	20,8	0,0	77,7	4,5	38,1	30,0
February	56,3	106,1	8,3	46,9	24,6	64,5	51,1
March	55,6	38,8	14,4	38,3	14,9	19,5	30,3
April	76,4	10,4	0,7	39,6	11,1	110,7	41,5
May	4,3	24,8	14,9	0,0	12,9	38,6	15,9
June	2,0	0,0	0,7	16,5	2,0	0,0	3,5
July	0,0	0,0	7,8	0,5	0,0	0,0	1,4
August	0,0	2,0	0,0	12,9	58,9	0,0	12,3
September	4,0	2,0	0,5	12,1	19,8	92,4	21,8
October	118,1	36,0	74,6	87,6	56,1	32,2	67,4
November	82	28,1	155,7	193,8	53,0	23,8	89,4
December	75,9	36,8	39,3	34,7	87,1	39,6	52,2
Total	**513,4**	**305,8**	**316,9**	**560,6**	**344,9**	**459,4**	

Table A.2 – Rainy days.

	Rainy days per year (#)							
Months	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**Total**	**Average**
January	12,0	7,0	0,0	11,0	6,0	10,0	46,0	7,7
February	10,0	9,0	5,0	7,0	14,0	9,0	54,0	9,0
March	11,0	8,0	8,0	8,0	6,0	5,0	46,0	7,7
April	11,0	4,0	1,0	7,0	8,0	8,0	39,0	6,5
May	2,0	10,0	6,0	0,0	2,0	6,0	26,0	4,3
June	3,0	2,0	1,0	5,0	4,0	0,0	15,0	2,5
July	0,0	0,0	1,0	2,0	0,0	0,0	3,0	0,5
August	1,0	2,0	1,0	1,0	2,0	0,0	7,0	1,2
September	2,0	1,0	3,0	3,0	4,0	7,0	20,0	3,3
October	18,0	10,0	9,0	11,0	5,0	10,0	63,0	10,5
November	11,0	5,0	13,0	12,0	5,0	3,0	49,0	8,2
December	10,0	7,0	10,0	6,0	7,0	13,0	53,0	8,8
Total	**91,0**	**65,0**	**58,0**	**73,0**	**63,0**	**71,0**		

Table A.3 – Average irradiation and total number of sun-hours.

Months	Average Irradiation ($Wh/m^2/day$)	Sun-hours (#)						
		2003	2004	2005	2006	2007	2008	Average
January	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
February	10,8	10,8	10,8	10,8	10,8	10,8	10,8	10,8
March	11,9	11,9	12,0	11,9	11,9	11,9	12,0	11,9
April	13,1	13,1	13,2	12,9	13,3	13,1	13,1	13,1
May	14,0	14,0	14,2	13,8	14,1	14,1	14,2	14,1
June	14,6	14,6	14,7	14,3	14,6	14,7	14,7	14,6
July	14,4	14,4	14,4	14,1	14,5	14,4	14,4	14,4
August	13,5	13,5	13,6	13,2	13,6	13,6	13,6	13,5
September	12,4	12,4	12,5	12,1	12,5	12,5	12,4	12,4
October	11,2	11,2	10,3	11,0	11,3	11,3	11,2	11,1
November	10,2	10,2	8,6	10,0	10,2	9,8	10,2	9,8
December	9,6	9,6	8,0	9,5	9,7	9,5	9,7	9,3
	Total	**145,6**	**142,3**	**143,6**	**146,4**	**145,7**	**146,2**	

Table A.4 – Maximum (M) and minimum (m) temperatures and thermic amplitude (A) per month.

	Temperature (ºC)																	
	2003			2004			2005			2006			2007			2008		
Months	M	m	A	M	m	A	M	m	A	M	m	A	M	m	A	M	m	A
Jan	16,4	7,8	8,6	17,4	8,8	8,6	15,5	5,7	9,8	14,6	6,8	7,9	16,7	6,7	9,9	17,9	9,3	8,7
Feb	16,7	7,8	8,9	16,8	9,1	7,6	16,0	5,5	10,5	15,7	7,3	8,4	17,5	10,0	7,5	18,1	11,3	6,8
Mar	18,5	11,2	7,3	18,4	9,5	8,9	17,5	10,3	7,3	18,1	10,5	7,6	18,6	9,5	9,1	20,2	9,9	10,3
Apr	19,3	11,8	7,5	20,5	10,8	9,7	21,0	12,7	8,4	20,6	12,1	8,5	20,5	11,7	8,8	21,3	12,5	8,8
May	24,8	15,7	9,1	21,3	13,7	7,7	23,8	15,3	8,4	24,8	15,6	9,2	23,6	14,3	9,3	21,1	13,5	7,6
Jun	27,7	18,7	9,0	28,4	19,5	8,9	27,8	18,9	8,9	25,7	17,8	8,0	25,1	16,9	8,1	27,5	17,7	9,8
Jul	29,7	19,0	10,8	31,1	20,5	10,6	28,2	19,2	9,0	31,1	20,0	11,1	30,0	18,9	11,1	29,1	19,0	10,1
Aug	31,5	21,0	10,6	29,3	20,0	9,3	28,2	20,1	8,2	29,5	20,6	9,0	27,1	18,3	8,9	28,5	18,1	10,4
Sep	27,1	18,2	8,9	26,2	16,4	9,8	26,3	17,6	8,7	29,9	19,0	10,9	25,8	18,7	7,1	25,0	17,3	7,7
Oct	22,5	15,8	6,7	22,4	15,0	7,4	22,6	15,5	7,1	24,1	17,2	6,9	24,4	15,6	8,9	23,3	14,8	8,4
Nov	19,1	11,1	8,0	19,2	10,9	8,3	18,6	10,2	8,4	20,7	13,4	7,3	20,5	11,0	9,5	18,7	8,9	9,8
Dec	16,4	8,8	7,6	16,9	8,2	8,7	16,7	9,3	7,4	16,7	8,1	8,6	17,5	8,6	8,9	16,3	7,7	8,6

Table A.5 – Average maximum (M) and minimum (m) temperatures and thermic amplitude (A), from the year 2003 to the year 2008.

	Average Temperature (ºC)		
Months	**M**	**m**	A
January	16,4	7,5	8,9
February	16,8	8,5	8,3
March	18,5	10,1	8,4
April	20,5	11,9	8,6
May	23,2	14,7	8,5
June	27,0	18,2	8,8
July	29,9	19,4	10,4
August	29,0	19,7	9,4
September	26,7	17,9	8,8
October	23,2	15,7	7,6
November	19,5	10,9	8,5
December	16,8	8,5	8,3

Table A.6 – Average temperature per month.

	Average Temperature (ºC)						
Months	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**Average**
January	12,3	13,2	10,5	10,9	11,5	13,7	12,0
February	12,2	13,1	10,5	11,6	14,0	15,0	12,7
March	14,9	14,3	14,3	14,7	14,4	15,3	14,7
April	15,9	16,1	17,0	16,9	16,1	17,3	16,6
May	20,6	17,7	19,9	20,4	19,1	17,7	19,2
June	23,3	24,0	23,5	22,1	21,2	23,1	22,9
July	24,2	25,9	23,9	25,3	24,4	24,2	24,7
August	25,6	24,6	24,5	25,2	23,6	23,9	24,6
September	22,7	22,1	22,1	23,3	22,6	21,6	22,4
October	19,3	19,3	19,5	20,8	20,2	19,1	19,7
November	15,4	14,9	14,5	17,5	15,7	13,8	15,3
December	12,6	12,6	13,1	12,2	13,1	12,5	12,7
Average	18,3	18,2	17,8	18,4	18,0	18,1	

Table A.7 – Application of Least Square Regression Model to environmental data.

Month	Biomass Productivity (g DWT.L^{-1}.d^{-1})	Thermic Amplitude (ºC)	Average Temperature (ºC)	Irradiation (Wh.m^{-2}.day^{-1})	Sun-hours (#)
January	0,15	8,90	12,02	2.555,00	10,01
February	0,17	8,27	12,73	3.091,00	10,79
March	0,24	8,40	14,65	4.650,00	11,93
April	0,19	8,61	16,55	5.574,00	13,11
May	0,25	8,54	19,23	6.877,00	14,06
June	0,22	8,76	22,87	7.194,00	14,58
July	0,19	10,44	24,65	7.507,00	14,37
August	0,20	9,37	24,57	6.756,00	13,52
September	0,21	8,84	22,40	5.377,00	12,39
October	0,18	7,56	19,70	4.040,00	11,06
November	0,17	8,55	15,30	2.596,00	9,83
December	0,16	8,30	12,68	2.124,00	9,33

	Biomass Productivity (g DWT.L^{-1}.d^{-1})	Thermic Amplitude (ºC)	Average Temperature (ºC)	Irradiation (Wh.m^{-2}.day^{-1})	Sun-hours (#)
Variables	Y	X1	X2	X3	X4
Type of variable	dependent	independent	independent	independent	independent
Coefficients		C1	C2	C3	C4

Interception	C1	C2	C3	C4
0,7215	-0,0235	-0,0063	0,0001	-0,0463

Standard Deviation Error	C1	C2	C3	C4
	0,0353	0,0000	0,0035	0,0100

Coefficient of determination (r^2)	Standard Deviation Error of Estimate	F ratio	Degrees of freedom	Error sum of squares	Regression sum of squares
0,7792	0,0184	6,1750	7,0000	0,0083	0,0024

Y = 0,7215 - 0,0235 X1- 0,0063 X2 + 0,0001X3 - 0,0463 X4

Appendix B - Semi-structured interview script

UNIVERSIDADE DO ALGARVE
Faculdade de Economia

Introdução: No âmbito da Dissertação do Mestrado de Economia de Inovação e do Empreeendedorismo, a Necton SA foi escolhida como estudo de caso para a determinação da curva da experiência e para a avaliação do processo de aprendizagem relativos às tecnologias de produção de microalgas.

Data: ____/____/______

Nome: ____

Função:____

1. Quando iniciou a sua actividade na Necton?

2. Durante quanto tempo desempenhou essa função na Necton?

3. Com quais das seguintes tecnologias teve oportunidade de trabalhar?

Tecnologia 1 - Raceways ____

Tecnologia 2 - PBR FPFT ____

Tecnologia 3 - GreenWall ___

Tecnologia 4 - PBR tubular____

4. Como experienciou a instalação e a operação de cada tecnologia?

Por exemplo, em termos de produtividade, operatividade, flexibilidade produtiva, manutenção, etc.

Tecnologia 1	Tecnologia 2
Comentários	*Comentários*

Tecnologia 3	Tecnologia 4
Comentários	*Comentários*

5. Se possível, defina temporalmente o início e a duração das fases do ciclo de vida das tecnologias 1, 2, 3 e 4:

Crescimento <-> Maturidade <-> Declínio <-> Revigoramento

tendo em conta o desempenho tecnológico (quantidade de biomassa produzida, domínio das técnicas de produção, etc).

6. Se possível, identifique e quantifique (em % de tempo) qual dos mecanismos de aprendizagem esteve presente em numa, ou mais de uma, fase do ciclo de vida das tecnologias 1, 2, 3 e 4.

Nota: Antes de realizar a pergunta, descrever os tipos de mecanismos de aprendizagem: Learning-by-doing (LD); Learning-by-using (LU); Learning-by-searching (LS); Learning-by-interacting (LI)

7. Porquê é que se abandonou a tecnologia de produção 1? Porquê é que se transitou de uma tecnologia 2 para a tecnologia 4?

Obrigada por participar!

Appendix C – Data extracted from interviews

Table C.1 - Data extracted from interviews regarding the learning mechanisms experienced in the MPS Raceways.

		Learning Mechanism			
Worker	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth					
1	12	40	20	30	10
2	3	100	0	0	0
Average	**8**	**70**	**10**	**15**	**5**
Maturity					
1	12	30	40	15	15
2	7	100	0	0	0
Average	**10**	**65**	**20**	**8**	**8**

		Learning Mechanism			
Life-cycle	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth	8	70	10	15	5
Maturity	10	65	20	8	8

Table C.2 - Data extracted from interviews regarding the learning mechanisms experienced in the MPS GreenWall.

		Learning Mechanism			
Worker	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth					
1	36	20	10	50	20
2	36	92	3	3	3
3	36	20	10	50	20
4	36	0	0	0	100
Average	**36**	**33**	**6**	**26**	**36**

		Learning Mechanism			
Life-cycle	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth	36	33	6	26	36

Table C.3 - Data extracted from interviews regarding the learning mechanisms experienced in the MPS FPFT PBR.

		Learning Mechanism			
Worker	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth					
1	10	50	10	40	0
2	12	92	3	3	3
3	10	40	50	5	5
4	20	60	35	5	0
5	6	100	0	0	0
Average	**12**	**68**	**20**	**11**	**2**
Maturity					
1	75	20	30	20	30
2	73	0	100	0	0
3	96	20	60	10	10
4	73	100	0	0	0
5	86	0	100	0	0
Average	**81**	**28**	**58**	**6**	**8**
Decline					
1	24	20	55	20	5
2	12	0	100	0	0
3	40	0	100	0	0
4	24	20	55	20	5
5	12	0	100	0	0
Average	**22**	**8**	**82**	**8**	**2**

		Learning Mechanism			
Life-cycle	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth	12	68	20	11	2
Maturity	81	30	48	16	6
Decline	22	8	82	8	2

Table C.4 - Data extracted from interviews regarding the learning mechanisms experienced in the MPS tubular PBR.

		Learning Mechanism			
Worker	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth					
1	12	40	20	20	20
2	2	92	3	3	3
3	6	40	50	5	5
4	12	60	35	5	0
5	7	50	50	0	0
Average	**8**	**56**	**32**	**7**	**6**
Maturity					
1	12	20	30	20	30
2	12	0	100	0	0
3	14	20	60	10	10
4	12	100	0	0	0
5	12	0	100	0	0
Average	**12**	**28**	**58**	**6**	**8**

		Learning Mechanism			
Life-cycle	**Duration (months)**	**LD (%)**	**LU (%)**	**LS (%)**	**LI (%)**
Growth	8	56	32	7	6
Maturity	12	28	58	6	8

Table C.5 - Data extracted from interviews regarding learning mechanisms experienced, in average, in MPS.

	Life-Cycle Phase											
	Growth				**Maturity**				**Decline**			
MPS	Learning Mechanism Role (%)											
	LD	**LU**	**LS**	**LI**	**LD**	**LU**	**LS**	**LI**	**LD**	**LU**	**LS**	**LI**
Raceways	70	10	15	5	65	20	8	8				
GreenWall	33	6	26	36								
FPFT PBR	68	20	11	2	30	48	16	6	8	82	8	2
Tubular PBR	56	32	7	6	28	58	6	8				
Average	**57**	**17**	**14**	**12**	**41**	**42**	**10**	**7**	**8**	**82**	**8**	**2**