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Editorial

The Democratization of Science: Blue Ocean or Chimera?

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Knowledge builds on itself. Scientific progress is achieved through piecewise advances, and is based on the enlightenment of prior evidence and discoveries. Accessing prior information has been a tremendously complex venture for centuries, and restricted to the privileged few. Technological progress and namely, the advent of Internet have opened a world of possibilities, including the instant sharing and diffusion of information. Reaping the full benefits of technological advances has however been prevented by the prerogatives of the publishing industry, which have been increasingly challenged over the last two decades. Major historical milestones include the creation of ArXiv.org, an online repository of electronic preprints in 1991; the launch of SciELO in Brazil in 1997 and its extension to 14 countries; the foundation of PLOS by the Public Library of Science, established as an alternative to traditional publishing and nowadays known as PLOS ONE, which is by far the world's largest series of journals with over 30,000 papers published in 2015; the Budapest Declaration on Open Access in 2002; the campaign Access2Research and the US Fair Access to Science and Technology Research Act, a foundational piece in the establishment of Open Access in the USA; and the initiative of the European Commission to require all research publications funded under Horizon2020 to be openly accessible, free of charge. All these initiatives converged towards the same aim: fostering free and unrestricted access to publications, so as to ensure the widespread and rapid diffusion of research findings within, across and outside scientific communities.

The two original pathways to Open Access (OA), namely the Green and Gold routes, are increasingly complemented and even superseded by the hybrid model. The Green route refers to the online access to peer-reviewed and published papers, usually via a repository and after some embargo while the Gold route entails the immediate, unrestricted online access to peer-reviewed published papers, free of charge for the readers. The hybrid model offers authors in subscription journals the possibility to give free access to their individual articles against a pre-publication fee. Such a model has raised concerns of "double dipping", as payment can occur twice, i.e. through the subscription paid by institutions and the fee paid by individual authors. This model is seen as a potential transition for the publishing industry, and appears to be lucrative for publishers as a recent study by the Research Council UK points out. The review of the implementation of the RCUK policy on open access unveils that the average Article Processing Charge (APC) charged by hybrid journals is significantly higher than the APC charged by fully open access journals, stressing the double dipping concern as hybrid journals still benefit from a stable revenue stream from subscriptions. This study further reveals that the expenditures of a sample of 20 Higher Education Institutes in the UK, trebled between 2013 and 2014, both in terms of APC spending and in terms of absolute number of articles subject to a publication fee. Concomitantly, expenditures for subscription increased. These numbers reveal an increased compliance with the open access policies applicable to publicly funded research, which is certainly laudable. Yet, in times of tightened public funding for research, the question of the efficient use of resources should be raised and a cost-benefit analysis of adopting the hybrid model might bring stimulating insights to shape future publication strategies.

In parallel, numerous repositories and platforms have emerged, offering typical social media features: following peers and being followed, tracking updates, sharing questions, documents, providing feedbacks, etc. Beyond the digital storage functions, these profitable private ventures also provide data analytics and compute, relying on proprietary algorithms, impact metrics and represent a core component of the new ecosystem for researchers, as individuals, for organizations and for the promotion of research findings. The convergence between this segment of the social media industry and the publishing firms, and the subsequent acquisitions, is self-explanatory and raises the question of the attainability of the strategic intent of free dissemination of knowledge, as new business models flourish. Are we shifting from subscriptions-based journals to access and disseminate knowledge to a subscription-fee for a social media network membership?

The growing awareness towards open access publication strategies is also exemplified by the development of tools to monitor the penetration of and compliance to OA policies. The Registry of Open Access Repository Mandates and Policies (ROARMAP), which defines itself as "a searchable international registry charting the growth of open access mandates and policies adopted by universities, research institutions and research funders that require or request their researchers to provide open access to their peer-reviewed research article output by depositing it in an open access repository" (ROARMAP website), nowadays records about 800 mandates and provides interesting visualization tools showing the policy alignment to H2020 of individual institutions and countries. The European Commission reports that 54% of all scientific peer-reviewed publications produced during the lifetime of FP7 are open access and estimates that the target of 60%, set to be achieved in 2016, is well underway (DG Research and Innovation). The proportion of papers downloadable for free reaches 76% in Brazil, and 70% Switzerland, while these numbers revolve around 65% in the USA and Canada. As reported by Archambault et al., out of 4.6 million scientific papers from peer-reviewed journals indexed in Scopus during 2011-2013, 2.5 million were available for free in April 2014. Significant disparities across fields exist, with clinical medicine, biomedical research, physics and astronomy taking the leading positions (Archambault et al., 2014). Another noteworthy finding of this study is the huge citation advantage to publishing in Green OA, as opposed to the citation disadvantage on average for almost all fields for the Gold OA model.

From the broader perspective of the entire lifecycle of research, OA publication is providing answers to the dissemination of scientific findings, and is thus focusing exclusively on the outcome phase of the research process. OA publication is undeniably essential to foster faster diffusion and re-use of scientific results, yet facilitating the stepwise, incremental process of generating new knowledge requires more: Open Data and Open Research Data. Over the last few years, open data initiatives have been flourishing, with the launch of open data portals such as the European Open Data Portal (https://data.europa.eu/euodp/en/data) embracing datasets on topics ranging from employment and working conditions to agriculture, forestry and fisheries; the opendata.swiss portal records almost 1200 open datasets, the US data.gov portal offers access to almost 200,000 datasets, and the Queensland University of Technology promotes the Research Data Finder, which provides descriptions about shareable, reusable datasets available via open or mediated access (https://researchdatafinder.qut.edu.au/).

Opening up *research* data to wider exploitation, mining, dissemination and reuse is the new frontier. The benefits of Open *research* data are multifold: reproducibility and replicability of research, acceleration of the pace of discovery, catalyst for cooperation, multi-stakeholder involvement, avoidance of duplication efforts, fraud prevention and integrity, to name a few.

Open research data has been progressively introduced as a requirement under the H2020 funding scheme, with the ultimate goal of achieving FAIR (findable, accessible, interoperable and re-suable) data sharing as the default for scientific research by 2020. An ongoing pilot initiative under H2020 showed a lower adhesion level to open research data than to OA publication, with 65% of projects in the selected thematic areas opting-in (DG Research and Innovation). Open research data is also opening up a wealth of opportunities: the formalization of new skills and expertise, and the emergence of professional “Core data experts” as coined by Mons et al. in the report “A cloud on the 2020 Horizon” (2016), the development of new service offerings for professional open data management plans, new business ventures combining extensive data mining capabilities and content provider as illustrated by the recent partnership between IBM Watson and PLOS. Such partnerships are certainly desirable, and should be fostered as long as they do not jeopardize academic freedom and restrict research exclusively to profitable ventures. Open research data is also perceived as a means to foster citizen engagement and facilitate science- and evidence-based policy making.

Moving further upstream of the research process, Research Ideas and Outcomes, also known as RIO, was launched in September 2015 and aims to publish proposals, experimental designs, data and software, thus covering "research from all stages of the research cycle" (Nature, 2015). Sharing experiences and publishing information about research failures may now be the next frontier.

Open Access and Open Research Data constitute two cornerstones of Open Science. As a key element of the Digital Single Market strategy in Europe, Open Science is defined as “the transformation, opening up and democratization of science and research through ICT, with the objective of making science more efficient, transparent and interdisciplinary, of changing the interaction between science and society, and of enabling broader societal impact and innovation” (European Commission). In “Reinventing Discovery: the New Era of Networked Science”, Nielsen depicts Open Science as “the idea that scientific knowledge of all kinds should be openly shared as early as is practical in the discovery process". While Open Science has undeniable benefits for society, it entails a paradigm shift in the way research is conducted, researchers collaborate and knowledge is disseminated. It also requires revisiting the traditional evaluation and appraisal models, departing from the metrics currently used for assessing candidates for funding, appointment and tenure, as well as the performance of institutions themselves.

The democratization of science will hardly be ubiquitous as long as individualistic appraisal models and proprietary-based publishing metrics prevail. The definition and progressive adoption of Altmetrics, and more globally of responsible metrics, as well as the reshaping of incentives and rewards mechanisms should support the transformation towards Open Science. In the long run, we argue that Open Science, and its underlying practices of OA and Open Research, will blossom conditional upon their ability to build *credibility*, to perform *selectivity*, to guarantee *autonomy*, to benefit from *interconnectedness* and to achieve societal *impact*. Credibility will be gained through the application of stricter, more rigorous, and positively discriminating mechanisms and systems. DOAJ recently delisted some 3,300 titles from questionable and inactive publishers, as part of its effort to tighten its standards for inclusion, is a noteworthy development in building OA legitimacy and credibility (Nature, 2016). In an era of plethoric amount of information, selectivity is key. Yet, selectivity should not imply following a closed club rules, and should be exclusively assessed based on the merits of the proposed content, in terms of originality, novelty, and rigor. Autonomy is an essential prerequisite to perform unbiased research, driven by intellectual curiosity and cross-fertilization of ideas, and is a value that should always be nurtured. Interconnectedness is part of our daily lives, with its benefits and its pitfalls. Sharing feelings, perceptions and emotions at the very moment these are experienced is now commonplace, and will inevitably further influence the way research is performed. Building on technological capabilities, research ideas can benefit from instant confrontation with a broad audience. Generating a sustainable impact should be the target of every research initiative, whether the intended impact is in the foreseeable future or pertains to the longer term.

The Journal of Innovation Management constantly embeds these criteria in its development and in its operations. Credibility is built through a rigorous peer-review process conducted by a large multidisciplinary panel of associate editors and editorial board members, to whom, along with all reviewers, we would like to address our sincere and deep gratitude. Selectivity is achieved through the implementation of quality criteria, and their appreciation with regards to different fields, areas, and domains of applications. Autonomy is secured through independence, both intellectually and financially. The use of social networks to promote our publications spurs fast, wide dissemination and interconnectedness. Impact is reflected in the latest statistics, accessible on our website, and through the increasing penetration of the Journal of Innovation Management in different academic, industrial and policy spheres. Striving for Open Science to deliver its best and flourish for the greater benefits of society, we wish you a rewarding and fruitful reading of this Summer Issue.

Innovatively Yours,
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Editors

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CRIAQ and CARIC: An Innovation Journey - Insights on How to Build Successful Research and Development Collaborations in Aerospace: The Case of the Quebec and Canadian Ecosystems

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Abstract. The Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ) and the Consortium for Aerospace Research and Innovation in Canada (CARIC) are organizations whose missions are to facilitate collaboration of researchers from the aerospace industry, academia and research centres, and to launch initiatives whose primary purpose is to promote responsive, impactful R&D. This letter presents the distinctive characteristics of these models and their impact on Quebec and Canada's aerospace innovation culture.

Keywords. Innovation, Aerospace industry, Industrial research, Technology transfer.

1 Introduction

The Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ) and the Consortium for Aerospace Research and Innovation in Canada (CARIC) are organizations, respectively in Quebec and Canada, which develop and stimulate collaborations between industry specialists and academic researchers in aerospace research and development projects. The two organizations work in synergy to offer their members competitive financial leverage and a rich collaborative ecosystem for all parties. Highly focused on aerospace industry challenges, CRIAQ and CARIC support industrial and academic teams from project ideas to completion. Overall, the projects and activities of CRIAQ and CARIC strengthen the technological foundation for tomorrow's aerospace innovations in Quebec and Canada.

Today, the two consortiums have 107 members[1], out of which 73 are industrial members and 34 are research organizations. Since CRIAQ's inception 13 years ago and CARIC's two years ago, their members have launched 132 research projects[2], representing $132 million in collaborative R&D investments in Canada. The consortiums also support international projects with France, India, Sweden, Austria, China and Germany, and are currently establishing collaborative agreements with Hamburg, Japan and Belgium. These initiatives position Canadian companies on the

1 As of May 2016
2 74 completed projects and 58 ongoing projects

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international scene and enrich Canada's university expertise. More than 1,200 students work or have worked on CRIAQ and CARIC projects, including over 120 post-doctorates, 300 PhDs and 400 Masters students.

There is no doubt that CRIAQ and CARIC are models of success[3]. But what explains this success? What factors and distinctive elements of these models make them true benchmarks of collaborative open innovation? For, beyond the numbers and the statistics, there is a story rich in lessons. Although we can claim to have told it many times, it is possible that we did not say all there is to say. Accordingly, this letter will focus on CRIAQ and CARIC's models of success. The main elements of these models will be presented to highlight their principal characteristics — an interesting and original addition to the existing literature on innovation project management. This letter will conclude with a discussion on the future orientations of both consortiums.

1.1 Takeoff of an innovation culture

Portrait of Quebec's aerospace industry. Quebec's aerospace industry provides over 40,000 jobs at 190 businesses, including about 15 general contractors, integrators and equipment manufacturers. Exports represent over 80% of the $15.5 billion in aerospace sales. The Greater Montreal Region is at the heart of this ecosystem, and alone accounts for over 70% of all Canadian aerospace R&D[4]. This area includes two of the 10 largest investors in R&D in Canada[5], namely Bombardier and Pratt & Whitney Canada. In turn, the Canadian aerospace industry generates 180,000 jobs and $1.8 billion is allocated to R&D in this sector[6].

A tightly link dynamic exists between industries in the Quebec aerospace industry. Three tiers of companies represent the entire production chain, from conception based on client requirements to the production of specialized parts. In addition to this vertical supply chain structure, many other companies have specialized horizontally in niche markets. The broad spectrum of expertise needed to build an aircraft creates a dynamic of complementary expertise rather than direct competition between the companies. Indeed, the expertise of the four original equipment manufacturers (OEMs) in Quebec complements each other. Bombardier Aerospace integrates and assembles aircraft components, Bell Helicopter manufactures helicopters, Pratt & Whitney Canada specializes in engines and CAE supplies flight simulators and comprehensive pilot training solutions. This strength of the Quebec aerospace sector has been put to good use by CRIAQ and CARIC projects.

CRIAQ's early days. CRIAQ was officially launched in 2003. From the start, the Consortium had the support of the sector's major OEMs and key universities with engineering programs. To stimulate further collaboration between companies and

[3]See Guedda, Chiraz. "Les dynamiques de collaboration entre les partenaires de la grappe aéronautique québécoise : le cas des projets du CRIAQ", Université du Québec à Montréal, 2015

[4]Stratégie québécoise de l'aérospatiale, Réinventer l'horizon 2016-2026, available online : https://www.economie.gouv.qc.ca/fileadmin/contenu/documents_soutien/strategies/strategie_aerospatiale/strategie_aerospatiale.pdf

[5]http://www.researchinfosource.com/pdf/CIL%20Top%20100%20corp%20R%26D%20Spenders%202015.pdf

[6] AIAC, The State of the Canadian Aerospace Industry, 2015 report, available online: http://aiac.ca/wp-content/uploads/2015/11/The-State-of-the-Canadian-Aerospace-Industry-2015-Report.pdf

research centres, and between companies themselves, the Board of Directors instituted the "2+2" model from the very beginning. All projects had to include at least two industrial partners and two research partners. With this policy, the idea was to force companies and research organizations to collaborate. As mentioned by Blum, collaboration between businesses and universities has long existed in the aerospace industry. What's unique about the CRIAQ model is two-fold: institutionalizing this collaboration and, above all, forcing companies and universities to collaborate[7].

It is worth noting that, with Montreal's industrial structure, organizations can profit from this rule in two ways: (1) OEMs are not natural competitors, which encourages "co-development" when it comes to generic technology and processes on "low technology readiness level" projects; and (2) the presence of small and medium-sized companies (SMEs) in the whole supply chain leads to compelling multi-party research collaborations that create ties with future suppliers.

1.2 First project implementation

Research Forums. To both foster relationships between aerospace companies and research organizations and identify research projects, CRIAQ initiated the Research Forum model[8]. Research Forums, held every two years, can be seen as a platform for the dissemination of project ideas to the entire Quebec, Canadian and abroad aerospace community-seeking partners. These Forums, organized by the CRIAQ team, are actually a large gathering of the R&D community whose primary objective is to present research project ideas and identify potential partners for them. Over the years, these Forums have become a true benchmark in the field[9] and a concrete example of the open innovation concept. Here's a glance at the key success factors of these Forums:

- *Projects are presented by industrial partners*. The presentation by industrial partners ensures that the projects are part of their internal technology roadmap and are therefore financially supported.
- *Project ideas are presented in two-three minutes in plenary session at the Forum*. The presentation to all Forum participants maximizes the idea's exposure and the time limit is enough to present project objectives, a brief description and the necessary industry and academic expertise sought.
- *Forums are open events*. Members and non-members of the Consortium can meet and talk freely throughout the Forum. No confidentiality agreement is necessary for this event. This encourages cross-fertilization and access to interdisciplinary projects. Many projects benefit from expertise that had not been considered initially.
- *All participants can show interest in the projects*. Interest in any project idea is collected on the spot. Afterwards, a project launch process[10] is led by the CRIAQ

[7] Blum, Guillaume, "L'émergence des connaissances dans le secteur québécois de l'aéronautique : une étude de l'innovation conduite par le concept d'avion vert", Université du Québec à Montréal, 2014, p.341
[8] See website for the latest CRIAQ Research Forum: http://criaq.aero/forum2016/?lang=en
[9] 2014 CRIAQ Forum: 1,300 participants, including 10 international delegations, 2016 CRIAQ Forum: 730 participants, including 8 international delegations.
[10] http://criaq.aero/forum2016/wp-content/uploads/2016/04/processus_projets_intl_EN.pdf

team to formalize the project teams.

Over the years, these Forums have become special moments for the entire ecosystem, going far beyond Quebec's borders with the participation of many international delegations. Without a doubt, this is a significant achievement for the Consortium — both its presentation format and open approach are a testimony to the innovation culture that CRIAQ promotes in the aerospace ecosystem.

1.3 Consolidation through formalization

To properly manage the increase in the Consortium's activities, including membership, project numbers and services, CRIAQ's internal structure and practices had to change. Based on its first five years of experience, CRIAQ has adopted a series of practices and measures designed to provide greater support to its growth strategy. Here are a few examples.

Legal Committee. CRIAQ is involved in the entire project launch process, from supporting teams during grant applications to dealing with intellectual property agreements. CRIAQ team soon realized that the average signing lead-times for multi-party intellectual property agreements were too long. Because CRIAQ projects involve at least four partners, often six or seven, each agreement must be reviewed and commented on by the legal department of every organization involved in the project. CRIAQ's team then had the idea to create a legal committee with legal representatives of industrial partners and members of university research offices and research centres. This committee's mandate was to create a generic agreement template that could be applied to all "low technology readiness level" projects. A generic agreement was created and is compulsory for all low-TRL research projects funded by CRIAQ. The model grants exclusive, royalty-free licenses to industries in their aerospace-related fields of use. The legal committee meets twice a year to review occasional modification requests made by members and resolve agreements-related conflicts. The many advantages of this generic template agreement include the following:

- Pre-approved agreement by the corporate legal departments since they are always identical, reducing revision time
- R&D project portfolio review made easier for companies as IP allocation rules are known in advance. This makes it easier to identify projects submitted to CRIAQ and those kept in-house.
- All partners start on an equal footing, making sure that SMEs do not feel they're at a disadvantage versus large companies[11].

Creating this committee has resulted in lower barriers to signing agreements, ensuring that the lawyers for OEMs and university research offices meet in person to review common issues.

Project design structure. Since its inception, CRIAQ has aimed to simplify multilateral project management for its partners. Over time, the team has developed tools to control internal procedures, manage their standardization and, more recently, monitor the project launch process.

[11] Blum, Guillaume, "L'émergence des connaissances dans le secteur québécois de l'aéronautique : une étude de l'innovation conduite par le concept d'avion vert", Université du Québec à Montréal, 2014, p. 340

For “low technology readiness level” projects, proposals are traditionally drafted by the academic team based on objectives defined by the industrial partners. In CRIAQ’s early days, the structure of project proposals could vary greatly. To help CRIAQ scientific committee evaluate the proposals and prevent any confusion about future expectations on deliverables, CRIAQ suggested including a Work Breakdown Structure (WBS) in the research proposal, which has been used in the industry and has proven to be very effective for collaborative R&D projects.

To carry out a WBS, the project is broken down into ever-smaller work units that are easy to manage. One of the benefits of this approach is that it provides a graphical representation of the project structure, with the number of levels based on the project’s complexity. In CRIAQ’s case, two realms had to be considered: industrial and academic. Also, projects are divided as in work units with associated deliverables. For each deliverable, a manager is appointed. Then, these deliverables are each broken down into specific tasks. At this point, structuring converges with educational logic as each task is linked to a specific student research element. During the project kickoff meeting, CRIAQ uses and presents the same structure as a monitoring tool of the project. Implementing these tools, initially considered additional work by some project partners, is now quickly and routinely done. And today, they are fully adopted and lend CRIAQ credibility as a genuine advisor and facilitator — in addition to its funding role.

Online Portal. In pursuing its efforts to create greater synergy within its ecosystem and foster discussion between various stakeholders, CRIAQ has developed an online collaborative platform. Its purpose is to simplify contact during each collaborative project planning stage and promote a number activities to the ecosystem.

The Aero-Collaboration portal[12] offers both a public and private space. The public space allows users to sign up for CRIAQ events, gives them special access to projects in the planning stage and permits them to show their interest in participating in a collaborative research project. It also enables users to suggest project ideas and exchange information directly with community members. The private space gives users access to the CRIAQ member directory and a collaborative research infrastructure inventory (reserved for CRIAQ members). It also allows users to take part in discussions on on-going projects.

The introduction of these procedures has enabled CRIAQ to support projects from Financing Rounds 4, 5 and on. This has led to a significant increase in activity — from 13 projects financed in Round 3 to 29 in Round 4 and 25 in Round 5. These successes demonstrate the Consortium’s impressive achievements and serve as a stepping stone to expand its activities across Canada.

2 CARIC: A national network

2.1 Creation of CARIC

In late 2012, the federal government conducted an aerospace review of all policies and programs related to the aerospace industry to develop a federal policy framework to maximize the competitiveness of this sector. As part of the review process, various

[12]Available at : https://aero-collaboration.org/connexion

industry-led working groups were assembled, composed of industry representatives, academic and research institutions, unions and federal government officials (as observers). One of these working groups looked specifically at technology development, demonstration, and commercialization. This work led to an aerospace review report, known as the Emerson Report[13]. One of the key recommendations of this report was the creation of a national collaborative aerospace network, which led to the creation of CARIC, the Consortium for Aerospace Research and Innovation in Canada.

2.2 Frontiers to Overcome

Although the Emerson Report focused on CRIAQ as a model to deploy on a pan-Canadian scale, it did not provide the path to follow. In fact, there were many *frontiers* to overcome before launching a national network.

The first *frontier*: the territorial challenge. To successfully roll out across the country, CARIC relies on provincial ecosystems and their communities. Through signed framework agreements with local aerospace associations in various regions and the appointment of Regional Directors close to key aerospace players in their territory, CARIC has set the stage for a successful launch in Canada by adapting to the local landscape.

The second *frontier*: from a manufacturing base to services and multi-sectoral industries. The development of interprovincial projects has already exceeded expectations but CARIC must now maintain its efforts to ensure the involvement and integration of the entire aerospace value chain across Canada, even where industry density is lower and of a different nature or the collaborative research culture is less developed.

CARIC goes even further by crossing a third *frontier* — supporting industry during the technology transfer from the research environment to the industrial world. CARIC helps to achieve this by directly funding companies during the joint R&D projects, in the form of direct contributions. This allows technologies and processes developed at lower technology readiness levels to *be transplanted* into businesses and take root. The research side of it remains but the bulk of the project work is done in an industrial setting. CARIC's programs therefore offer funding and support for activities that take these projects from the world of research to the industrial realm.

2.3 Solid Foundation

As we have seen, setting up a national network has had its share of challenges. To launch the Consortium's activities quickly on a solid foundation, a series of strategic and operational decisions were taken to make the rapid launch possible and build awareness of the Consortium on a national level. This included the following:

A flexible structure. The Consortium's governance structure includes representation from Canadian regions renowned for their aerospace innovation capabilities and a mix of industry, universities, colleges and research centres. Moreover, the CRIAQ and CARIC Boards of Directors have opted for an integrated approach to operating the two

[13] http://aerospacereview.ca/eic/site/060.nsf/eng/home

networks to maximize benefits for their members, both in terms of funding and program access.

From a team standpoint, the overall CRIAQ team has been involved in helping roll out CARIC's activities quickly and is still involved in running it today. In addition, many tools (such as the online project platform and database) and costs were shared. CARIC's acknowledgement of CRIAQ membership has also allowed CRIAQ members to take advantage of many benefits, including the following:

- Access to a wider network of partners
- Access to additional funding from CARIC for collaborative projects and dedicated industry financing
- Pan-Canadian coverage for the organization and its research activities

Established co-funding mechanisms. Building on CRIAQ's credentials and long history in structuring projects funded by multiple sources, working collaborations were easily established between CARIC and other funding bodies in Canada, such as the Natural Sciences and Engineering Research Council of Canada (NSERC) and Mitacs, a not-for-profit organization designing and delivering research and training programs in Canada. Beyond the co-funding of projects, CARIC has regular interactions with these organizations to optimize submission, review and reporting processes. It is in this context that CARIC and Mitacs recently harmonized their processes, reducing turn-time and leading to faster project implementation.

Joint confidentiality agreements and intellectual property guidelines. CRIAQ's generic project agreement mentioned earlier has been adapted to include CARIC and is now used for all "low technology readiness" research projects. This has led to faster sign-offs on the first projects involving CARIC members. Moreover, an 'umbrella' confidentiality agreement, common to both organizations, has been developed to foster an open exchange of ideas by all CRIAQ and CARIC members and discussions on future collaborations.

Quebec's regional CARIC office managed by CRIAQ. CARIC has five regional directors based in Halifax, Montreal, Toronto, Winnipeg and Vancouver to maintain a presence in local ecosystems. CARIC has relied on service contracts with various aerospace associations or groups in each Canadian region to deliver the services of these regional directors. In the Quebec region, CARIC's regional director is also CRIAQ's Vice-President, Business Development and International. Once again, this maximizes synergy.

2.4 First successes

Building upon a proven model, CARIC's first projects were rapidly set up. Financing for 27 multi-partner collaborative projects, valued at $36M, in the first two years of operation demonstrates the value of the network. Due to this coverage and recognition as a key player in Canadian aerospace R&D, CARIC has been named by the European Commission as the official contact for co-development international research projects. This initiative, known as CANNAPE, has led to the first coordinated aerospace project call between Canada and the European Union. This coordinated project call has allowed key players in industry and academia to expand their collaborative network. CARIC and the Natural Sciences and Engineering Research Council of Canada (NSERC), along with the European Commission, announced the launch of three collaborative research projects[14] in February 2016. These research projects are the result of sustained discussion between Canadian and European experts. They will require the close collaboration of 30 partners: half from Canada and the other half from Europe (from eight different countries, including France, the United Kingdom, Poland, Germany, Italy, Sweden, Spain and the Netherlands.

It should be noted that, two years after its launch, CARIC has 50 members who were not CRIAQ members. Finally, out of the first 23 projects launched, 13 projects include partners outside Quebec and 12 have partners from two provinces or more.

3 CRIAQ and CARIC: Beyond the horizon

As shown by their numerous achievements, CRIAQ and CARIC have undoubtedly played different roles in establishing a culture of research and innovation in the Quebec and Canadian aerospace sectors: as facilitators definitely but also as intermediaries between large and small businesses, intermediaries between industry and universities, educational catalysts for students and *lieux de rencontre*[15]. The 132 projects launched since 2003 represent a high level of expertise in terms of collaborative project development, financing and management. Given their track record, they help enrich and develop know-how on state-of-the art technology and create a collaborative dynamic that so many industry players are seeking. Benefitting from the support of industry and both the Quebec and Canadian aerospace communities, CRIAQ and CARIC now have new challenges to face, outlined as follows:

- *Leadership in research program development*. CRIAQ and CARIC must now assume a greater leadership role in the development of technological priorities in aerospace. Their involvement in defining the aerospace community's research program will be part of CRIAQ and CARIC's role in future years.
- *SMEs*. SMEs require greater assistance with their technological development projects. What's more, these SMEs must develop a leadership position when it comes to managing innovation projects and migrate from a 'build-to-print' model to a 'design, build and integrate' model. CRIAQ and CARIC aim to develop specific programs for SMEs.
- *International*. More and more, a consolidated approach, combining innovation and the integration of global supply chains, is the model that will give SMEs access to the commercial outlets they need for their innovations[16]. To this end, CRIAQ and CARIC must stimulate international collaborative R&D by forging

[14] CARIC and NSERC, together with the European Commission, launches three collaborative research projects on crucial research areas for the aerospace sector
http://www.newswire.ca/fr/news-releases/caric-and-nserc-together-with-the-european-commission-launches-three-collaborative-research-projects-on-crucial-research-areas-for-the-aerospace-sector-567341941.html

15 Blum, Guillaume, « L'émergence des connaissances dans le secteur québécois de l'aéronautique: une étude de l'innovation conduite par le concept d'avion vert »», Université du Québec à Montréal, 2014.

16 As discussed in Strengthening Symbiosis: International Business Innovation, Conference Board of Canada,http://www.conferenceboard.ca/press/newsrelease/16-05-12/thinking_globally_could_improve_canada_s_innovation_performance.aspx

ties with international companies and research institutions.

- *Cross-sectoral and value chain.* CARIC has successfully helped boost aerospace R&D activity in Canadian provinces. Nevertheless, each Canadian region possesses a unique culture and the local industry structure is different than Quebec's own one. Thinking outside existing norms is central to initiating R&D projects in these different environments. A key success factor for CARIC is its solid understanding of regional ecosystems. To generate stronger interest in these regions, greater visibility must be given to initial research collaborations and project results.

In light of the issues discussed here, it can be concluded that, through their rich histories, CRIAQ and CARIC have shown us that the strength of these groups undoubtedly comes from the collaborative culture that they have fostered between industry and universities. It is a culture based on trust, openness and transparency. Far beyond policies, procedures and systems, even beyond funding, these models prove that the real artisans who make the projects work, who make the entire structure work, are the people who participate, who give their time and who believe in it. And perhaps the most valuable lesson of all is that, by gradually introducing a collaborative culture in the Quebec and Canadian aerospace sectors, they created sustainable change within business practices, questioned preconceived ideas and successfully introduced a collaborative research model that has become the norm within the Canadian aerospace ecosystem.

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Universities' Performance in Knowledge Transfer: An Analysis of the Ibero-American Region Over the Golden Decade

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Abstract. Universities play a crucial role in the systems of innovation by transferring the results of R&D activities to society and industry. This contribution is even more important in the Ibero-American countries given that the other critical 'player' (i.e., the industry) exercises a less active role in the development of innovation compared to the OECD countries. The aim of this paper is to analyze the knowledge transfer activities of the Ibero-American Higher Education Systems over the period 2000-2010. Using that database by Barro (2015), this study provides an accurate diagnosis of the Ibero-American universities' performance in knowledge transfer, suggesting a number of practical implications for university decision-makers.

Keywords. Ibero-America, Technology transfer, University, Patenting, R&D activities, R&D resources.

1 Introduction

Universities play a critical role in the ecosystem of innovation (Etzkowitz and Leydesdorff, 2000). Thus, their mission is no longer limited to research and education, instead they have included a 'third' dimension, namely to contribute to the economic growth of their regions (Branscomb et al., 1999; Ertkowitz et al., 2000). In doing so, universities have fostered their processes of knowledge transfer.

In the specific context of Ibero-America, universities gain even further relevance in the ecosystems of innovation, as the other agents -mainly firms or the private industry- play a secondary role compared to regions with a similar level of development. This fact makes extremely necessary to study the contribution of Higher Education Institutions (HEIs) in knowledge transfer. To date, there are few studies that have investigated this issue (Santelices, 2010; De Moya-Anegón, 2012; Cruz, 2014). In addition, most of them have tended to focus on one aspect of the technology transfer process or in a few universities rather than adopting a broader approach which includes more emphasis on outputs of technology transfer as well as more HEIs.

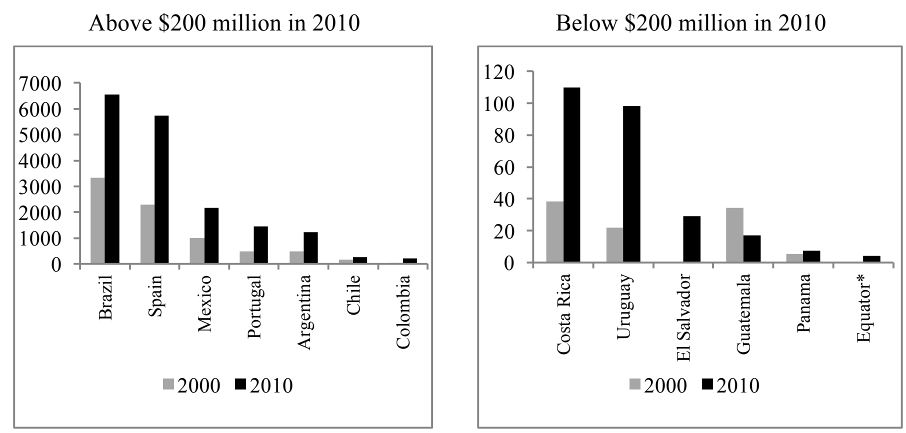
The goal of this paper is to analyze the knowledge transfer activities of the Ibero-American Higher Education Systems (HES's) during the first decade of the 21st century from an input-output approach. In doing so, a recent study by Barro (2015) provides us with an original and longitudinal database which gathers information in this issue unpublished to the date. Using that database, this study provides an accurate diagnosis of the Ibero-American universities' performance in knowledge transfer, which allows us to suggest a number of practical implications. Although there has been more available information for those countries that make up the higher education systems of the Ibero-American region, namely Argentina, Brazil, Mexico, Portugal and Spain, the paper analyses a range of countries wider than in the previous studies by Santelices (2010) or by Cruz (2014).

Following this introduction, the next section describes the human and financial resource endowment allocated to academic R&D. The third section presents the main outputs from the knowledge transfer activities measured in terms of publications, and patenting activity. Finally, we present the main conclusions, as well as a set of recommendations that can be drawn from the previous findings.

2 Gaining muscle mass: financial and human R&D resources

2.1 Financial R&D resources

During the decade 2000-2010, the financial R&D resources of Ibero-American HES's have risen markedly in absolute terms. Almost all the region's countries, except Guatemala, have considerably increased the expenditure on university R&D. In fact, this amount has doubled in most countries and even multiplied by three in Portugal and Costa Rica, and by four in Colombia and Uruguay (Fig. 1). However, we must note that in Spain and Portugal, for which we have data also for 2011 and 2012, this indicator is falling as a consequence of the severe crisis their economies have suffered since 2008.

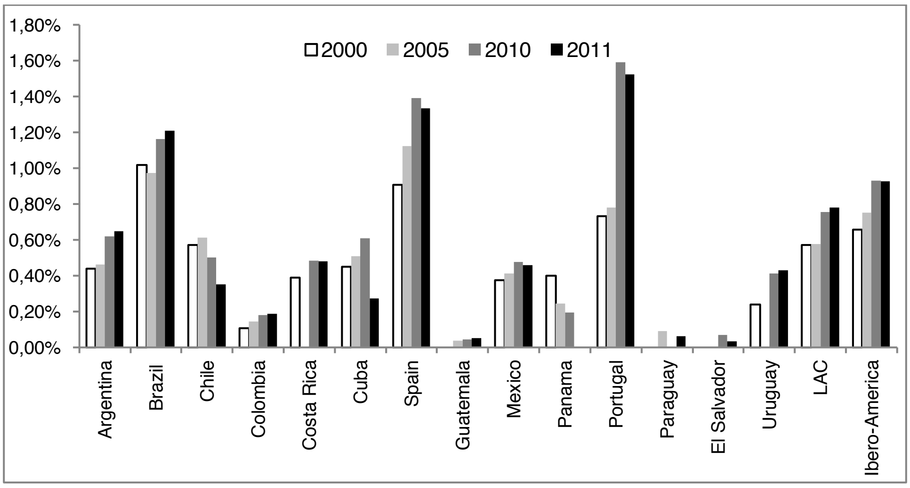


Notes: Countries are ordered according to R&D expenditure at current prices and purchasing power parities (PPPs) in 2010. * 2008. Source: Barro (2015)

Fig. 1. R&D expenditure at current prices and PPPs performed by the HES in some countries of the region (2000-2010).

This impressive growth is mainly due to two overall trends: 1) a relatively strong GDP growth over the 'golden decade', especially in Latin American and Caribbean

(LAC), which has been rising at a 5% for several years (OECD, 2014), and 2) an increasing intensity of R&D investment, since the ratio of R&D expenditure to GDP has been growing even faster than their economies (Van Noorden, 2014) (Fig. 2). In spite of both trends, the LAC's spending on R&D still underperforms slightly relative to its 5–6% share of world population and GDP, since it accounted for 3.2% of total R&D expenditure in 2011 (RICYT, 2013).



Source: Barro (2015)
Fig. 2. Ratio of R&D expenditure to GDP in some countries of the region (2000-2011).

In addition, the government is the main source of R&D financing (around 50%) in the Ibero-American countries, whereas about 40% of R&D expenditures are financed by industry. Both figures has remained largely the same since 1997 (Crespi et al., 2010; Santelices, 2010), with the exceptions of Chile and Portugal, where industry has increased its share in R&D financing. Conversely, in OECD countries the business' share in R&D financing represented around 59% in 2010 (OECD, 2015).

These patterns make the universities' R&D activities strongly dependent on the economic development of the region's countries, rather than on a deliberate policy to involve government, industry and universities on R&D.

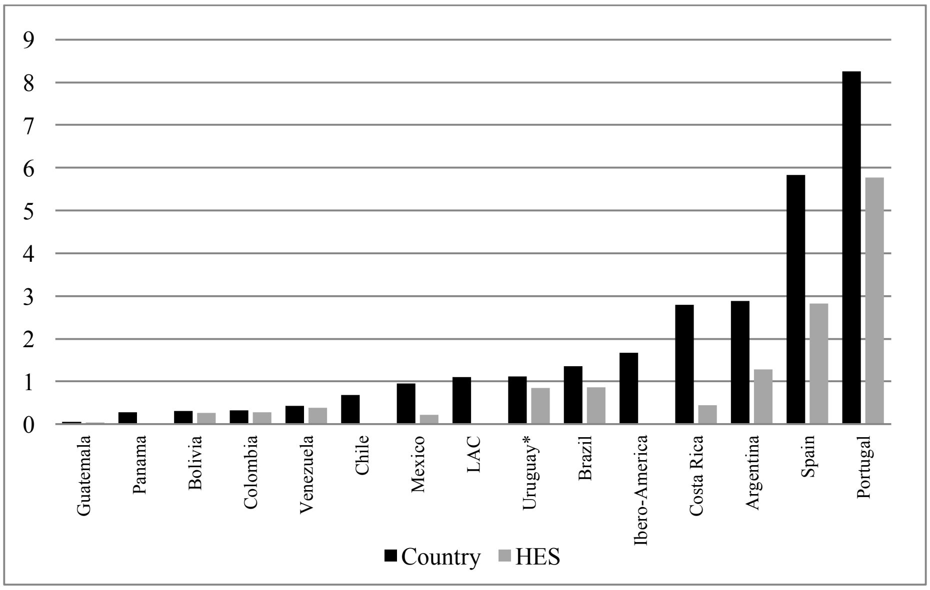
2.2 Human R&D resources

Similarly, the number of researchers in full-time equivalent (FTE) in the region's universities experienced significant growth rates. This indicator has multiplied by two in Argentina, Brazil, Colombia and Costa Rica and by three in Portugal and Venezuela, whereas this growth has been more moderate in the rest of countries. Overall, researchers (FTE) in the HES's account around 60% of the countries' researchers (FTE). This pattern significantly differs from OECD countries where the business sector absorbs more than 50 percent of researchers (Crespi et al., 2010).

However, the data show a shortage of R&D support staff for those HES's where information is available. In this context, researchers are usually forced to accept the huge bureaucratic workload of running R&D activities, undermining the overall system's efficiency.

Growth in the number of researchers has also been accompanied by an improvement in their quality. The region's countries have implemented different strategies to attract high-skilled human capital, from the repatriation of scientist working abroad (Mexico), to the design of academic careers with more stability and scholarships for researchers (Brazil or Argentina).

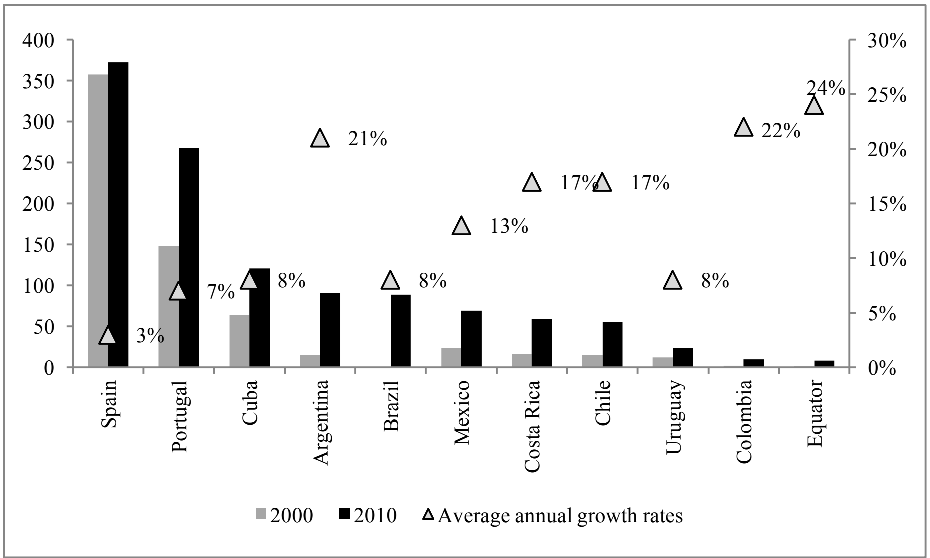
Nevertheless, there are huge differences among the region's countries. These differences become more obvious when considering the researchers (FTE) per 1,000 labor force (Fig. 3). While the number of the country's researchers (FTE) per 1,000 labor force was similar to those of the OECD countries only in Portugal (over 7.5 in 2009) (FORFÁS, 2011), most of LAC countries were struggling to bring this indicator closer to 1 over the decade. Moreover, in 2010 only Argentina, Spain and Portugal had more than 1 researcher (FTE) in the HES per 1,000 labor force.



Notes: Countries are ordered according to total researchers per 1,000 labor force. * 2011
Source: Basic data from Barro (2015)

Fig. 3. Number of researchers (FTE) per 1,000 labor force in some countries of the region (2010).

The same trends are also observed for the PhD graduates. While the number of PhD graduates has shot up significantly over the decade 2000-2010, with annual growth rates beyond 2 digits for a set of countries (Fig. 4), when considering the number of PhD graduates to the labor force, the gap between countries becomes more evident. Thus, in 2010 most of the countries were still under 100 PhD graduates per million of labor force, and even less than 10 PhD graduates in Colombia and Ecuador.

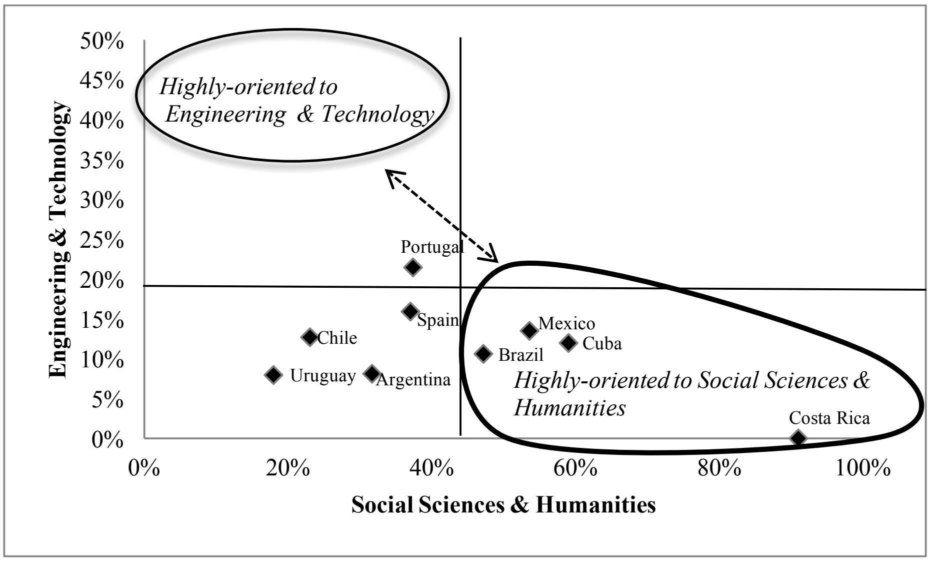


Source: Barro (2015).

Fig. 4. PhD graduates per million of labor force in some countries of the region (2000-2010).

In any case, in the past decade all HES's have driven reforms aimed at fostering the growth of advanced human capital, since it acts as facilitators for a subsequent development of R&D results. Whereas the larger HES's have strongly promoted training PhD students through national programs, the smaller HES's (i.e., Bolivia, Guatemala, Honduras, Nicaragua. Paraguay or El Salvador, among others) continue the policy of sending PhD students abroad or training them through co-operation programs with foreign universities, mainly Spanish universities.

The number of PhD graduates in Humanities and Social Sciences, both fields of knowledge less related to applied research, represents very high percentages of the total number of PhD graduates (Fig. 5). The complete opposite can be appreciated in the field of Engineering and Technology, where it is easier to use applied research in commercial products. Thus, with the exception of Portugal, where the number of PhD graduates in this area represented 21% of the total PhD graduates in 2010, they are around 15% or less in the rest of the countries for which data are available. These figures show that the region's university research still suffer from a low specialization in 'horizontal' scientific areas, i.e., with a transversal impact in various industries, such as Engineering, Sciences related to materials and Computer Technology and Interdisciplinary research. It is essential to acquire scientific abilities in these 'horizontal' sciences, as they generate spillovers on other scientific areas (BID, 2010).



Source: Basic data from Barro (2015)

Fig. 5. Percentage of PhD graduates in Social Sciences & Humanities and in Engineering & Technology in some countries of the region (2010).

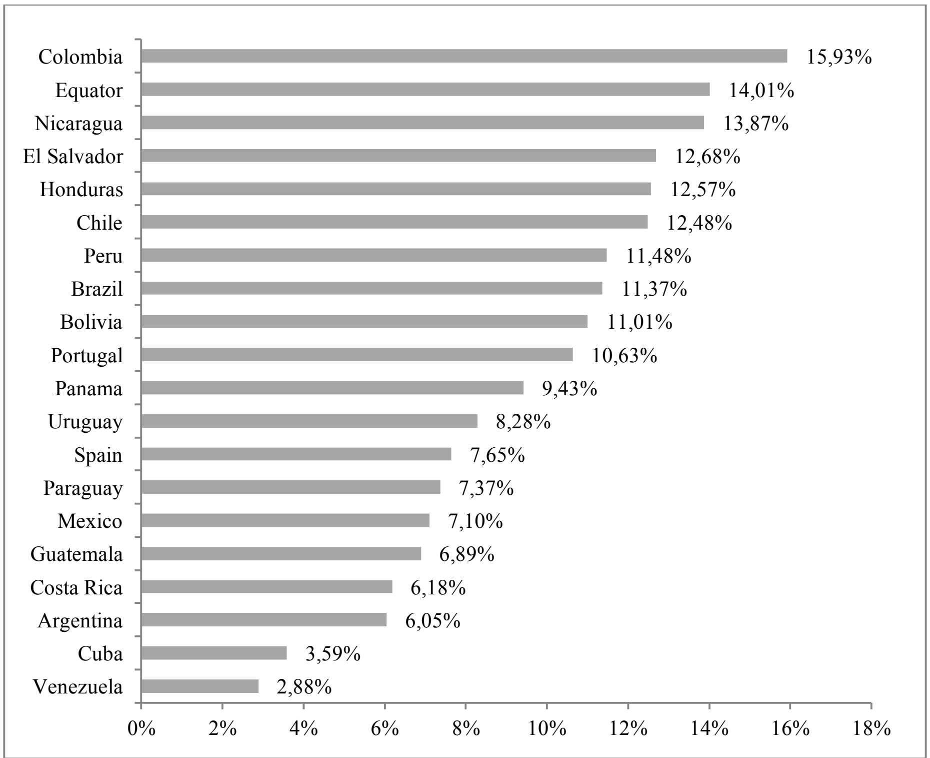
Finally, the HES's of Brazil and Spain represent nearly 70% of the total expenditure on R&D performed by the HES's of the region, as well as 62% of the researchers (FTE) and 72% of the PhD graduates. When adding Mexico, Portugal and Argentina these percentages exceed 90% for the three indicators and these figures have been reasonably stable throughout the decade 2000-2010. These differences are not only between countries, but within countries as well. Thus, in most of the HES's analyzed, especially in LAC, R&D resources tend to concentrate in a few universities, leaving a residual role on R&D the rest of them. Furthermore, this distribution usually follows a centralizing trend around large cities (in Argentina, Brazil or Chile), as well as public universities, because private HEIs, with a few exceptions, still focus their offer on teaching (in Mexico).

3 Falling behind in power: publications and patenting

3.1 Publication activity

The publication activity of the region's universities has experienced two opposing trends over the decade. On one hand, there is an outstanding growth in the number of publications in the Science Citation Index (SCI). Thus, countries such as Spain and Mexico have doubled their number of publications, while Chile and Portugal have tripled theirs. In fact, the average annual growth rates registered throughout the decade are over 6% for the HES's shown in Fig. 6, except Cuba and Venezuela. On the other hand, there has been a fall in the number of citations. Both trends have also been highlighted by Van Noorden (2014) for the national science systems of South

America.



Source: Basic data from Barro (2015)

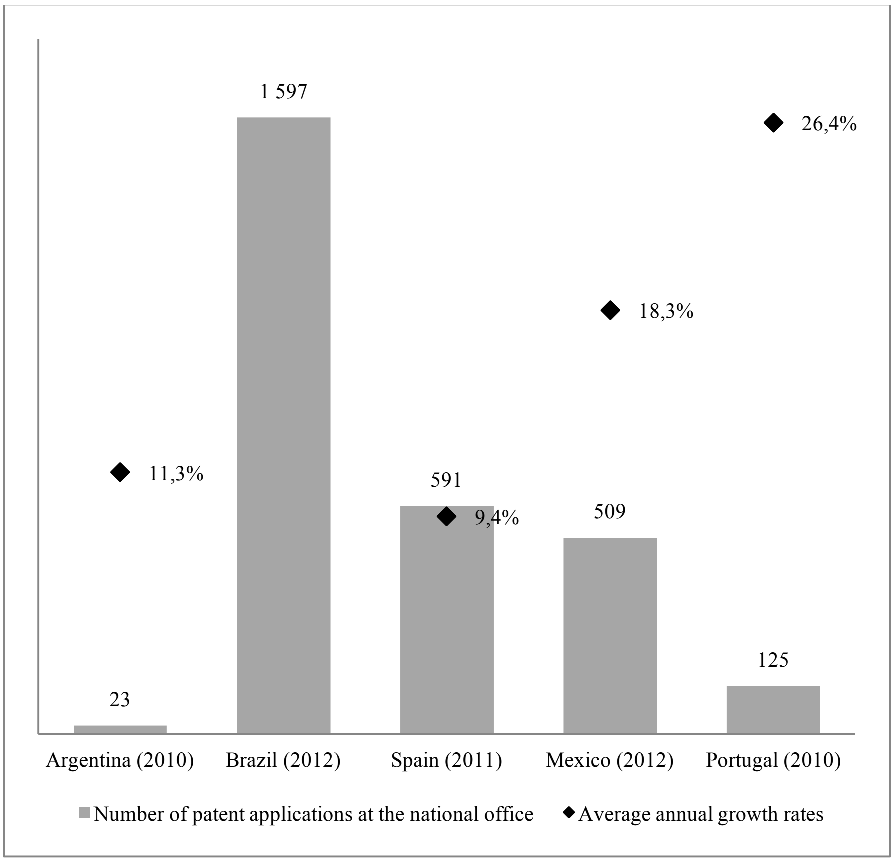
Fig. 6. Average annual growth rates of the HES' publications in *SCI* in some countries of the region (2000-2010).

The universities' publication activity has also been characterized by a low percentage of international collaborative publications, While in Colombia, Chile and Portugal, it represents 50-60% of all their publications in the SCI, it is around 35 to 42% in the rest of the countries. This percentage tends to be negatively related to the size of national science system, i.e., universities in the region's less developed countries are more likely to collaborate beyond the region, which increases the number of citations (Santelices, 2010; Van Noorden, 2014).

Again, the biggest HES's in the region (Spain, Brazil, Mexico, Portugal and Chile) concentrate 90% of the region's publications in SCI. However, in the publication activity the 'size effect' has been partly offset by the researchers' efficiency. Thus, when considering the number of publication per million inhabitants, Chile, whose HES is smaller than those of Argentina, Brazil or Mexico, occupies the third place with almost 500 publications per million inhabitants in 2010. These figures are only surpassed by Spain and Portugal, with nearly 900 publications in the SCI per million inhabitants. The rest of the HES's are far behind (under 180).

3.2 Patenting activity

Considerable effort has been devoted in the HES's for which data are available to applying for patents at the national office, since they display average annual growth rates over the 9% in this indicator during the period 2000-2010 (Fig. 7). However, there are huge differences among the HES's. While the number of patent applications annually filed by the Brazilian HES has been around 1,500 in the past few years, in Spain and Mexico, it has been of over 500 and in Portugal over 100. Argentina is far behind with around 30 patents in 2010. In any case, these figures are eclipsed by nearly 15,000 new patent applications filed by only 70 of the higher education institutions integrating the *Association of University Technology Managers* (USA) in 2013, which represents 41 new patent applications a day (AUTM, 2014).



Source: Basic data from Barro (2015)

Fig. 7. Number of the HES' patent applications at the national office and average annual growth rates of this indicator over the period 2000-2010 in some countries of the region.

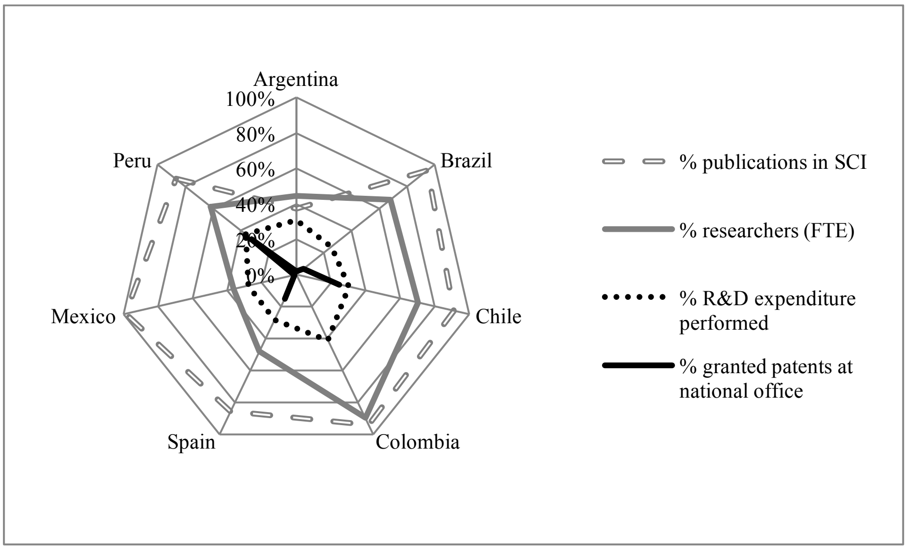
The Brazilian HES has filed more Patent Cooperation Treaty (PCT) applications than those at the national office (2,084 in 2012). In contrast, in Spain the number of filed PCT applications represents around 40% of those filed at the national level. In both countries, these percentages have barely changed in the last decade. Meanwhile, the Portuguese HES shows an important growth, partly due to the fact that its starting point was very low, so in 2010 the number of filed PCT applications represents around 30% of those filed at a national level.

The ‘success rates’, approximated as the ratios of patents granted to patents applications or patent applications five years earlier, have also shown significant differences. While Portugal shows success rates over 50%, in Argentina, Brazil and Mexico there has been a slight fall, as in Argentina and Brazil granted patents are around 10-13% of patent applications and 30% in Mexico. Spain has also experienced a fall, however its HES has the highest ‘success rate’ (with over 60% of patent applications granted).

De Moya-Anegón (2012) also presents a detailed analysis of patents granted by the *United States Patent and Trademark Office* (UPSTO) to Ibero-American applicants for the period 2003-2009. Out of the 900 Ibero-American applicants, 6% are universities (54 institutions in total) which own 171 patents. Thus, the HES’s have a relevant presence in the patents granted by the USPTO.

3.3. Where is the universities’ focus on R&D activities?

When considering the HES’s shares in the R&D resources and results of the countries, it becomes obvious that the university research activities are focused on publication rather than on patenting. Thus, the universities’ shares in the publications in SCI exceed 80% in most of the region’s countries, over performing in relation to their R&D resources. Conversely, the HES′s patenting activity underperforms, in some cases dramatically, in relation to R&D resources (Fig. 8).



Source: Basic data from Barro (2015)

Fig. 8. Percentage of the HES’s to the national science system (2010) in some countries of the region.

This low level of patenting activity is a common feature of the region's economies, which are mainly based on natural resources, dependent on imported technology, and formed primarily by SMEs with hardly any inclination towards innovation (Lederman et al., 2014). This overall context does not help patenting activity. Nonetheless, universities share a responsibility in low patenting performance, since they barely maintain relationships with industry and academic careers mainly focused on publications.

However pessimistic the situation might seem based on the previous data, there are two bright spots concerning university patenting activity. First of all, in all countries for which data are available, patents granted to HES's at a national level have increased over the decade. Secondly, the percentage of HES's patenting activity at a national level could be underestimating the university patenting output. On one hand, patents developed by academic researchers are sometimes owned by private companies. This is the case of Spain, where only 29% of all European patent applications from university researchers belong to universities, as opposed to 69% belonging to private companies (Fundación CYD, 2013). On the other hand, when the patents granted to universities are compared to patents granted to residents, the percentage of HES's patents increases up to 11% in Brazil, 60% in Chile, 25% in Colombia or 40% in Mexico.

Finally, in the particular case of LAC, the publication and the patenting activities are usually concentrated in a few HEIs with more R&D resources available, showing dramatic differences among universities within the same country. In order to minimize the effects of this 'Matthew effect' (Merton, 1968), national policies aiming at decentralizing the geographical concentration of research have been developed (that is the case of Argentina, for instance), but until now results have not been significant.

4 Conclusions and policy implications

The HES's of the region present huge differences in their dimension and results, which together with a systematic lack of information, make it enormously difficult to draw conclusions that could summarize the knowledge transfer activities in Ibero-American universities. Thus, we find that the Portuguese and Spanish HES's are close to those of developed countries. In turn, within LAC there is a need to detach Brazil, Argentina, Mexico or Chile from the rest of the countries, because, depending on the indicator analyzed, their HES's gather around 90% of all activity in LAC.

Apart from the differences in size, the Ibero-American HES's are crucial agents within the national science system, due to the importance of their share both in R&D resources and results. Regarding resources, in 2010 they performed around 30% of the R&D expenditure and concentrated over 50% of the researchers (FTE), being responsible for qualifying PhD graduates. Both figures have barely changed in the last 15 years. In addition, for some of the region's countries, the HES's concentrate a high part of the infrastructure and facilities their governments allocate to R&D activities (Barro and Fernández, 2015).

Regarding results, the HES's of the region produce around 80% of all publications in the SCI and, despite the limited amount of patents granted, when considering patents granted to residents at national offices they play a significant role.

The importance of HES's in the region's R&D makes it so urgent to promote a good number of improvement actions in order to bridge the gap with other regions.

Over the period 2000-2010 the financial R&D resources of Ibero-American HES's have proven to be extremely linked to the economy of the countries, putting universities' R&D activities seriously at risk in the coming years, since most of the region's countries are likely to experience only a moderate economic growth in the near future (Brazil, Chile, Mexico, Portugal or Spain, among others). Under this climate of macroeconomic volatility, greater efforts are needed to ensure a minimum level of financial R&D resources which enable universities to develop quality R&D and transfer their results to industry and society.

Despite the improvement both in the quantity and quality of researchers, there is not enough 'researcher density' yet to apply an intensive program of technological development in HES's and consolidate research group. Similarly, a lack of R&D support staff has been detected. Management to achieve a critical mass of R&D human resources involves clear scientific careers, with incentives attached not only to publications but also to other knowledge transfer activities, which guarantee stability for researchers who reach clearly defined goals. Regarding R&D support staff, once the administrative and technical workload attached to R&D processes was clear, the HES's need to professionalize these tasks by training support staff and, if necessary, by hiring personnel with specialized profiles.

PhD graduates in the fields of Social Sciences and Humanities outnumber those in the Experimental Sciences and Engineering. Overall, LAC does not offer many programs on emerging subjects (for instance, Genomics, Nanotechnology, Advanced Computer Science, among others). The challenge is to train PhD tutors and encourage them, together with the PhD students, to engage in emerging areas and more 'horizontal' subjects, whose results are more easily transferable to industry.

Over the decade, although the number of publications in the SCI has increased, their quality, measured as the number of citations, has dropped. The international collaborative publications represent a percentage of around 50-60% for most HES's, and it is negatively related to the size of the HES. These figures would also explain why there is less interest in the research carried. Continued efforts are needed to foster the quality of research, which usually involves publication outputs with a high impact. The challenge is also to encourage the collaboration with prestigious researchers at a national and international level and fund headhunting programs while retaining the staff.

There are many reasons explaining the low number of patents granted in the region. Obviously, changing some of them exceeds the universities' missions. However, there are several courses of action which can be taken by universities. Thus, researchers ought to be encouraged to explore which research results could be patented. Incentives could include sharing royalties with the researcher and recognizing the results patented or protected in any other way. Besides, researchers need to be supported by the Technology Transfer Offices (TTOs). Thus, it is necessary an expert team able to deal with the time-consuming and expensive process of patenting and the commercialization of R&D results. When unavailable, HES's ought to engage with public or private agents with experience in this field. There is also a need to go beyond patent grants and exploit them economically. In this sense, prior to filing a patent application, the expert team must estimate its economic value in order to prioritize applications most likely to be successfully exploited. Finally, when possible, HES's need to compel legal changes so as to make the patenting process easier, because, in general, the national regulation frameworks in the region's countries tend to be fairly restrictive.

Lastly, with the exception of the Spanish and Portuguese HES's, R&D activities tend to concentrate around a few LAC universities, namely public universities located in the larger cities of LAC. To break this circle, several actions are possible, however we advise against the demagogic approach of dividing resources without considering scientific and strategic criteria. On one hand, differences between universities must be considered in order to encourage them to specialize in knowledge fields related to strategic national industries and somehow close to the university. On the other hand, the co-operation among universities must be enforced, especially between those with a long background in knowledge transfer processes and those with a less experience in these tasks. This is possible if they promote expert mobility and share best practices and experiences, among other options.

One of the difficulties we encountered when elaborating this study was the lack of information on many of the knowledge transfer processes at universities, which made it difficult to design policies geared towards improving the efficiency of HEIs. It is recommended that further work be undertaken in gathering enough reliable information. Further research needs to be done to establish standardized indicators for each HES. These indicators could be based on those used by institutions with recognized background experience in the field (AUTM or OTRI Network, among others).

The findings of this study have proved to show a number of important implications for future practice. Unless governments and university authorities adopt some of the previous recommendations, improving the economic value creation from university R&D activities will not be attained in the Ibero-American region.

5 Acknowledgements

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Diffusion Dynamics of Sustainable Innovation - Insights on Diffusion Patterns Based on the Analysis of 100 Sustainable Product and Service Innovations

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Abstract. There is a growing consensus about the urgent necessity to green the economy and to decouple economic growth from environmental pressure. Against this background, the article explores three questions: (1) What are key factors influencing diffusion dynamics of sustainable product and service innovations? (2) To what extent do diffusion processes of sustainable product and service innovations differ from each other, and can different groups of diffusion processes be identified? (3) Which factors, actors, and institutional settings are characteristic of different groups of diffusion processes?
While diffusion research on sustainable innovation so far has been limited to case studies with just one or a small number of cases or has been focused on individual sectors, the empirical data presented here cover a large number of cases from a broad variety of product fields. This allows for generalizations as well as relevant insights and conclusions for sustainability, environmental and innovation policies.
The empirical investigation of 100 sustainable product and service innovations revealed that diffusion processes of sustainable innovations differ substantially: The cluster analysis showed that five groups of sustainable innovations can be differentiated which differ significantly in terms of the factors influencing the diffusion process. The empirical results thus both support the assumption that different types of diffusion paths do in fact exist and also permit characterization of the various types of diffusion paths. The evolutionary concept of diffusion paths develops significant explanatory power on the basis of which faster or slower cases of diffusion and the success or failure of sustainable innovations can be better understood.

Keywords. Innovation, Diffusion of innovations, Sustainable development, Environmental protection, Comparative analysis, Evolutionary economics, Path concept.

1 Introduction

There is overwhelming evidence that mankind has become a geological force (Crutzen, 2002) and that we are overloading the Earths's carrying capacities. Rockström et al. (2009) explored planetary boundaries and conclude, "Anthropogenic pressures on the Earth System have reached a scale where abrupt global environmental change can no longer be excluded." (Rockström et al., 2009, p. 1) Despite the fact that there has been an intensive political as well as scientific debate about the concept of sustainable development for more than 20 years (United Nations, 2012), even today not a single nation on the planet can claim to be sustainable in the sense that it provides for human well-being within Earth's carrying capacities (United Nations Environment Programme (UNEP), 2011, p. 21). Many countries enjoy a high level of human development – but at the cost of a large ecological footprint (Burns et al., 2010). Others have a very small footprint, but face urgent needs to improve access to basic services such as health, education, and potable water (Malik, 2013).

Against this background, there is a growing consensus about the urgent necessity to green the economy and to decouple economic growth from environmental pressure (Organisation for Economic Co-operation and Development (OECD), 2011). Greening the economy requires a strategy for sustainable transitions and fundamental changes in production and consumption patterns (UNEP, 2011). One key element in promoting and managing the multilevel challenge of sustainable transitions (Geels, 2010) is the development, implementation, and diffusion of radically new or significantly improved products (goods or services), processes, or practices which reduce the use of natural resources and decrease the release of harmful substances across the whole life cycle (Eco Innovation Observatory (EIO), 2013, p. 2). Thus, sustainable innovation and its diffusion are a key strategy for a societal transformation process toward sustainable development and a green economy. Understanding of diffusion of sustainable innovations recently has gained more importance given the fact that some sustainable innovations are already at a mature stage (Karakaya, Hidalgo & Nuur, 2014).

The central problem – and this is the evaluation of the status quo on which the present study is based – is not a lack of sustainable innovations, but that their diffusion throughout the economy and society is too narrow and too slow to solve the urgent challenges of sustainability such as climate protection and resource conservation. In other words: from a sustainability perspective, we are not confronted primarily with a problem of innovation, but a problem of diffusion!

Against this background the objective of this work is to contribute to the clarification of the following questions:

- What are key factors influencing diffusion dynamics of sustainable product and service innovations?
- To what extent do diffusion processes of sustainable product and service innovations differ from each other, and can different groups of diffusion processes be identified?
- Which factors, actors, and institutional settings are characteristic of different groups of diffusion processes?

This article will explore these questions by presenting and discussing the results of an empirical study of 100 cases of diffusion of sustainable products and services from ten different sectors. In the first part of the paper, we develop a conceptual framework for investigating the diffusion of sustainable product and service innovations. In Section 3 we define the unit of analysis, present the guiding research questions, and explicate the methodology of our empirical investigation. The methodological approach of the empirical study is innovative because it blends case study methodology using process-generated data with statistical identification of factors and clusters. In the following part of the paper (Section 4) we present the correlation and results from the factor analysis as well as the results from the cluster analysis. Based on these results we characterize five different clusters of diffusion of sustainable innovation. In the final part of paper we draw conclusions with regard to the guiding research questions, describe the limitations of the study, and outline further research needs.

2 Conceptual framework

Based on an extensive literature review, in the following section we will clarify the term "sustainable innovation" and present key insights from diffusion research in regard to factors influencing the adoption rate of innovation in general and sustainable innovation in particular. Building on central concepts of sustainable innovation and diffusion research, we then develop a conceptual framework for the analysis of the diffusion of sustainable innovation. We do this by drawing on insights from evolutionary economics in the construction of a path concept of diffusion, by providing a concept of how changes in the diffusion path come about, by looking at possibilities for assessing environmental effects of diffusion processes, and finally by pulling these elements together in a conceptual framework for the empirical investigation of the diffusion of sustainable product and service innovations.

2.1 Sustainable innovation

Sustainability-oriented innovation and technology studies have received increasing attention over the past 10 to 15 years (Markard et al., 2012, p. 955). The importance of sustainable innovation management is growing both in practice and in academia (Schiederig et al., 2012). What exactly is meant by "sustainable innovation"? Numerous terms to describe similar phenomena have been used widely in academia. The key terms used since the mid-1990s include "environmental innovation" and "eco-innovation" (Fussler, 1996; Rennings, 2000; Kemp & Pearson, 2007; Jänicke 2008; OECD, 2009; Gerstlberger & Will 2010, Horbach et al., 2012), "sustainability innovation" (Fichter & Pfriem, 2007; Arnold & Hockerts, 2011; Belz, Schrader & Arnold, 2011), "sustainable innovation" (Wüstenhagen et al., 2008; Nill & Kemp, 2009; Hockerts & Wüstenhagen, 2010), "sustainability-oriented innovation" (Klewitz & Hansen, 2014), and "green innovation" (Schiederig et al., 2012). While a distinction between social and environmental issues in innovation is made to some extent, a clear line is difficult to draw. A recent analysis of 8,516 journal publications shows that "40.7% (3,469) apply the notion 'environmental innovation', 31.9% (2,716) the notion 'sustainable innovation', 17.6% (1,495) 'eco-innovation' and 9.8% (836) the notion 'green innovation'. It appears that more than 80% of the publications use only one notion, indicating that the notions are used consistently within individual publications." (Schiederig et al., 2012, p. 183) The analysis shows that three different ideas of green, eco/ecological, and environmental innovation are used largely synonymously, while the notion of sustainable innovation broadens the concept and includes a social dimension.

There has been a rich debate in the economic literature about the distinctive features of environmental innovations and eco-innovations as opposed to general innovations

(Rennings, 2000). One of the most referenced definitions is provided by Kemp and Pearson (2007): "Eco-innovation is the production, application or exploitation of a good, service, production process, organizational structure, or management or business method that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resource use (including energy use) compared to relevant alternatives". (Kemp and Pearson, 2007, p. 7). The EU-funded Eco-Innovation Observatory (EIO) describes eco-innovation as "any innovation that reduces the use of natural resources and decreases the release of harmful substances across the whole life-cycle" (EIO, 2013, p. 10). This broad definition builds on an existing understanding of innovation and emphasizes types of inputs, outputs, as well as full life-cycle impact as key indicators of eco-innovation. Concepts of sustainable or sustainability innovation include these ecological aspects as a key feature, but also explicitly claim that radically new or significantly improved products (goods or services), processes, or practices should contribute to economic and social goals of sustainable development (Wüstenhagen et al., 2008). Rather than just focusing on short-term profits, stakeholders expect firms to meet a triple bottom line of economic, environmental, and social value creation (Elkington, 1999; Schaltegger & Wagner, 2011). Against this background, Fichter (2005) defines sustainable innovation as "the development and implementation of a radically new or significantly improved technical, organizational, business-related, institutional or social solution that meets a triple bottom line of economic, environmental and social value creation. Sustainable innovation contributes to production and consumption patterns that secure human activity within the Earths's carrying capacities." (Fichter, 2005, p. 138) In this paper we will follow this concept of "sustainable innovation."

2.2 Diffusion research

While "innovation" is the process of developing and implementing a radically new or significantly improved solution, we define "diffusion" as the process of imitation and adaptation of an innovation by a growing number of adopters. It comprises the period after the first successful implementation or after market introduction.

With regard to key factors influencing diffusion dynamics, diffusion research offers a vast array of concepts and empirical studies that deal with diffusion processes in general as well as with factors influencing the adoption rate of sustainable innovation in particular (Clausen et al., 2011, Karakaya, Hidalgo & Nuur, 2014). Rogers's pioneering work on diffusion processes underlines the importance of the attributes of innovations. Rogers (2003, p. 219 ff.) indicates that the relative advantage, compatibility, complexity, trialability, and observability of an innovation are important variables that can influence the speed of adoption. When these attributes are applied to the diffusion of sustainable product innovations, they can be considered to be relevant product-related variables. For these reason, they were used as product-related factors for examining diffusion paths of sustainable innovations.

Besides product-related variables, adoptor-related factors also play an important role in explaining the diffusion of innovations. It appears established that the adoptor group of "innovators" plays an important role during market introduction and in the first phase of diffusion, and this holds for both individuals (Rogers, 2003) and organizations (Gurisatti et al., 1997; Mukoyama, 2003). In reference to the adoptor-related factors affecting the diffusion trajectory, the question of the "presence" and participation of user-innovators as well as their early involvement in the innovation process seem to play important roles (Baldwin, Hienerth & von Hippel, 2006; Lüthje & Herstatt, 2004). The necessity of behavior changes and the requirement to develop new (consumption) routines inhibit the diffusion of innovations (Konrad & Nill, 2001; Scholl, 2009). Uncertainties concerning the function and the quality of the product, but also the regulatory environment of an innovation, delay the adoption process in the case of individuals as well as businesses (Hintemann, 2002). Fundamental differences seem to exist between private individuals and businesses as adoptors when it comes to decision-making and in the relative importance of cost-effectiveness and liquidity. In businesses, decisions are usually made collectively, and companies tend to value function, quality, and cost-effectiveness more highly (Mukoyama, 2003). In contrast, the price plays a lesser role if cost-effectiveness is given, even if SMEs (small and medium-sized enterprises) routinely mention limited availability of capital when surveyed concerning obstacles to adopting innovations (Hitchens et al., 2004). In the case of private individuals, on the other hand, a high price is often a constraint even independently of cost-effectiveness because of limited liquidity (Bottomley and Fildes, 1998; Andrews & DeVault, 2009).

Concerning supplier-related factors, various authors point to the role of pioneering suppliers of innovations (Wüstenhagen et al., 2008; Hockerts & Wüstenhagen, 2010), whereby their orientation toward sustainability could also play a role in the context of sustainability. Suppliers' sizes and reputations are important, besides the availability of relevant products and services on the market (Barney, 1991; Fombrun, 1996; Shapiro & Varian, 1999). Against this background, the variables (sustainability) goals of innovators, size and reputation of innovators, and the completeness and availability of products and services on the market can be considered to be relevant factors potentially influencing diffusion dynamics.

Concerning suppliers, Nelson (1994) in particular also refers to the development of supporting structures within the sector, so sector-related factors could be relevant for the analysis as well. The existence and activities of industry trade associations appears to be relevant especially in the context of obtaining financial support from the government, reducing regulatory obstacles, or developing exnovation tools for phasing out predecessor products (Nelson, 1994; Bruns, Köppel, Ohlhorst, & Schön, 2008). The role of market leaders also appears to be relevant for diffusion. For example, whether they spend years litigating against laws promoting renewables or whether innovators in the field in question are involved from the beginning can be expected to have a significant impact on the speed of diffusion. Intermediaries as change agents should also be taken into consideration as a possible supporting factor (Antes & Fichter, 2010).

Because of the double externality problem of environmental innovations, the political factors of government intervention play a special role in their development and diffusion (Jänicke, 2008, 2005; Rennings, 1998). The diverse political instruments used by governments to support the diffusion of environmental innovations (Jänicke, 2008) as well as the societal forces impacting innovation and diffusion processes can be grouped in four different factors: governmental push and pull activities as well as institutional obstacles (Andersen & Liefferink, 1997; Jaffe & Stavins, 1995), lead market policies (Beise & Rennings, 2005), media reporting, and campaigns by non-governmental organizations (Brunner & Marxt, 2013).

Furthermore, diffusion research based on evolutionary economics also stresses the fact that there is an inherent dynamic in the diffusion path because of path dependencies, competing industry standards, and dominant designs (Nelson & Winter, 1982; Brown, Hendry & Harborne, 2007), and due to self-reinforcing effects such as the critical mass phenomenon (Arthur, 1989; Cowan, 1990; Lehmann-Waffenschmidt & Reichel, 2000, p. 349) or network effects (Geroski, 2000; Rogers, Medina, Rivera & Wiley, 2005; Vollebergh & Kemfert, 2005). The path-specific factors include the historical ties and self-reinforcing forces with effects on (routine) paths to date, the effects of price developments (up or down), and the forces resulting in new ties when new paths are established. Against this background, we constructed three path-specific factors to examine the diffusion paths of sustainable innovations: path dependencies due to historical ties, interactions between competing diffusion paths, and self-reinforcing effects within the diffusion path itself.

Based on theoretical and empirical work on factors influencing the diffusion process, six key areas of influence on diffusion speed can be distinguished: (1) product-related factors, (2) adoptor-related factors, (3) supplier-related factors, (4) sector-related factors, (5) government-related factors, and (6) path-related factors. Within the key areas, different factors have been identified (Clausen, Fichter & Winter, 2011).

2.3 Path concept of diffusion

When it comes to explaining why the diffusion speed of sustainable innovations does differ and what the key factors influencing diffusion dynamics are, evolutionary economics is a powerful theory to build on. During the past 30 years, numerous authors have placed the path concept developed in evolutionary economics at the center of their studies and approaches for explaining innovation and diffusion trajectories, using the work by Nelson and Winter (1982) as a starting point (Clausen et al., 2011). The path concept provides a good basis for studying existing path dependencies, potential exit options for creating new paths (Sydow, Schreyögg & Koch, 2009), and the factors emerging over the course of the diffusion process. To date, studies of trajectories have considered linear chains of events, bifurcation and multifurcation points, and linkages between different paths (Lehmann-Waffenschmidt & Reichel, 2000; Lehmann-Waffenschmidt, 2010). While lock-in to a particular path and the path dependencies that arise or have an effect here are discussed intensely, the questions as to how and why bifurcation and multifurcation points emerge and how actors can intentionally create new paths have received little attention. Precisely at this point, however, creating a link to the insights and conceptualizations of innovation process research appears promising (Van de Ven, 1999) because it deals with the emergence and the trajectories of innovation processes. In order to be able to create this linkage, however, it is vital to first make clear that innovation is a specific mode of transformation, and just one of several possible modes. Fundamentally speaking, four modes of transformation can be differentiated, and all of them are relevant for the sustainability of innovations (Fichter, 2014):

1. *Variation*: Gradual changes to existing technologies and practices optimize the path. Schumpeter characterizes this mode of transformation as "adaptive response" (Schumpeter, 1947).
2. *Innovation*: the attempt to achieve a lock-in break in a routine path. In the successful case of "breaking away" from a routine path, a split (bifurcation or multifurcation) occurs, and a new path is formed (path creation). Schumpeter characterizes this mode of transformation as "creative response" (Schumpeter, 1947).
3. *Diffusion* by imitation and adaptation: Innovative solutions already being used successfully in other regions, markets, or organizations are taken on and adapted. A relatively young path is broadened and disseminated; chains of events (imitation and adaptation processes on the part of specific adoptors) within this path branch out further and multiply. In part, however, innovative solutions are also adapted and varied in specific ways.
4. *Exnovation*: Previously used technologies, products, or practices are discontinued or phased out. A previous path is terminated. Examples include the ban on light bulbs in the European Union, Germany's nuclear phase-out, and decisions by companies to withdraw products from the market due to unprofitability or insufficient turnover.

The path conceptions existing to date do not differentiate between the four modes of transformation described above, even though it is precisely these four modes that provide an explanation of how bifurcation and multifurcation points can occur. Understanding the dynamics of sustainable innovation requires a further move to "interdisciplinary crossovers" (Geels, Hekkert & Jacobsson, 2008, 527). On the basis of the fundamental understanding presented above, an innovation path can be interpreted from an interdisciplinary standpoint as an innovation process and thus as an intentionally organized process for branching out from routine paths. Hence, an innovation path encompasses the chain of events of an innovation project. Extending the concept of the innovation path, a diffusion path can be understood as a chain of events of a particular diffusion process over time. The diffusion path includes the imitation and adaptation events on the part of the adoptors as well as the activities and measures affecting those adoptors, including, for example, the activities of suppliers, the services provided by market intermediaries (e.g., wholesalers and retailers) and policy intermediaries (e.g., energy or climate protection agencies) (Antes & Fichter, 2010) as well as, for instance, the efforts on the part of the government to intervene in the form of legal provisions and support programs. Thus, the diffusion path is embedded within a diffusion system which, as a social system (Rogers, 2003, p. 23 ff.), encompasses both diffusion-relevant actors and specific institutional arrangements. Against this background, we defined the term "diffusion path" as follows:

> *A diffusion path encompasses the chain of events of a certain diffusion process over time and its embeddedness in a specific diffusion system. It depicts the diffusion of an innovative solution by means of imitation and adaptation and can be caused by the efforts of actors to stabilize a new path and to establish it long-term or by self-reinforcing effects.*

2.4 Conceptual framework for the analysis of the diffusion of sustainable innovation

We used the diffusion path concept developed above to analyze the diffusion of sustainable innovation. On that basis we defined a diffusion path as the chain of events of a certain diffusion process. A diffusion path is embedded in the diffusion system of a specific region or sector and influenced by its actors, institutions, and resources (Geels et al., 2008). We distinguished six key areas of influence on diffusion speed on the basis of theoretical and empirical work on factors influencing the diffusion process (cf. Section 2.2): (1) product-related factors, (2) adoptor-related factors, (3) supplier-related factors, (4) sector-related factors, (5) government-related factors, and (6) path-related factors. A total of 22 variables potentially influence diffusion dynamics and were taken into account when analyzing diffusion dynamics. Major qualitative changes in the direction or speed of diffusion can be classified as tipping points (market introduction of a product, reaching critical mass, bifurcation or multifurcation points, change of direction and abrupt changes in the trajectory and market exit of the product) (Schelling, 1971, p. 181 ff.; Granovetter & Soong, 1986; Coenen, Benneworth & Truffer, 2012; Hess, 2014).

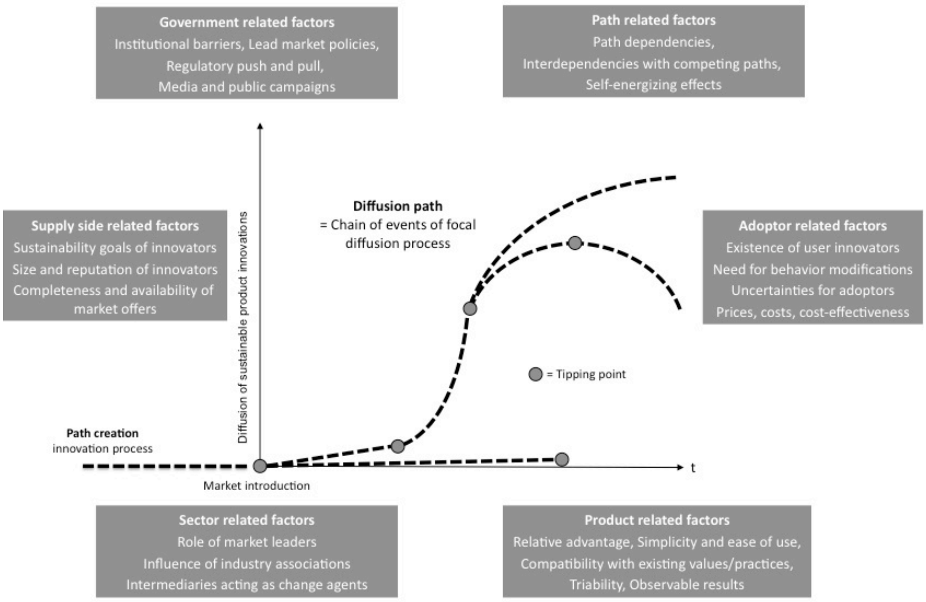

Fig. 1. Research framework for analyzing the diffusion of sustainable innovation

3 Material and methods

In the following section we give a precise definition of the unit of analysis employed in the empirical investigation, introduce the guiding research questions, and describe the methodology of our empirical research design.

3.1 Unit of analysis

The unit of analysis of the empirical investigation presented in this paper is diffusion dynamics of sustainable product and service innovations. Since diffusion processes are very complex fields of investigation, we limited the scope of the study in three ways. (1) We decided to focus on product and service innovations. We did this for two reasons: First, because products and services have a huge impact on production and consumptions patterns and on achieving economic, environmental, and social goals. Second, because the diffusion of marketable goods can be observed more easily (e.g. based on market data and other publicly available information) than process-related, institutional, or social innovation. This is especially important when investigating a large number of cases. (2) Furthermore, we decided to investigate the diffusion process in a specific geographical region or country. Because of funding constraints (cf. Acknowledgements), we decided to choose a European country and selected Germany as the largest national market in Europe. (3) Finally, we decided to focus the analysis on the period between market introduction and the time of investigation (2011). In order to study the diffusion process sufficiently, we defined that the duration between market introduction and the time of investigation had to be at least three years. Thus, we chose only products that had been introduced to market before 2008.

3.2 Guiding research questions

The guiding research questions for the empirical investigation are:

1. What are key factors influencing diffusion dynamics of sustainable product and service innovations?
2. To what extent do diffusion processes of sustainable product and service innovations differ from each other, and can different groups of diffusion processes be identified?
3. Which factors, actors, and institutional settings are characteristic of different groups of diffusion processes?

3.3 Methodology

Since no large-scale study across sectors or product fields on the diffusion of sustainable innovations has been conducted to date, this study broke new ground for empirical research. Two different methodological approaches were available for this task:

The first approach would attempt to study the diffusion of a marketable good (product or service innovation) across a long period of time, using selected indicators such as market share, parallel to the process itself. Such a longitudinal study was not feasible in the context of the 3-year duration of the project on which the present study is based because it would have required an observation period of more than three years. A second, alternative approach would be to model the diffusion of an innovation retrospectively using process-generated data, i.e., using authentic data created over time and for purposes other than answering the research questions formulated here. Such data covering long periods of time are often not available, or not in the quality desirable for purposes of research, for which reason such a procedure was out of the question here as well. In order to do justice to the present research problem nonetheless, we selected a research approach that encompasses a new form of methodological triangulation and which must therefore be briefly described and justified:

As sufficient data generated during the process itself are not available for the object of this study – diffusion of sustainable innovations – we decided on the following procedure for surveying data.

Selection of cases. First, we selected all those product fields from the universe of all marketable goods that are of particular importance for sustainable development and that can make a major contribution to reaching national and international sustainability goals. We used studies and sustainability strategies at the national and international levels for this purpose. The selection of product fields was to refer to the geographical area selected for the study (Germany). Both the lead markets and the fields already identified in German and European environmental and innovation policy were to be taken into account. They include the lead markets for environmental technology mentioned in the Umwelttechnologie-Atlas für Deutschland (Environmental Technology Atlas for Germany) "GreenTech made in Germany 2.0" (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), 2009) as well as the future markets for environmental innovations identified by the European Commission in the EU Lead Market Initiative (Commission of the European Communities (COM), 2007). When selecting cases, it was important to ensure that a sufficient range of products and services were covered in order to guarantee that the study actually included numerous sectors and product fields. Against this background, we decided to study at least 10 different product fields. Thus, we oriented sampling toward the main criteria: relevance for sustainability and range of the product fields.

In addition, the goal was to ensure that it would be possible to study a certain range of different products, services, and technologies in each product field in order to be able to elaborate possible commonalities and differences within each one. Against this background, we decided to use 10 different products from 10 different product fields for the study (cf. Table 2).

Defining independent variables. We performed a comprehensive evaluation of the literature as the basis for the empirical study. It yielded 22 potential factors influencing the diffusion trajectories of sustainable innovations in six fields of influence (cf. Section 2.2 and Figure 1) for which it can justifiably be assumed that they have an influence on the diffusion trajectories of sustainable product and service innovations or correlate with the dynamics of diffusion. We used these 22 potential factors as independent variables for the empirical study. We developed a coding system for each factor to assess the value of the variable (cf. Appendix 1).

Construction of the dependent variable "diffusion dynamics". One of the key goals of the study was to elaborate obstacles and drivers in the diffusion process, so we had to assess the progress of the diffusion process in this regard. Market penetration, i.e., market share, is most useful as a measure of diffusion of marketable goods. The amount of time required for the process, measured as the time since market entry, is relevant as well. Finally, a study across sectors and product fields must consider that a comparison across product fields cannot be carried out readily because of their very different underlying conditions. For this reason, the typical innovation and market cycles of a product field must be taken into account when constructing a dependent variable to be used as an indicator of diffusion dynamics across product fields.

That is why we drew upon three sub-indicators when constructing the indicator "diffusion dynamics." We defined them as follows with regard to the sample to be studied:

(1) Market share, using the scale:

a. up to 1% (coded as 1)

b. more than 1 and up to 10% (coded as 2)

c. more than 10 and up to 50% (coded as 3)

d. more than 50% (coded as 4)

(2) Duration of the diffusion process, measured as the time since market introduction:

a. before 1980 (coded as 1)

b. from 1980 to 1989 (coded as 2)

c. from 1990 to 1999 (coded as 3)

d. since 2000 (coded as 4)

(3) The diffusion speed of a specific innovation in relation to the other innovations in the product field in question. We set the two values mentioned above for a particular innovation in relation to the values of the other innovations in the product field, thus generating a ranking order. After all, what constitutes "rapid" diffusion varies considerably depending on the product field. The goal of adding 2 points to the value or subtracting 2 points from it was to enhance the value of the two most successful innovations in each product field and to reduce it for the two least successful ones. In individual product fields where it appeared impossible to differentiate reasonably between the three top innovations, we applied this method to the top or bottom three innovations. In other product fields, where the gap between the top or bottom two innovations was so large that it appeared unreasonable to assign them the same values, we did so for just the one top or bottom innovation. Table 1 shows the classification, Table 2 the results. The variable "diffusion dynamics" results from the summation of the values of the sub-variables market share, duration of diffusion process, and rank of a specific product/service within the product field. The minimum value of the variable "diffusion dynamics" is 0 (no dynamics), the maximum value is 10 (very high dynamics).

Table 1. Assessment of the rank of a specific product/service within the product field

Product field	**2 points subtracted from value**	**2 points added to value**
Organic food	Max. 1% market share	More than 10% market share
Renewable resources	Max. 10% market share and market introduction before 1990	More than 50% market share
Renewable energy systems	Max. 10% market share and market introduction before 1990	More than 50% market share or more than 10% market share and market introduction after 1980
Low-exergy energy systems	Max. 10% market share and market introduction before 1980 or max. 1% market share and market introduction before 1990	More than 10% market share
Energy-efficient electric devices and lighting	Max. 10% market share and market introduction before 1990	More than 10% market share and market introduction after 2000 or more than 50% market share and market introduction after 1990
Construction and heating technology	Max. 10% market share and market introduction before 1990	More than 10% market share and market introduction after 1990
Green IT end devices	Max. 10% market share	More than 10% market share and market introduction after 2005
Energy efficiency in data centers	Max. 10% market share and market introduction before 2005	More than 10% market share and market introduction after 2000
Telecommunications and online media	Max. 10% market share and market introduction before 2000	More than 10% market share and market introduction after 2000 or more than 50% market share and market introduction after 1990
Sustainable mobility	Max. 1% market share and market introduction before 1990	More than 10% market share

Table 2. Construction of the dependent variable "diffusion dynamics"

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
Organic food	Organic baby food	1969	1	50 to 100%	4	+2	**7**
	Bionade (organic soft-drink brand)	1995	3	1 to 10%	2	0	**5**
	Organic food subscriptions	1985	2	0 to 1%	1	-2	**1**
	Organic wine	1965	1	0 to 1%	1	-2	**0**
	Organic bread	1991	3	1 to 10%	2	0	**5**
	Fair trade coffee	1992	3	1 to 10%	2	0	**5**
	MSC-certified fish	1997	3	10 to 50%	3	+2	**8**

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
	Free-range eggs	1990	3	1 to 10%	2	0	**5**
	Organic milk	1991	3	1 to 10%	2	0	**5**
	Tea from the Teekampagne	1985	2	1 to 10%	2	0	**4**
Renewable resources	Starch-based biodegradable packaging	2005	4	0 to 1%	1	0	**5**
	Natural fiber plastic composites	1990	3	1 to 10%	2	0	**5**
	Biogenic lubricants	1999	3	1 to 10%	2	0	**5**
	Insulating materials from renewable resources	1982	2	1 to 10%	2	-2	**2**
	Natural paints	1980	1	1 to 10%	2	-2	**1**
	Wood-plastic composite (WPC) deck flooring	2004	4	1 to 10%	2	0	**6**
	Laundry detergents based on renewable resources	1985	2	50 to 100%	4	+2	**8**
	Organic cotton	1990	3	0 to 1%	1	0	**4**
	Woolen rugs with the Rugmark/Goodweave seal	1995	3	1 to 10%	2	0	**5**
	Organic shoes	1990	3	1 to 10%	2	0	**5**
Renewable energy systems	Biodiesel	1990	3	1 to 10%	2	0	**5**
	Biogas facilities	1980	2	10 to 50%	3	+2	**7**
	Large-scale hydroelectric facilities	1880	1	50 to 100%	4	+2	**7**
	Small-scale hydroelectric facilities	1980	2	50 to 100%	4	+2	**8**
	Pellet heating systems	1998	3	1 to 10%	2	0	**5**
	Photovoltaics	1985	2	1 to 10%	2	-2	**2**
	Skysails	2005	4	0 to 1%	1	0	**5**
	Thermal solar power	2007	4	0 to 1%	1	0	**5**
	Wind power (onshore)	1975	1	10 to 50%	3	0	**4**
	Wind power (offshore)	1991	3	0 to 1%	1	0	**4**
Low-exergy energy systems	Solar-powered absorption refrigeration systems	1960	1	0 to 1%	1	-2	**0**
	Small-scale cogeneration plants	1880	1	10 to 50%	3	+2	**6**
	Bioenergy villages	2005	4	0 to 1%	1	0	**5**
	Geothermal and hydrothermal cooling	1995	3	0 to 1%	1	0	**4**
	Long-term thermal energy storage	1995	3	0 to 1%	1	0	**4**
	Mobile heat transport	2009	4	0 to 1%	1	0	**5**
	District heating	1880	1	10 to 50%	3	+2	**6**

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
	Solar thermal energy	1978	1	1 to 10%	2	-2	**2**
	Deep geothermal facilities	1984	2	0 to 1%	1	-2	**1**
	Heat pumps	1975	1	10 to 50%	3	+2	**6**
Energy-efficient electric devices	Highly efficient freezers	2004	4	10 to 50%	3	+2	**9**
	Highly efficient refrigerators	2004	4	1 to 10%	2	0	**6**
	Highly efficient clothes dryers	1998	3	1 to 10%	2	0	**5**
	Energy-saving light bulbs	1985	2	1 to 10%	2	-2	**2**
	Highly efficient dishwashers	1999	3	50 to 100%	4	+2	**9**
	Induction cookers	1987	2	1 to 10%	2	-2	**2**
	LED lighting fixtures	2007	4	1 to 10%	2	0	**6**
	Master-slave multiple-socket outlets	2000	4	1 to 10%	2	0	**6**
	Highly efficient circulation pumps	2000	4	1 to 10%	2	0	**6**
	Highly efficient washing machines	1998	3	50 to 100%	4	+2	**9**
Construction and heating technology	Passive houses	2000	4	1 to 10%	2	0	**6**
	Prefabricated wood building	1920	1	10 to 50%	3	0	**5**
	Composite insulation systems	1957	1	1 to 10%	2	-2	**1**
	Heat recovery ventilation	1970	1	1 to 10%	2	-2	**1**
	Windows with triple glazing	1990	3	50 to 100%	4	+2	**9**
	Condensing boilers	1990	3	10 to 50%	3	+2	**8**
	Underfloor and wall heating	1980	2	10 to 50%	3	0	**5**
	Radiator thermostats	1969	1	50 to 100%	4	0	**5**
	Time-controlled thermostat	1999	3	1 to 10%	2	0	**5**
	Hydronic balancing	1970	1	10 to 50%	3	0	**4**
Green IT end devices	Inkjet printers	1984	2	50 to 100%	4	0	**6**
	Multifunctional devices	1994	3	50 to 100%	4	0	**7**
	80-plus power supply units	2005	4	50 to 100%	4	+2	**10**
	2 ½” hard disks	1992	3	50 to 100%	4	0	**7**
	Windows energy options	1995	3	1 to 10%	2	-2	**3**
	Notebooks	1987	2	50 to 100%	4	0	**6**
	Netbooks	2007	4	10 to 50%	3	+2	**9**
	Nettops/Mini-PCs	2005	4	10 to 50%	3	+2	**9**
	Thin clients	1997	3	1 to 10%	2	-2	**3**
	LCD monitors	1989	2	50 to 100%	4	0	**6**

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
Energy efficiency in data centers	Energy-efficient servers	2005	4	10 to 50%	3	+2	**9**
	Server energy management	2003	4	10 to 50%	3	+2	**9**
	Solid-state drives	2006	4	1 to 10%	2	0	**6**
	Fiber optic cables	1983	2	10 to 50%	3	0	**5**
	Highly efficient uninterruptible power supplies	2002	4	50 to 100%	4	+2	**10**
	Water-cooled racks	2007	4	1 to 10%	2	0	**6**
	Hot aisle/cold aisle separation	2000	4	1 to 10%	2	-2	**4**
	Free cooling	1980	2	50 to 100%	4	0	**6**
	Blade servers	2001	4	10 to 50%	3	+2	**9**
	Server virtualization	1999	3	10 to 50%	3	0	**6**
Telecommunications and online media	E-mail	1993	3	50 to 100%	4	+2	**9**
	Teleconferencing	1993	3	10 to 50%	3	0	**6**
	Videoconferencing	1991	3	1 to 10%	2	-2	**3**
	Virtual answering machines	1997	3	1 to 10%	2	-2	**3**
	Teleworking	1989	2	10 to 50%	3	0	**5**
	MP3 music files	1995	3	10 to 50%	3	0	**6**
	Video on demand	2006	4	10 to 50%	3	+2	**9**
	Online marketplaces for second-hand goods	1999	3	10 to 50%	3	0	**6**
	Digital cameras	1991	3	50 to 100%	4	+2	**9**
	E-book readers	2008	4	0 to 1%	1	0	**5**
Sustainable mobility	Hybrid vehicles	1997	3	0 to 1%	1	0	**4**
	Electric cars	1995	3	0 to 1%	1	0	**4**
	3-liter (75 mpg) cars	1999	3	0 to 1%	1	0	**4**
	Natural gas cars	1995	3	0 to 1%	1	0	**4**
	Low-resistance tires	1992	3	1 to 10%	2	0	**4**
	Carsharing	1988	2	0 to 1%	1	-2	**1**
	Ride-sharing agencies	1968	1	0 to 1%	1	-2	**0**
	Mobile navigation devices enabling drivers to avoid traffic jams	2006	4	50 to 100%	4	+2	**10**
	German half-price railcard	1992	3	10 to 50%	3	+2	**8**
	Auto trains	1930	1	0 to 1%	1	-2	**0**

Case analysis. We prepared a qualitative profile for each case, using secondary information. This secondary information was available in the form of market analyses, life-cycle analyses, websites of inventors, manufacturers, wholesalers, and retailers as well as product- or use-related Internet sources. In total, about 5,000 sources of information were accessed and about 1,200 were cited in the 100 case studies. The description of the cases in each of the profiles followed a defined format and a given coding system (cf. Appendix 1). This included key data on the object of innovation and the diffusion process as well as the 22 variables (cf. Table 3) which we had elaborated as potentially relevant for the trajectory of the diffusion process. In this way, it was possible to survey qualitative secondary information quantitatively. At the same time, this en-sured that we surveyed the same data for all cases. In other words, the procedure is similar to participant observation.

The profile format fulfilled the function of a standardized survey instrument, similar to a standardized observation protocol. We surveyed the variables using 3-point scales (2, 1, 0 or 0, -1, -2) and 5-point scales (-2 to +2). The result of the survey was a dataset including key data about 100 cases of sustainable innovations as well as values for the 22 independent variables.

A coding team evaluated the independent variables using the 3-point and 5-point scales and assigned a value to each factor in each case. For example, we coded the case “heat pumps” with the value of 0 for the variable “perceptibility,” since the innovation is hardly visible to the public and perceptibility can thus neither be assigned an effect promoting (+1 or +2) or inhibiting (-1 or -2) diffusion. The coding team comprised five researchers with specific expertise in the particular technology, product/service, or market.

We took two measures to ensure inter-rater reliability. First, we conducted a pretest in which all the researchers (observers) analyzed and coded the same case independently of one another. We specified details for assessing the cases in a uniform manner on this basis. Second, at least one person, usually two, checked and evaluated each of the 100 profiles again. The team of five researchers, who then jointly specified the evaluations, discussed any deviations. In this way, we quantified qualitative data in the present paper and made them accessible to statistical evaluation without claiming in the slightest to have depicted causal relationships or undertaken measurements. For this reason, we first carried out the quantitative evaluation descriptively with the goal of identifying groups of sustainable innovations that are comparable in terms of certain factors and their diffusion trajectories.

Factor analysis. We conducted a factor analysis to identify linkages between the independent variables. The goal of a factor analysis is to reduce the complexity of a dataset and potentially discover structures that may not have been surveyed but nonetheless exist empirically (Hair et al., 2006; Hardy & Bryman, 2004). A factor analysis produces new variables that indicate the linkage of each of the 22 empirical factors with the newly calculated factors in form of factor loading. In other words, the reduction of complexity is achieved by consolidating factors that “fit together,” as it were, to form a single new factor. The first step in the factor analysis was to perform calculations to verify the suitability of the 22 factors for factor analysis. Here, the variable “institutional obstacles” (factor 16) proved mathematically unsuitable; we excluded it from the further analysis for this reason. We then calculated the principal component analysis with a varimax rotation (Hair et al., 2006; Hardy & Bryman, 2004). Compared with other methods of factor analysis, this method has the advantage of maximizing the factor loadings of those factors with especially high loads. This serves to support content-related interpretation of the newly determined factors and their later use in cluster analysis. We based the naming of the new factors on our interpretation and oriented it toward the 22 original variables and their loading on the factors.

Cluster analysis. In order to identify diffusion paths, it was necessary to elaborate groups of innovations that are as similar as possible with a view to the factors. In other words, we posited that some of the sustainable innovations studied here are similar concerning the factors we had identified in the factor analysis and that influence the diffusion process. To this end, we used the method of cluster analysis. In cluster analysis, cases are assigned to groups on the basis of influencing factors. They are assigned in such a way the homogeneity within a group is maximized while homogeneity between groups is minimized. In the present case, we conducted a cluster center analysis using the latent variables identified in the factor analysis (Hair et al., 2006; Hardy & Bryman, 2004).

4 Results

4.1 Correlation and results from the factor analysis

We tested the correlation between the 22 independent variables and the three dependent variables "market share," "diffusion time" and "diffusion dynamics" (cf. Table 3).

Table 3. Correlations between 22 independent variables and 3 dependent variables of 100 diffusion cases

		Dependent variables		
Factor group	Kendall's tau-b and approximate significance Independent variable	Market share	Duration of the diffusion process since market introduction	Diffusion dynamics
Product-related factors	Relative advantage of the innovation			
	Perceptibility			
	Compatibility			0.158*
	Low complexity			
	Trialability			
Adoptor-related factors	User innovators	-0.203*	-0.175*	-0.190*
	Low need for behavior modification	0.316**		0.235**
	Uncertainties on the part of adoptors	0.264**		0.292**
	Price, costs, cost-effectiveness	0.198*		0.160*
Supplier-related factors	"Green" pioneers	-0.207*		
	Renown and reputation of suppliers	0.326**		0.276**
	Completeness and availability of service	0.269**	0.201*	0.315**
Sector-related factors	Role of the industry trade association			
	Role of market leaders	0.235**	0.330**	0.385**
	Intermediaries as change agents			
Policy-related factors	Institutional obstacles			
	Governmental push and pull activities		-0.328**	-0.164*
	Lead market policies			
	Media and campaigns			
Path-related factors	Path dependencies			
	Price development	0.176*		
	Self-reinforcing effects	0.285**		

*Values of Kendall's tau-b: 0 to 0.05: no correlation; up to 0.2: weak correlation; up to 0.5: medium correlation; more than 0.5: strong correlation. Only those correlations that are at least significant and at least weak are shown. * significant at 5% level; ** significant at 1% level*

The fact that we could identify a significant correlation with regard to the key dependent variable "diffusion dynamics" for just 9 of the 22 factors suggests that further latent variables are hidden behind the surveyed variables. For this reason, we conducted a factor analysis (cf. Chapter 3.3) to clarify whether such latent variables that impact the diffusion trajectory exist. We carried out a principal component analysis with a varimax rotation (cf. Table 4). We drew mostly on the strong factor loadings (> 0,5 or < -0,5) for the substantive interpretation and characterization of the new factors. The factor analysis explains 62.9% of the variance, i.e., the seven newly developed factors can explain 62.9% of the variance in the field. According to Bartlett's test of sphericity, the analysis is highly significant (p < 0.01).

Table 4. Factor analysis: Rotated component matrix

Component	Market power of established suppliers	Political push & pull	Small Influence of pioneers	Incentive to buy	Compatibility with routines	Price and cost-effectiveness	Comprehensibility of the innovation
	1	2	3	4	5	6	7
Factor 1: Relative advantage of the innovation	-.095	.187	-.082	.687	.135	-.055	.273
Factor 2: Perceptibility of the innovation	.170	.017	.561	-.015	-.167	-.015	-.147
Factor 3: Compatibility of the innovation	-.106	-.139	.035	.113	.602	.272	.250
Factor 4: Complexity of the innovation	.064	-.078	-.002	.032	.004	.077	.831
Factor 5: Trialability of the innovation	.293	-.634	.297	.063	-.099	-.108	.085
Factor 6: User-innovators	-.167	-.180	.741	.173	-.032	.085	-.002
Factor 7: Need for behavior modification	.128	.060	-.168	-.031	.779	-.183	-.102
Factor 8: Uncertainties on the part of adoptors	.031	-.001	-.268	.112	.290	.082	.487
Factor 9: Price, costs, cost-effectiveness	-.030	.184	-.157	.019	-.013	.805	.312
Factor 10: "Green" pioneers	-.034	.180	.705	-.231	.249	-.258	.025
Factor 11: Size and reputation of suppliers	.730	.040	-.092	.236	.201	.099	.044
Factor 12: Completeness/availability of service	.467	-.092	.160	.134	.501	.122	.220
Factor 13: Role of the industry trade association	.354	.626	-.181	-.064	-.036	.156	-.154
Factor 14: Role of market leaders	.495	-.285	-.417	.196	.089	-.368	-.014
Factor 15: Intermediaries as change agents	.620	.280	.195	-.142	-.083	-.101	.369
Factor 17: Governmental push and pull	-.142	.744	.171	.164	.036	-.314	.141
Factor 18: Lead market policies	.069	.725	.197	.167	-.172	.119	-.014
Factor 19: Media and campaigns	.483	.193	.417	.209	-.210	.282	-.060
Factor 20: Path dependency	.552	-.264	-.056	-.269	-.003	-.011	-.133
Factor 21: Price development	.149	.003	.057	.812	-.008	.124	-.100
Factor 22: Self-reinforcing effects	.306	-.227	.168	.250	.226	.564	-.300

Values of the factor loadings: > 0.5 and < -0.5: strong loading; 0.4 to 0.5 and -0.4 to -0.5: weak loading

The principal component analysis with a varimax rotation revealed seven new factors. The derivation of the seven new factors can be explained as follows:

Factor 1: Market power of established suppliers. The variables "size and market power of suppliers," "intermediaries as change agents," and "path dependency" load highly on the factor. The variables "role of market leaders," "media and campaigns," and "completeness and availability of products and services on the market" round out the picture with weak loadings. Overall, a factor emerges that encompasses both the suppliers themselves and the market and policy intermediaries active in their environment. The new factor is therefore most aptly described as "market power of established suppliers." The high loading of the variables "size and reputation of suppliers" as well as the high loading of the factor "path dependency" imply the existence of a factor that would tend to describe the diffusion of incremental innovations of existing and established products that have already formed their paths. The factor explains 11.3% of the variance of the 22 original factors.

Factor 2: Political push & pull. "Governmental push and pull activities" and "lead market policies" load highly on the factor, the "role of the industry trade association" loads weakly. If the role of an industry trade association in relation to the prevalence and support of an innovation is considered mainly as political lobbying, then the new factor can be most precisely described by the term "political push & pull." The factor is the only one that describes the effect of governmental support instruments on the diffusion of innovations. The factor explains 11.25% of the variance of the 22 original factors.

Factor 3: Small influence of pioneers. What is remarkable about this factor is that both the variables "user-innovators" and "green pioneers" load similarly, even though the user-innovators take on a pioneering role on the demand side, while the "green" pioneers are on the supply side. This shows that the influence of the two sides – suppliers and adoptors – should not be considered separately, but can certainly be combined in a single aggregate factor. This factor is described most accurately as "small influence of pioneers", since user innovators and small green pioneers usually have significantly less resources and power to influence market penetration than established market leaders and big companies. The factor also refers to possible cooperation between pioneering "green" suppliers and user-innovators, who are supported by strong "perceptibility of the innovation" as well as a presence in "media and campaigns." The fact that the role of market leaders loads slightly negatively points to the fact that they often are not among the first to supply an innovation. For this reason, one may assume that there is often a division of labor, as it were, between pioneering suppliers and market leaders. While it is mostly newly established and small companies that take on the role of pioneering suppliers in the case of radical innovations, the established companies are more strongly represented in the case of incremental innovations. In the case of radical innovations, market leaders often appear to enter into the market as followers only at a later point in time. The factor "small influence of pioneers" explains 10.17% of the variance of the 22 original factors.

Factor 4: Incentive to buy. The variable "price development" loads very highly on the factor, the variable "relative advantage of the innovation" somewhat less highly. The factor refers to the high incentive to buy that is triggered by significant price reductions. The fact that the factor "relative advantage" also loads highly suggests that besides a good price, adoptors must perceive both a useful function and an advantage in order to make the decision to buy. The new factor is therefore most aptly described as “incentive to buy.” The factor explains 7.7% of the variance of the 22 original factors.

Factor 5: Compatibility with routines. The adoptor-related variable “need for behavior modification,” the product-related variable “compatibility,” and the supplier-related variable “completeness and availability of service” load highly on the factor, whereby “need for behavior change” loads most highly by far. All three original variables refer to “compatibility with routines,” which is why this is an appropriate term for the new factor. It suggests that the adoptors are in principle change-averse in terms of both purchasing and use and that it is safe to assume that an innovation’s ability to prevail as well as its diffusion dynamics depend decisively on its compatibility with routines during purchase and use. The factor explains 7.65% of the variance of the 22 original factors.

Factor 6: Price and cost-effectiveness. The variable “price, cost, cost-effectiveness” loads highly on the factor, the variable “self-reinforcing effects” does so somewhat less. In contrast to the factor “incentive to buy” (see above), this is about the price difference between the innovation and (established) competing products or about the cost-effectiveness of innovative durable consumer goods or investment goods. High cost-effectiveness seems to result in self-reinforcing effects which obviously also have an effect in the case of this factor. The new factor is to be called “price and cost-effectiveness.” It explains 7.5% of the variance of the 22 original factors.

Factor 7: Comprehensibility of the innovation. The product-related variable “complexity of the innovation” loads highly on this factor, the adoptor-related variable “uncertainties on the part of adoptors” significantly less highly. If the comprehensibility of a product increases, i.e., if its complexity is reduced, this apparently diminishes uncertainties on the part of adoptors. That is why the new factor will be called “comprehensibility of the innovation.” It explains 7.4% of the variance of the 22 original factors.

The analyses show that the original classification of the 22 factors in product-, adoptor-, supplier-, sector-, policy, and path-related factors for descriptive purposes does not readily result in the identification of individual factors as primary drivers of the diffusion process. Instead, the seven newly identified factors make clear that influences from several “spheres of influence” (product, adoptor, supplier, sector, policy, path) interact and have joint impacts. The new factors then had to be tested for their significant effects on the dependent variables and their sustainability effects. Since the newly formed factors are metric variables, we calculated the Pearson coefficient of correlation.

Various correlations between the seven new factors and the dependent variables exist. In our sample, the factor “market power of established suppliers” correlates most strongly with the dependent variables. This is true of the market share, the speed of diffusion, and the indicator for diffusion dynamics.

Table 5. Correlation between 7 independent variables and 3 dependent variables of 100 diffusion cases

	Pearson coefficient of correlation		
Factor	**Market share** (Kendall's tau-b)	**Duration of the diffusion** (Kendall's tau-b)	**Diffusion dynamics** (Pearson)
Market power of established suppliers	0,240**	0,209**	0,321**
Political push & pull		-0,144*	
Small influence of pioneers	-0,217**	-0,193**	-0,294**
Incentive to buy			
Compatibility with routines	0,190*		0,255*
Price and cost-effectiveness	0,156*		
Comprehensibility of the innovations			

**The correlation is significant at the 0.05 level (2-tailed). **The correlation is significant at the 0.01 level (2-tailed).*

For the factor "political push & pull," we could not determine any significant correlations with the indicators market share and diffusion dynamics. Possible reasons include that government interventions and political lobbying on the part of trade associations are not equally relevant across all diffusion cases, but differ according to product field and type of diffusion. In other words, this could be an indication that it is important to differentiate between different kinds of innovations and diffusion paths.

The fact that the factor "small influence of pioneers" correlates negatively with the dependent variables can be explained by the fact – as is also the case with the individual original factors – that many innovations introduced to the market by "green" pioneers are (1) marketed by lesser-known firms, so they cannot benefit from the advantages of a well-known brand or company in terms of brand awareness and trust, and (2) that far fewer resources are available for marketing and distributing these innovations because they are often supplied by small businesses. User-innovators are also typically individuals who may vigorously advocate an innovation because they expect concrete advantages from using it, but generally have a small amount of resources to promote the prevalence and availability of the innovation. In addition, it is important that the share of the radical innovations introduced to the market by "green" pioneers is higher, which explains longer diffusion times. For at the 1% level (p = 0.002), there is a significant correlation of medium strength (tau-b = 0.276) between the characteristic "radical innovation or incremental innovation" and the diffusion time, which is longer for radical innovations.

The factors "incentive to buy" and "comprehensibility of the innovation" do not display any correlations with the dependent variables in the sample studied. Here, too, this may be caused by the fact that the price development of innovative products and their relative advantage as well as the comprehensibility of a new product or service on the market may not be equally important across all product groups and diffusion cases. This could be an indication that it is important to differentiate between different kinds of innovations and diffusion paths.

"Compatibility with routines" displays a significant correlation both for market share and for the indicator "diffusion dynamics." Thus, the factor appears to be of substantial importance for the trajectory of the diffusion process across all 100 diffusion cases studied. The results also suggest that compatibility with routines is very strong specifically in the case of the incremental innovations offered by market leaders and that this has positive effects on market share and diffusion dynamics.

“Purchase price and cost-effectiveness” display a weakly significant correlation with market share. The dependent variable “diffusion dynamics” is more important, however. Here, we could not ascertain a significant correlation in the sample studied. In this case, too, the reason might be that the factor is not equally important across all product groups and diffusion cases. So this could also be an indication that it is important to differentiate between different kinds of innovations and diffusion paths.

4.2 Results from the cluster analysis

As the calculations of the correlations and the factor analysis have shown, it is possible only to a limited extent to identify factors significant across all diffusion cases. For this reason, it made sense to examine whether certain groups of diffusion processes could be identified within the totality of all diffusion cases. In order to identify diffusion paths, it was necessary to elaborate groups of innovations that are as similar as possible with a view to the factors. The cluster analysis (cf. 3.3.6) yielded five clusters shown in Table 6.

Table 6. Cluster centers

	Cluster				
	Efficiency-enhancing investment goods from established suppliers	Comprehensible products for end users	Government-supported investment goods from pioneering suppliers	Radical innovations requiring major behavior modifications	Complex products with unclear or long-term benefits
	1	2	3	4	5
Market power of established suppliers	.99160	.34578	-.47389	-.64769	-.80748
Political push & pull	-.32205	-.32389	.86447	-.00058	.14153
Small influence of pioneers	-.55480	-.10547	.61458	.31545	-.37331
Incentive to buy	-1.11651	.31417	.02196	-.14456	.08638
Compatibility with routines	-.05103	.26034	.83118	-1.86155	-.20292
Price and cost-effectiveness	.72731	-.36589	.65029	.56147	-1.02361
Comprehensibility of the innovation	-.38440	.36159	.05332	.47251	-1.53775

The five clusters identified can be described by the key characteristics, actors, and strength of diffusion dynamics shown in Table 7.

Table 7. Characterization of clusters of diffusion of sustainable innovation

Cluster	Key characteristics	Actors	Diffusion dynamics	Examples
Efficiency-enhancing investment goods from established suppliers	High cost-effectiveness due to increased efficiency Predominantly investment goods Predominantly incremental innovations Minor functional benefit Require few behavior modifications Government support does not play an important role	Predominantly established suppliers with good reputations	High	Highly efficient uninterruptible power supply (UPS) Energy-efficient servers Videoconferencing services
Comprehensible products for end users	Good comprehensibility of the innovation Almost exclusively goods for end users Predominantly well-known products with improved characteristics Good trialability Require few behavior modifications	Predominantly established suppliers with good reputations	High	Organic milk Highly efficient dish-washer MP3 music file
Government-supported investment goods from "green" pioneering suppliers	Strong political push & pull Almost exclusively investment goods Good technical compatibility Few behavior modifications on the part of purchasers Cost-effectiveness (because of government support)	High significance of "green" pioneers and the government	Medium	Photovoltaics Passive houses Wind power plants
Radical innovations requiring major behavior modifications	Strong need for behavior modifications on the part of users Predominantly high degree of innovation Obstacles because of strong path dependence Good comprehensibility of the innovation No self-reinforcing effects yet in spite of government support	High significance of start-ups and young businesses	Low to medium	Thin client & server-based computing Bioenergy villages Carsharing
Complex products with unclear or long-term benefits	Complex products or systems High purchase price or unclear cost-effectiveness Low capacity for connection to existing technical system requires change of system Weak political push & pull	Predominantly small businesses with scant reputation	Low	Long-term thermal energy storage Absorption refrigeration systems 3-liter (75 mpg) cars

5 Conclusions

5.1 Key insights

In order to clarify the question “What are key factors influencing diffusion dynamics of sustainable innovation?”, we tested the correlation between 22 independent variables and three dependent variables: “market share,” “diffusion time,” and “diffusion dynamics.” The fact that we could identify a significant correlation with regard to the key dependent variable “diffusion dynamics” for just 9 of the 22 factors suggests that further latent variables are hidden behind the surveyed variables. For this reason, we conducted a factor analysis, which enabled us to identify seven new factors. Three of these new factors proved to correlate significantly with the diffusion dynamics of all 100 sustainable innovations investigated. The “market power of established suppliers” and the “compatibility with routines” correlate positively with diffusion dynamics and the “small influence of pioneers” negatively.

As the calculations of the correlations and the factor analysis have shown, it is possible only to a limited extent to identify key factors significant across all diffusion cases. For this reason, it made sense to examine whether certain groups of diffusion processes could be identified within the totality of all diffusion cases. The cluster analysis showed that five groups of sustainable innovations differ significantly in terms of the factors influencing the diffusion process and in terms of diffusion dynamics. The empirical investigation of 100 sustainable product and service innovations thus revealed that diffusion processes of sustainable innovations differ substantially and in which regard. This answers our second research questions “To what extent do diffusion processes of sustainable innovation differ from each other, and can different groups of diffusion processes be identified?” The characterization of clusters of diffusion of sustainable innovation allows for insights which factors, actors, and institutional settings are characteristic of different groups of diffusion processes, which clarifies our third research question.

5.2 Limitations

Since no large-scale study across sectors or product fields on the diffusion of sustainable innovations has been conducted to date, this study broke new ground for empirical research. As a pioneering empirical investigation in a very young field of research, the study naturally had to limit its scope. The results can claim validity only for sustainable product and service innovations and not for other types of innovations such as process, institutional, or social innovations. Furthermore it should be underlined that the investigation was limited to diffusion processes in one specific country (Germany). Despite the fact that this is one of the first large-scale studies on the diffusion of sustainable product and service innovations, the number of 100 cases is still limited when it comes to applying techniques of inductive statistics. In our sample we had 83 product innovations, but only 13 service innovations and 4 mixed product-service innovations.

5.3 Managerial implications

We identified three factors that correlate significantly with diffusion dynamics. This finding is particularly relevant for innovation management and new venture creation: (1) "Market power of established suppliers" correlates positively and the "small influence of pioneers" negatively with diffusion dynamics. Start-ups often underestimate the power and relevance of established companies and market players. If a new venture follows a strategy of fast growth, it should thoroughly check market forces and consider strategic alliances with established companies. (2) "Compatibility with routines" correlates positively with diffusion dynamics. This finding underlines the urgent necessity to assess the impact of a new product or service on user behavior in a very early stage of product development and to check the compatibility with routines systematically in the testing phase. Innovation management literature provides a broad array of methodologies and tools for user integration in idea and product development as well as in product testing. Innovation managers and decision makers should take this aspect of compatibility with routines very seriously when deciding on market introduction and developing marketing strategies.

The three factors which we identified as especially relevant for the diffusion success of sustainable product and service innovations as well as the differences between the five clusters of diffusion cases also have important implications for policy makers: (1) Our findings point out that some types of sustainable product innovations require substantial governmental support in order to diffuse. While the group of "Government-supported investment goods from green pioneering suppliers" (photovoltaics, wind energy etc.) is already well supported in Germany, policy makers and governmental organizations should thoroughly check the group of "Complex products with unclear or long-term benefits" as to their need for additional governmental intervention. (2) The fact that "compatibility with routines" correlates positively with diffusion dynamics leads to the recommendation that governmental R&D funding programs should consider this aspect more explicitly. This can, for example, be done by making it a requirement to assess this aspect in government-funded R&D projects and by providing a higher funding rate for radical innovations which require major changes in user behavior or organizational routines.

5.4 Further research

As the seven factors developed in the factor analysis demonstrate, what matters in the development of intervention strategies is precisely the interplay of the various fields of intervention and the simultaneous design of the factors. It is therefore the task of further analysis and research to develop a multi-intervention approach for influencing the diffusion of sustainable innovations. The evolutionary concept of diffusion paths presented in this article develops significant explanatory power on the basis of which faster or slower diffusion and the success or failure of sustainable innovations can be better understood. The next step in research on diffusion paths of sustainable innovation is to connect the insights on the factors, actors, and institutional settings which are characteristic of different groups of diffusion processes with the examination of key events (tipping points) in the trajectory of these processes.

The limits of our investigation outlined above indicate further research needs. One important question, for example, is whether there are significant differences between the diffusion processes of innovative sustainable products and innovative sustainable services. Answering this kind of questions will permit the development of diffusion paths of sustainable innovation and will offer concrete starting points for interventions by policy-makers, innovation actors, and societal groups.

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Appendix 1: Profile and coding system for diffusion cases

Table 8. Case profile

Description of the diffusion case

Object:

What exactly is the object of innovation?

What about it is new?

How can the innovation be differentiated from previous/other products/services/solutions?

Is this a product [ ], a service [ ], or a combination of the two [ ]?

Market introduction:

When was the innovation introduced to the market in Germany?

Was it introduced to the market by established suppliers [ ], new companies[1] [ ], or both [ ]?

Adoptors:

Who are the adoptors?

End users (households) [ ], professional users (businesses, public sector, etc.) [ ]?

End users: Is this a product/service purchased routinely (i.e., purchased more than once per year) [ ] or not [ ]?

Professional users: Is this a capital good (depreciable) [ ] or a consumable [ ]?

Sector

The innovation is in which sector?

Description: NACE code: [2]

When was the industry or trade association in Germany established? ______

Key events

Which events had major effects on the diffusion trajectory to date, and which ones are responsible for bifurcation and multifurcation points or for linkages between paths?

Squeeze out

Is the innovation on the market at the same time as its predecessor product, or is only one or the other on the market?

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[1] A "new company" is defined here as a company that was established for the purpose of developing and marketing the innovation in question.

[2] Nomenclature statistique des activités économiques dans la Communauté européenne (NACE) is the Statistical Classification of Economic Activities in the European Community.

Both at the same time [ ], one or the other [ ]

Basic innovation

Is this a basic innovation or an incremental innovation?

Basic innovation [ ], incremental innovation [ ]

Data collection about the individual diffusion cases and coding of the values of the individual factors followed the format described above.

For each diffusion case, exactly one value was assigned to each factor. We gathered the information required for this coding from documents available online and offline and documented the sources in an appendix. We studied a total of approx. 5,000 sources, most of them on the Internet, and cited approx. 1,200. In order to ensure intersubjective reproducibility and inter-rater reliability, a coding team composed of several people coded the case profiles, and team members reviewed each other's work.

As a matter of principle, the coding referred to the entire diffusion process to date, i.e., to the period from market introduction to today, using the information available. Where differentiation according to various phases was necessary, we noted this explicitly.

Coding followed the principle of rejecting the null hypothesis. In general, we assumed each factor to have zero influence. Only in cases where the empirical information suggested a different assumption in a manner that was indisputable and intersubjectively transparent did we assign a value of 1 or 2 for a supporting or very strongly supporting influence or -1 or -2 for an inhibiting or very strongly inhibiting influence.

Table 9. Code system for the assessment of factors in diffusion cases

Product-related factors	Code
1. Relative advantage of the innovation: Which functional or economic advantage does the innovation have in comparison with the predecessor product?	2: New useful function or strong cost advantage 1: Less important new function or small cost advantage 0: No relative advantage discernible
2. Perceptibility: In the absence of particular efforts to provide information about the innovation, can third parties perceive its use?	2: Clearly perceptible AND perceptible in public 1: Less clearly perceptible or perceptible only in interior spaces or the like 0: Not perceptible
3. Compatibility: Does the innovation have the capacity for connection to the existing technical, institutional, and cultural systems?	2: The innovation can easily be connected and has synergies with its environment 1: The innovation can easily be connected and results in small advantages in its environment 0: Neutral -1: Connection requires time and effort or learning -2: Capacity for connection can be established only with difficulty
4. Complexity: Is the innovation complex for the adoptor, and is specialized knowledge required to understand it?	0: Uncomplex -1: Slightly complex -2: Requires specialized knowledge
5. Trialability: Can users try out the innovation without much time and effort?	2: Easy to try out and at low cost 1: Trying out the innovation requires considerable time and effort 0: Cannot be tried out

Adoptor-related factors	Code
6. User innovators: Can user innovators be identified during the *innovation process* or at the time of market introduction? If so, who are they, and what kind of innovators are they? Are there indications that user innovators were integrated in the manu-	2: A larger group of innovators exists 1: A smaller group of innovators exists 0: Unknown

facturer's innovation process in a targeted fashion?

7. Need for behavior modification: Does use of the innovation require behavior modification on the part of the adoptor?	0: No behavior modification required -1: Behavior modification required -2: Significant behavior modification required
8. Uncertainties on the part of adoptors: To what extent were or are there uncertainties on the part of the adoptors concerning the innovation?	0: No uncertainties known -1: Minor uncertainties -2: Significant uncertainties
9. Price, costs, cost-effectiveness: To what extent do aspects relating to price, costs, or cost-effectiveness support or inhibit adoption of the innovation?	2: High cost-effectiveness or cheaper 1: Lower cost-effectiveness or somewhat cheaper 0: Neutral -1: Slightly uneconomical or somewhat more expensive -2: Significantly uneconomical or significantly more expensive

Supplier-related factors	**Code**
10. "Green" pioneers: Do pioneering suppliers of the innovation have ecological goals and convictions?	2: The innovation was/is supplied by pioneers with explicitly "green" or sustainable goals 1: "Green" or sustainable goals played a (minor) role 0: No "green" goals on the part of the pioneering suppliers
11. Renown and reputation of the suppliers: Do suppliers of the innovation who are well-known and have a good reputation exist already?	2: Well-known companies with a good reputation supply the innovation 1: Less well-known companies supply the innovation 0: Only suppliers who are not well-known
12. Completeness and availability of service: Is the innovation offered for sale on the market with a complete service package, and is it easily available to customers?	2: Availability and service are guaranteed everywhere 1: Minor limitations to availability or service 0: Neutral -1: Poor availability or lacking service have slightly inhibiting effects -2: Poor availability or lacking service have distinctly inhibiting effects

Sector-related factors	Code
13. Role of the industry trade association: Is an industry trade association in existence at the time of market introduction; does it have political influence, and does it use it for supporting the innovation?	2: Strong and active industry trade association 1: Less strong or less active industry trade association 0: No industry trade association
14. Role of market leaders: Who were the market leaders in the industry in which the innovation was introduced, and do they support or inhibit its diffusion?	2: Market leaders were involved in introducing the innovation from the beginning 1: Market leaders provided slight support for the innovation 0: Market leaders remained neutral -1: Market leaders slightly inhibited the diffusion -2: Market leaders steadfastly opposed the diffusion
15. Intermediaries as change agents: To what extent have market intermediaries (e.g., wholesalers and retailers) and policy intermediaries (e.g., energy, efficiency, climate protection agencies) accelerated or inhibited the diffusion trajectory to date?	2: Numerous intermediaries steadfastly supported the diffusion 1: Some intermediaries supported the diffusion 0: No active intermediaries known

Political factors	Code
16. Institutional obstacles: To what extent have legal or administrative rules inhibited the diffusion of the innovation to date?	0: No obstacles -1: Minor obstacles -2: Significant obstacles
17. Governmental push and pull activities: To what extent was the diffusion of the innovation accelerated by regional, national, or EU-wide provisions (push) or support activities (pull)? Did explicit environmental or sustainability goals play a role?	2: Significant support 1: Limited support 0: No support
18. Lead market policies: Is the innovation part of a targeted lead market policy at the regional, national, or EU level? Do explicit environmental or sustainability goals	2: A lead market policy is being pursued actively 1: Minor aspect of a lead market 0: Unknown

play a role?

19. Media and campaigns: To what extent did the media (press, radio, TV, etc.) and NGO campaigns accelerate or inhibit the diffusion trajectory?	2: The innovation was a topic in the media for a longer period of time 1: The innovation has been a topic in the media sporadically 0: Reporting about the innovation is rare

Path-related factors	**Code**
20. Path dependencies: To what extent have technological or economic path dependencies inhibited the speed of diffusion to date?	2: The innovation developed very rapidly to become the dominant design 1: The innovation has achieved the status of dominant design in some market segments 0: Neutral -1: Predecessor products inhibited diffusion because of minor lock-in effects -2: Predecessor products inhibited diffusion because of major lock-in effects
21. Price development: How has the price (adjusted for inflation) developed over the course of the diffusion process?	2: The price has decreased significantly since market introduction, for example through economies of scale or subsequent innovations 1: The price has decreased slightly 0: The price has remained constant or has increased
22. Self-reinforcing effects: Can self-reinforcing effects, e.g., imitation of role models/celebrities/opinion leaders or critical mass phenomena be observed?	2: Significant critical mass phenomenon 1: Slight critical mass phenomenon 0: No self-reinforcing effects

Data collection about the effects of the diffusion followed the format documented below.

Table 10. Code system for the assessment of factors in diffusion cases

Categories of effects	Code
Effects at the product level: Does the individual product have a proven beneficial social or ecological effect? Are facts and figures available in this regard?	2: Significant improvement compared with the predecessor product 1: Slight improvement 0: No improvement known
Rebound effects: Are rebound effects to be observed, or are they likely to occur in the future?	0: No rebound effects known or to be expected -1: Rebound effects very likely to be expected -2: Significant rebound effects are already proven or obvious
Ability for re-invention: Does the innovation provide the opportunity for regional or user-specific modifications and inventions? Does the innovation provide a basis for subsequent innovations?	2: This is a basic innovation that obviously creates many new opportunities 1: Individual modifications or subsequent innovations are known 0: Unknown
Diffusion curve: Which data about the diffusion have become known over time, and how large is the market share of the innovation in Germany today?	Uncoded: Documentation of development of market share over the longest possible period of time, depending on data availability
Market penetration: What is the market share of the innovation on the accessible market at this point in time?	4: 50 to 100% 3: 10 to 50% 2: 1 to 10% 1: 0 to 1%

A System Dynamic Approach to Modelling the Endogenous and Exogenous Determinants of the Entrepreneurship Process

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Abstract. The importance of entrepreneurship for economic development and overall social well-being is widely recognised by researchers, experts, and policy makers. Researchers have identified a variety of endogenous and exogenous determinants, such as individual-level factors, external macro-level factors, and country-level cultural factors, which can moderate the raise in entrepreneurial activity. From the other side, there is a feedback loop between entrepreneurship affecting economic growth and being, in turn, affected by country wealth. The main objective of this study is to build a model to capture the relationship between entrepreneurship and external macro-level determinants, and to explore the possible effects of changes in entrepreneurship supply-and-demand factors. The research applies system dynamics simulation and proposes a dynamic macro-level model of entrepreneurship. The model equations are developed based on regression analysis. The results show that although entrepreneurship does have a positive impact on the economy, this effect can be mitigated by other factors. Furthermore, even though an improvement in the external determinants level results in increased entrepreneurship activity and consequent economic growth over a longer period, the effect may depend on factors such as overall country population development, and especially the proportion of adult populations, institutional factors, and individual intentions towards entrepreneurship.

Keywords. Entrepreneurship, External factors, Economic growth, System dynamics.

1 Introduction

The importance of entrepreneurship for economic development and overall social well-being is widely recognised by researchers, experts, and policy-makers (Bosma et al. 2012; Cumming et al., 2014; Fritsch, 2013; Gilbert et al., 2004, and others). Entrepreneurial ventures are not only remarkable sources of new workplaces (Morrison et al., 2003; White and Reynolds, 1996), but also powerful generators for innovations (Acs and Varga, 2005).

An increase in entrepreneurial activity can be affected by individual-level factors (van Gelderen et al., 2006; Ferreira et al., 2012; Rauch and Frese, 2007), external macro-level factors (Casero et al., 2013; Stenholm et al., 2013), and country-level cultural factors (Petrakis, 2014; Sambharya and Musteen, 2014; Thai and Turkina, 2014).

An important outcome of entrepreneurship research is the recognition of the feedback loop between entrepreneurship rates and the national economy, when entrepreneurship affecting economic growth is in turn affected by national wealth (Petrakis, 2014; Shane 2003; Wennekers et al., 2005). However, this interconnection of entrepreneurship, internal (entrepreneurial intention), and external (institutional) factors (e.g. national wealth level and economic growth) remains understudied and is not explained by traditional cognitive analysis. The paper contributes to this research gap.

The eclectic theory of entrepreneurship presented by Verheul et al. (2002) provides a comprehensive framework in which external macro-level determinants, forming supply and demand for entrepreneurship, eventually affect the decision process of individuals. Discrepancies between supply and demand may lead to a non-optimal level of entrepreneurship. Hence, it is unclear to what extent the system can self-adjust and recover after a sudden external impact, and whether governmental interventions (e.g. through policy changes) can facilitate this process.

The main objective of this study is to build a model to capture the relationship between entrepreneurship and external macro-level determinants, and to explore the possible effects of changes in entrepreneurship supply-and-demand factors.

The research implements a system dynamics (SD) approach. The system dynamics simulation has proved its usefulness in military, logistics, management, and organisational studies (see, for examples and overview, e.g. Gary et al., 2008; Harrison et al., 2007; Kortelainen et al., 2010; Sterman, 2000). In entrepreneurial studies, system dynamics modelling has been used for analysing the decision-making process (Kefan et al., 2011) and studying the influence of fairness perceptions on the cooperation between new ventures and universities (van Burg and van Oorschot, 2013). However, the evidence for system dynamics model adoption in the entrepreneurship literature is still scarce (Zali et al., 2014).

We aim to contribute to the ongoing academic discussion by proposing a *dynamic macro-level model of entrepreneurship*. The model is based on the eclectic theory of entrepreneurship and takes into account the variety of external factors derived from the literature. We also aim to understand the relationship between entrepreneurship and economic growth. The developed model provides insights for the estimation of the possible policy impact on such a relationship.

However, as with any other model, our model is a trade-off between accuracy and complexity. Therefore, at this stage, we do not aim for exact predictions (which would require a much more detailed country-specific data analysis than is possible from open databases), but rather aim to estimate the general system behaviour under specified conditions and with stated assumptions.

The rest of the paper is structured as follow: the second part discusses the existing literature on the topic, the third part describes the system dynamics model, the fourth part contains the scenarios developed to test the research propositions, results, and discussion, whereas the fifth part summarises the results of the study.

In this study, we focus on two streams in entrepreneurial literature. The first examines the actual impact of entrepreneurship on a country's economy, whereas the second examines factors affecting entrepreneurial activity.

2 Literature review

Entrepreneurship theory can be traced back to the 18th century, when the concept of the entrepreneur was introduced by Cantillon. In a broad sense, entrepreneurship is a "process of starting and continuing to expand business" (Hart, 2003). In theory, a potential entrepreneur has possibilities to explore the opportunity without establishing a new firm (Shane and Venkataraman, 2000). On the other hand, venture creation is traditionally considered an essential outcome of the entrepreneurial process (Bygrave and Hofer, 1991; Gartner et al., 2010; Shook et al., 2003).

2.1 Entrepreneurial impact on the economy

Although entrepreneurship is often considered as a desirable phenomenon, van Stel et al. (2005) found that its positive impact on the economy, particularly on GDP growth rates, can be observed only for relatively high-income countries. Furthermore, the entrepreneur population is not homogenous and, consequently, different types of entrepreneurs may have different effects on economic growth. Following the classification developed in Global Entrepreneurship Monitor (GEM) studies, researchers often distinguish between 1) improvement and opportunity-driven, and 2) necessity-driven entrepreneurs. For the first group, the decision to become self-employed is voluntary and justified often not only by monetary reasons. However, for necessity-driven entrepreneurs, self-employment is the only option to achieve an income, as a so-called "last resort" (GEM, 2014). Sometimes a high-expectation group is also defined (GEM provides such data). In contrast to opportunity-driven entrepreneurs, who still may be just lifestyle entrepreneurs without high-growth aspirations (Freel and Robson, 2004), people belonging to the high-expectation group demonstrate a strong desire to expand their business and achieve significant growth rates (Bowen and De Clerq, 2008).

Applying a modified form of the Cobb-Douglas production function, Wong et al. (2005) found that only high-growth potential entrepreneurship has a significant impact on economic growth. Valliere and Peterson (2009), using a rich set of control variables attributed to three economic growth theories, emphasised that such a positive effect of high-expectation entrepreneurship emerges only in developed economies. Therefore, the research results reveal that the positive impact of entrepreneurship on economic development depends on the prevalence of high-expectation entrepreneurs and on the country's stage of economic development (van Stel et al., 2005; Valliere and Peterson, 2009.

2.2 Determinants of entrepreneurship

The variety of studies on entrepreneurship determinants varies by the level of analysis: macro, meso, and micro (Verheul et al., 2002). On a macro level, researchers focus on contextual country or regional characteristics, such as institutional, regulatory, and cultural variables (Bowen and De Clerq, 2008; Carree et al., 2002; Linan and Fernandez-Serrano, 2014; Thai and Turkina, 2014). Meso-level analysis covers specific industry and market settings (Carree and Thurik, 2000; Klepper, 2002). On the micro level of analysis, the main determinants of entrepreneurial activity are individual characteristics such as social capital and psychological profile (Ferreira, 2012; Rauch and Frese, 2007; Van Gelderen et al., 2006).

Even though some scholars tend to focus on individual-level analysis (e.g. Gartner et al., 2010), the importance of external context is also well recognised (Bowen and Clerq, 2008; Sambharya and Musteen, 2014; Urbano and Alvarez, 2014). The commonly applied institutional theory (Busenitz et al., 2000; Bruton et al., 2010) studies three dimensions, shaping the entrepreneurial activity in the country: regulatory, cognitive, and normative dimensions. Regulatory dimensions capture laws and policies imposed by the national government. Cognitive dimensions represent the perceptions about knowledge possessed by prospective entrepreneurs. The normative dimension addresses the informal norms and cultural beliefs adopted in the country.

However, the eclectic theory of entrepreneurship (Verheul et al., 2002) offers an extended framework that aims to combine the contextual factors with individual characteristics. The rate of entrepreneurship (i.e. the percentage of the population involved in entrepreneurial activities) depends on supply-and-demand factors influencing the individual decision-making process. The demand factors consist of variables representing economic and technical development level and determine the pool of opportunities available. The supply factors (particularly population characteristics, demographic dynamics, level of income, education level) determine the number of individuals considering an entrepreneurial career (potential entrepreneurs). By altering the external context through regulation policy, the government can attempt to regulate the rates of entrepreneurship (lines G in Figure 1).

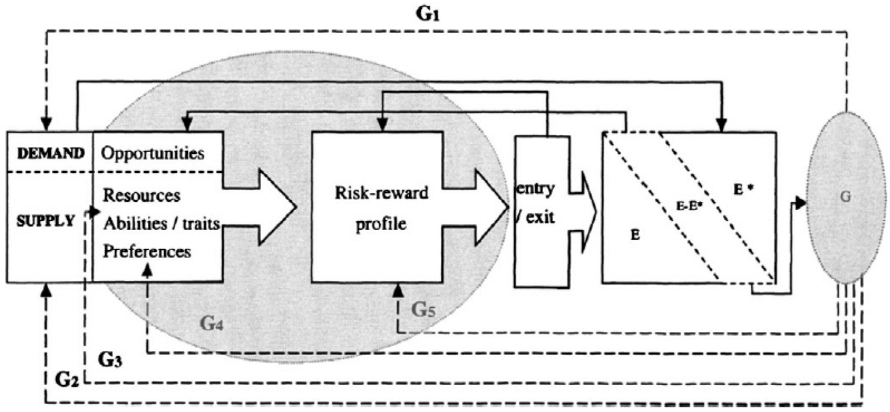

Fig. 1. Framework of determinants of entrepreneurship (adopted from Verheul et al., 2002)

Drawing on this theory, Wennekers et al. (2005) demonstrated the U-shaped relationship between entrepreneurial activity and national wealth. Casero et al. (2013) later extended these results. Comparing the discovered U-shape curve with the level of institutional development, they proposed that in factor-driven economies, improvement of institutional conditions leads to growth in regular employment, thus decreasing the entrepreneurship rates (reverse relationship). At the same time, in innovation-driven economies, a direct relationship between the institutional environment and entrepreneurship can be observed. In such economies, entrepreneurship is considered as self-realisation rather than as a "last resort" in the absence of employment. The transition economies lie somewhere between these two trends, forming the middle part of the graph (Casero et al. 2013).

Therefore, we start building our propositions on the existence of bilateral relationships between entrepreneurship activity and economic growth (Linan and Fernandez-Serrano, 2014; Shane, 2003; Valliere and Peterson, 2009; Wong et al., 2005). Furthermore, these relationships depend on the national level of economic development and contextual factors, including both institutional and cultural dimensions (Casero et al., 2013; Linan and Fernandez-Serrano, 2014; Stenholm et al., 2013; Wennekers et al., 2005). Thus, changes in contextual factors may affect entrepreneurship rates and consequently have an impact on the GDP growth (Acs and Varga, 2005; van Stel et al., 2005; Verheul et al., 2002). On the other hand, sudden changes in GDP growth rates due to external factors (e.g. an economic crisis) may affect the rates of entrepreneurship (Shane, 2003).

With our model, we aim to test several propositions:

(1) The entrepreneurial system is self-adjusting and will recover after an external shock has affected supply/demand factors.

(2) Governmental interventions can mitigate the negative effect of an external shock on the system.

(3) In the long run, entrepreneurship is affected by national trends such as population dynamics.

3 The system dynamics model

System dynamics methodology has been developing since the 1960s (Forrester, 1989) and has been proved to be a powerful tool for studying complex systems. The prerequisite of system dynamics-system thinking is an approach assuming pervasive interconnections between parts of the system. System dynamics deals with dynamic complexity, where the non-linear system behaviour results from the constellation of feedback loops, rather than with detailed complexity, which occurs due to the multiplicity of possible alternatives (Sterman, 2000).

In developing our model, we used the stages recommended for the system dynamics modelling process by Dooley (2002) and Sterman (2000). First, based on the existing literature, we develop a conceptual design and propose theoretical causal relationships to be tested. Second, we elaborate on the actual model equations. For that, we obtain the data (our model is based on the secondary data from the Global Entrepreneurship Monitor (GEM), Global Competitiveness Index (GCI), and World Bank databases). Then we perform a statistical analysis of the proposed causal relationships and create the model equations. The third step is to validate the results against the real data. After the model is validated and all the necessary corrections are introduced, we can shift to the fourth step, which consists of running experimental scenarios, result analysis, and interpretation.

3.1 The causal model

In this study, we combine the eclectic theory of entrepreneurship explaining the entrepreneurial rates through supply-and-demand factors (Verheul et al., 2002) with the approach applied by Wong et al. (2005) and Valliere and Peterson (2009), in which entrepreneurial activity is one of the factors explaining the rate of GDP growth. Wong et al. (2005) derived a modification of the Cobb-Douglas production function, where economic growth is explained through the stock of physical capital, labour, and disembodied factor productivity.

In our model, capital is measured as GDP per capita, and labour is measured as the country's population. The productivity factor consists of the entrepreneurship activity prevalence (we consider the total activity rate, as well as opportunity and necessity; see Table 1 for details) and the innovation level (indicator from the Global Competitiveness Index). The equation is therefore:

$$GDP_{growth} = \alpha_0 + \alpha_1 GDP_{per\ capita} + \alpha_2 GDP_{growth\ lag} + \alpha_3 POP + \alpha_4 TEA + \alpha_5 NEA + \alpha_6 OEA + \alpha_7 INN \qquad (1)$$

where:

GDP_{growth} – annual GDP growth rate;
$GDP_{per\ capita}$ – GDP per capita (PPP);
$GDP_{growth\ lag}$ – GDP growth rate for the previous year;
POP – country population;
TEA – total entrepreneurship activity rate;
NEA – necessity-driven entrepreneur share;
OEA – opportunity- and improvement-driven entrepreneur share;
INN – index for country innovation capability.

The next step is to define the factors affecting entrepreneurship rates. The eclectic theory identifies objective demand and supply factors that affect the individual decision-making process. Shane and Venkataraman (2000) also propose two essential components for entrepreneurship: opportunities and individuals willing to explore them. Consequently, we define the demand as the factors determining opportunities, which arise from economic and technical development: economic growth (rates of GDP growth), potential market size (overall population), and national technological and innovation level. Supply, on the other hand, is defined by population characteristics such as proportion of adult population, unemployment rates, average wealth (GDP per capita), education quality, and cultural characteristics. Following Morris et al. (1994) and Shambharya and Musteen (2014), we define three main country-level cultural characteristics affecting entrepreneurship: power distance, uncertainty avoidance, and collectivism. These dimensions were originally introduced by Hofstede (1984, 2001) and have been applied in numerous studies on entrepreneurship as determinants of cultural environment (Bruton et al., 2010). Consequently, the entrepreneurial intentions are modelled as follows:

$$EIN = \alpha_0 + \alpha_1 POP_{adult} + \alpha_2 UNP + \alpha_3 GDP_{per\ capita} + \alpha_4 PDA + \alpha_5 IND + \alpha_6 UA + \alpha_7 POP + \alpha_8 GDP_{growth\ lag} + \alpha_9 TEC + \alpha_{10} INN + \alpha_{11} EDU \qquad (2)$$

where:

EIN – entrepreneurial intentions;

POP_{adult} – share of adult population;
UNP – unemployment rate;
$GDP_{per\ capita}$ – GDP per capita (PPP);
PDA – power distance dimension;
IND – individualism dimension;
UA – uncertainty avoidance dimension;
POP – country population;
GDPgrowth lag – GDP growth rate for the previous year;
TEC – technological readiness;
INN – innovation;
EDU – higher education and training.

However, not all individuals who consider entrepreneurship to be a viable career option eventually become entrepreneurs. Factors such as taxes, labour market regulations, bureaucracy, and the actual venture registration process (the number of steps a potential entrepreneur should accomplish in order to get official status) can influence the rate of start-up emergence (Acs et al., 2008; Choo and Wong, 2006). In addition, unfavourable institutional conditions may increase the time needed for the process of venture creation (Klapper et al., 2006; Misra et al., 2012). That, in turn, may affect the actual number of new firms created, because some people may give up during the process or the opportunity may just expire (Levie and Autio, 2008). Consequently, we propose that the institutional regulatory dimension (overall institution quality, as well as market regulations) alters the transition from entrepreneurial intention to actual activity. In addition to the direct effect, we also examine possible moderation, so the equation is therefore:

$$TEA\ (NEA, OEA)\ = \alpha_0 + \alpha_1 EIN + \alpha_2 LMK + \alpha_3 GMK + \alpha_4 FIN + \alpha_5 INS + \alpha_6 LMK * EIN + \alpha_7 GMK * EIN + \alpha_8 FIN * EIN + \alpha_9 INS * EIN \quad (3)$$

where

TEA (NEA, OEA - we propose separate equations for each activity index) total, necessity, and opportunity entrepreneurship rates;
EIN – entrepreneurial intentions;
LMK – labour market efficiency;
GMK – goods market efficiency;
FIN – financial market development;
INS – institutions (quality)

Figure 2 presents a conceptual causal model diagram. To simplify the visual representation and readability, we did not include proposed causal linkages to variables OEA and NEA. At this stage of model development, we consider them equal to the TEA causal linkages. The main feature of the model is inclusion of the complex feedback loop between entrepreneurial activities (TEA, OEA, and NEA) and national economic growth (GDP growth). In theory, that should lead to the establishment of some optimal level of entrepreneurship (when the supply of potential entrepreneurs is aligned with the pool of opportunities); however, that level is also affected by other external factors, which may lead to deviations from the equilibrium state of the model.

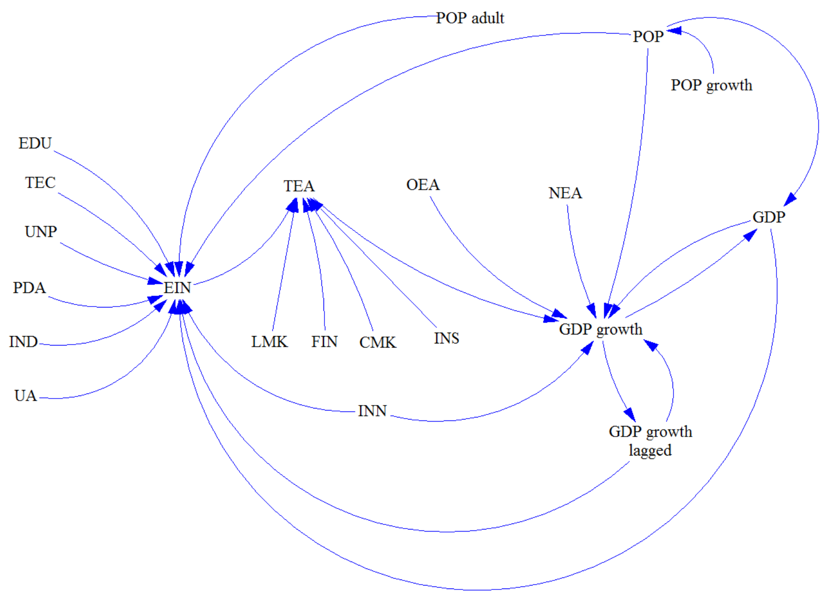

Fig. 2. Conceptual causal diagram

3.2 Data and variables

In our model, we used secondary data gathered from three main sources: the Global Entrepreneurship Monitor, Global Competitiveness Report, and World Bank Database. In order to assess the country-level cultural dimensions, we used Hofstede indicators (http://geert-hofstede.com/countries.html). The overview of the variables is provided in Table 1.

Table 1. Variables

Variable	Definition	Source
GDP growth	Annual GDP growth rate (%)	World Bank
GDP growth lagged	Annual GDP growth rate for previous year (%)	World Bank
GDP	GDP per capita, PPP (current USD)	World Bank
POP	Total country population (people)	World Bank
POP growth	Annual population growth rate (%)	World Bank
POP adult	Share of the national adult population (% to the overall country population)	World Bank
UNP	Unemployment rate (% total labour force)	World Bank
TEA	Total early-stage entrepreneurial activity (% to 18-64 population)	GEM
OEA	Improvement-driven opportunity entrepreneurial activity (% to TEA)	GEM
NEA	Necessity-driven entrepreneurial activity (% to TEA)	GEM
EIN	Entrepreneurial intentions (intent to start a business within 3 years) (% to 18-64 population, people involved in TEA excluded)	GEM

INN	Innovation (combined index, score 1-7)*	GCI
TEC	Technological readiness (combined index, score 1-7)*	GCI
LMK	Labour market efficiency (combined index, score 1-7)*	GCI
GMK	Goods market efficiency (combined index, score 1-7)*	GCI
FIN	Financial market development (combined index, score 1-7)*	GCI
INS	Institutions (combined index, score 1-7)*	GCI
EDU	Higher education and training (combined index, score 1-7)*	GCI
PDA	Power distance (non-dimensional relative scores)	The Hofstede Centre
IND	Individualism (non-dimensional relative scores)	The Hofstede Centre
UA	Uncertainty avoidance (non-dimensional relative scores)	The Hofstede Centre

**In GCI indexes, a value of 7 represents the highest possible score and 1 the lowest. The scale is continuous.*

Aiming to increase model applicability in different countries, we based our regressions on international datasets rather than on country-specific longitudinal data. An additional reason for that decision was the lack of historical data for certain variables. Thus, the latest time point available for the indicators from GCI is 2008 (in earlier reports, some indicators were not included). Therefore, for the development of model equations, we applied the data from 2013, which in our case was the latest year without a significant amount of missing data.

3.3 Model equations development

In order to develop actual model equations, we used the theoretical causal propositions developed in Chapter 3.1. We tested them on our dataset, consisting of 66 countries. As mentioned before, the relationship between entrepreneurship and economic growth may significantly differ between countries at various development stages (van Stel et al., 2005). In a similar way, the institutional effect may vary (Valliere and Peterson, 2009). To account for that effect, we divide our sample into three groups according to the classification of economies provided in the Global Competitiveness Report (WEF, 2012). GEM applies a similar classification. Stage 1 is factor-driven economies; Stage 2 is efficiency-driven, and Stage 3 is innovation-driven.

In our sample, Stage 1 is represented by the following countries: Algeria, Angola, Botswana, Ghana, India, Iran, Malawi, Nigeria, the Philippines, Uganda, Vietnam, and Zambia.

Stage 2 includes Argentina, Barbados, Bosnia and Herzegovina, Brazil, Chile, China, Colombia, Croatia, Ecuador, Estonia, Guatemala, Hungary, Indonesia, Jamaica, Latvia, Lithuania, Macedonia, Malaysia, Mexico, Namibia, Panama, Peru, Poland, Romania, Russia, South Africa, Surinam, Thailand, Turkey, and Uruguay.

Stage 3 countries are Belgium, Canada, the Czech Republic, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, Korea, the Netherlands, Norway, Portugal, Puerto Rico, Singapore, Slovenia, Spain, Sweden, Switzerland, Trinidad & Tobago, the United

Kingdom, and the United States.

The sample sizes for each stage are consequently as follows: Stage 1: n=12; Stage 2: n=30; Stage 3: n=24.

We added the variables GDP and POP to the equation in logarithmic form. The descriptive statistics and correlations are presented in the appendix. To examine the proposed relationships, we used stepwise linear regressions. This enables us to create the equations consisting only of significant variables, which we can then input into the model.

Unfortunately, due to the small number of valid observations, we had to exclude the Stage 1 countries from the analysis. We also excluded Stage 2 countries from the analysis, due to the low explanatory power of the model and consequently the lack of a strong relationship between the rate of entrepreneurship and the growth of GDP. Therefore, we were not able to build a meaningful equation 1 for this group, which made creation of the model impossible for these groups of countries. These results correlate with van Stel et al. (2005), who also noticed the lack of a significant relationship between entrepreneurial activity and economic growth for developing economies.

Surprisingly, we also did not find a significant effect on GDP growth for Stage 3 countries, neither from total early stage entrepreneurial activities (TEA), nor from necessity or opportunity or improvement entrepreneurship. We tested the model with data for different years (2009-2012) and found the significant ($p<0.01$) coefficient for TEA for 2010 but not for other years. On the other hand, model with the data for 2012 has significant coefficients for NEA and OEA ($p<0.05$). Such inconsistency in the results can be explained by the small size of the sample, which limits the reliability of regression analysis. Unfortunately, the available data does not allow analysis on the larger sample.

Taking into account these issues, we slightly increased the significance level ($p<0.2$) in order to be able to build the model. After that, we included the TEA variable in the equation (1). Other entrepreneurship activity indicators are insignificant even at this liberal level (for 2013 data). Therefore, after the estimation of equation 1, we continued our analysis only for Stage 3 countries.

To test possible moderation effects in model 3 (see equation 3), we first estimated the model without interaction terms. Among institutional-level determinants (LMK, GMK, FIN, INS) only labour market efficiency appeared to have a significant effect on total entrepreneurial activities (TEA). Therefore, for the following regression, we entered only one interaction term (LMK*EIN). However, the estimation revealed the insufficient significance of this additional predictor; therefore, it was not included in the final equation.

The following table (Table 2) provides the stepwise regression results for all four models described in part 3.1. For the first model, we also provide the estimation results for Stage 2 countries; however, we do not consider them in the further models.

Table 2. Regression results

	Model 1, Stage 2	Model 1, Stage 3	Model 2	Model 3
GDP growth	dependent	dependent	na	na
GDP growth lagged	1.183	0.639	x	na
GDP	x	x	-15.639	na
POP	x	x	-4.533	na
POP adult	na	na	0.646	na
UNP	na	na	x	na
TEA	-0.092 (Sig. 0.2703)	0.053 (Sig. 0.1875)	na	dependent
OEA	x	x	na	na
NEA	0.137	x	na	na
EIN	na	na	dependent	0.533
INN	x	x	9.171	na
TEC	na	na	x	na
LMK	na	na	na	2.103
EDU	na	na	-17.924	
GMK	na	na	na	x
FIN	na	na	na	x
INS	na	na	na	x
PDA	na	na	x	na
IND	na	na	x	na
UA	na	na	x	na
LMK*EIN	na	na	na	x
GMK*EIN*	na	na	na	na
FIN*EIN*	na	na	na	na
INS*EIN*	na	na	na	na
F	7.98	76.39	22.83	28.76
Adjusted R^2	0.428	0.867	0.865	0.735
Durbin-Watson	1.535	2.180	2.771	1.682
Pr>ChiSq	0.886	0.492	0.469	0.458

Dependent variables: Model 1: GDP growth; Model 2: EIN; Model 3: TEA.
The table contains unstandardized coefficients
All independent variables (except when separately mentioned) are significant at 5%
All models are significant at 1%
x – the variable was excluded from the final model
NA – the variable was not included in the model estimation
** were not included in the model (see the explanation above)*

The accomplished statistical analysis resulted in the correction of the theoretical causal diagram, as some variables appeared to be non-significant. Noticeably, only three external factors (higher education and training, innovation, and labour market efficiency) have significant coefficients and are therefore included in the model equations. The negative sign for higher education can be explained by the fact that although a better-educated individuals are more likely to discover and successfully explore an entrepreneurial opportunity (Lim et al., 2010; Rotefoss and Kolvereid, 2005), they also have better regular employment prospects (Shane 2003).

Interestingly, in our models we were unable to identify the impact of cultural setting on entrepreneurship. Although this contradicts other recent findings (e.g. Linan and Fernandez-Serrano, 2014; Petrakis, 2014; Wennekers et al., 2007), we could explain such a confusing result by the small sample size and relatively low variance in cultural variables within Stage 3 countries. On the other hand, although the exclusion of cultural variables can provide a certain bias for international comparison, it should not have a dramatic impact on a single country simulation.

The actual equations entered in the model are as follows:

$$GDP_{growth} = 0.11 + 0.64 * GDP_{growth\ lag} + 0.054 * TEA \quad \textbf{(1*)}$$

$$EIN = 127.12 + 0.646 * POP_{adult} - 15.639 * GDP - 4.535 * POP + 9.171 * INN - 17.924 * EDU \quad \textbf{(2*)}$$

$$TEA = -8.933 + 0.533 * EIN + 2.103 * LMK \quad \textbf{(3*)}$$

The new causal diagram is presented in Figure 3.

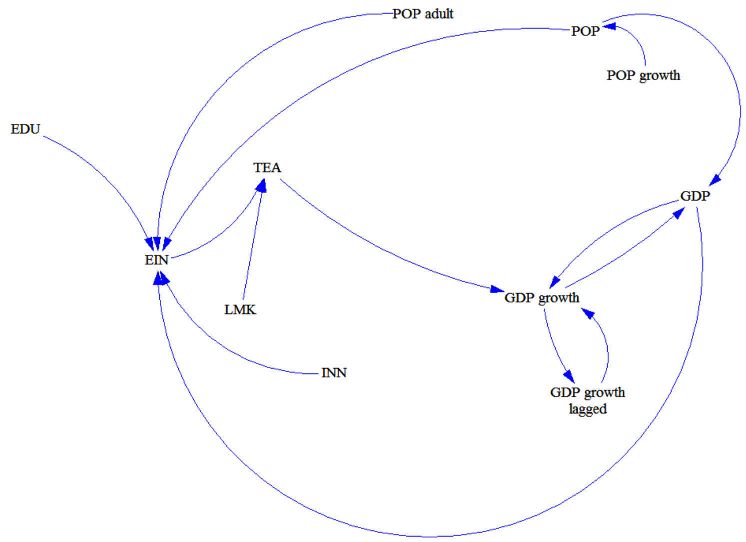

Fig. 3. Modified causal diagram used in the model

3.4 Model validation

The actual model was developed in the Vensim software package. After building the model, we did several simulation runs to validate the model. The validation is accomplished by comparing the simulated data with historical data for the period 2011-2014. We did not start our simulation from an earlier period in attempt to avoid the bias caused by the economic downturn in 2008.

For simulation purposes, we first choose Finland. The feature of this country is that although Finland has been among the world's most competitive economies for several years (4th place in 2014-2015, see the global competitiveness reports for details), the level of entrepreneurship activity is below the average for innovation-driven countries (5.29% versus 7.84% in 2013, according to GEM data). Thus, it is interesting to study whether there are reserves and possibilities to promote entrepreneurship through further institutional development, and whether there is a positive economic effect from these actions.

The model has two exogenous driving factors: population growth and adult population share. The following figure (Figure 4) presents the historical changes for the first factor, along with linear and non-linear regression lines.

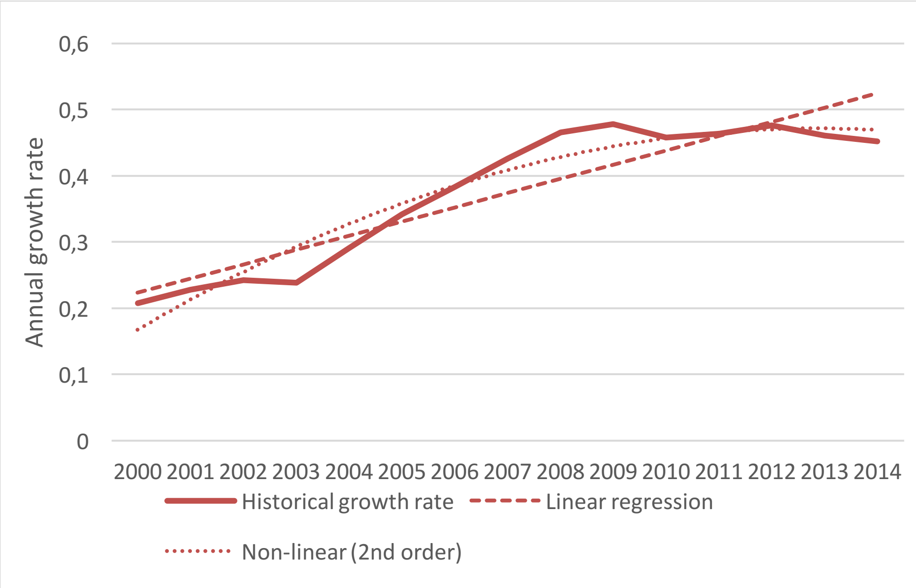

Fig. 4. The changes in Finnish population annual growth rate

The non-linear regression line provides a noticeable better fit ($R^2 = 0.936$ versus 0.845 for linear). The further increase in order produces a further increase in R^2, however it creates the danger of model overfitting. Therefore, for our simulation, we use the second-order regression equation:

$$POP_{growth} = -0.0018 * x^2 + 0.051 * x + 0.1183 \quad \textbf{(4)}$$

where:

POP_{growth} – annual rate of population growth;

x – time step (in our simulation due to the nature of the annual data values, we use a time set equal to one year).

Applying similar considerations for the second factor (adult population share), we came to the following equation:

$$POP_{adult} = -0.0262 * x^2 + 0.2467 * x + 66.443 \quad \textbf{(5)}$$

where:

POP_{adult} – annual rate of population growth;

x – time step (in our simulation due to the nature of the annual data values, we use a time set equal to one year).

The application of the non-linear model provides a noticeable improvement in fit

(R^2=0.926 versus R^2= 0.692).

Our model produces a number of variables as the result of running simulations. However, the main interest is in variables representing TEA and GDP growth. We also control for GDP per capita, total country population, and entrepreneurial intention emergence.

The errors are presented in the Table 3. Simulated TEA and entrepreneurial intention rates exceed the historical values drawn from statistics. Moreover, the error in GDP growth rate (predicted versus historical) is very high. This can be explained by some external factors affecting the national economy. Indeed, in our model, we focus on capturing the impact of entrepreneurship and, for the sake of simplicity, exclude most other factors. Thus, in the case of Finland, the GDP growth decrease is explained by the troubles in the country's main industries - technology (Nokia) and paper.

For further validation, we choose Norway - a country also demonstrating a high level of economic development and low entrepreneurship rates, but contrary to Finland not showing such a dramatic GDP growth rate drop for the analysed period. It is important to note that Norway has cultural characteristics that are quite similar to Finland, so that minimises the possibility for bias due to unobserved cultural impact (for cultural variables, see discussion in Chapter 3.3) The population growth rate and adult population share have consequently been modelled in a similar way, R^2 = 0.808 and 0.977. The equations are:

$$POP_{growth} = -0.0029 * x^2 + 0.1096 * x + 0.3007 \quad \textbf{(4*)}$$

$$POP_{adult} = -0.0126 * x^2 + 0.2955 * x + 64.405 \quad \textbf{(5*)}$$

where:

POP_{growth} – annual rate of population growth;

POP_{adult} – annual rate of population growth;

x – time step (in our simulation due to the nature of the annual data values, we use a time set equal to one year).

The results of comparing simulated and real data are also presented in Table 5. Compared to Finland, this model provides predictions that are more reliable. Especially noticeable are the differences between the real and predicted values in the same range for all key variables (GDP growth, TEA). The simulated values, on average, are slightly lower than in the real data.

Table 3. Average absolute errors in simulated data

	GDP per capita PPP	GDP growth	Entrepreneurial intentions	TEA
Finland	3.4%	518.9%	24.4%	27.4%
Norway	3.5%	40%	35.8%	10.9%

Therefore, we can conclude that our model provides quite reliable results under static conditions. However, it cannot predict sudden GDP growth rate changes if the reason for such changes lies outside the model boundaries. In other words, the model accounts only for the entrepreneurship effect and cannot fully predict national economic behaviour. Nevertheless, bearing in mind such a limitation, the model is still able to produce the results to test our propositions. Particularly, in the next chapter, we first examine the possible impact on TEA rates and consequently on national GDP growth provided by changes in the external environment, and then evaluate the reciprocal effect of changes in GDP growth rates on the national entrepreneurship activities.

4 Model simulation

After the validation of the model, we tested our research propositions. The following chapter consists of three parts. First, we present the scenarios developed to test the propositions; second, we report the results of the simulation; and finally, we discuss the results.

4.1 Scenarios

We have chosen the Norway model as the basis simulation, because this model better fits the historical data. Following the research propositions, we aim to explore how changes in supply and demand affect the system behaviour, and to what extent government interventions can control these changes.

The model has five exogenous variables determining supply, demand, and transition from intention to entrepreneurial activities: the share of adult population, higher education and training, total population, innovation, and labour market efficiency (Table 4).

Table 4 The list of exogenous variables included in the model (the sign in parentheses denotes the impact "+" positive, "-" negative)

Intention (supply)	Intention (demand)	TEA
POP adult (+)	POP (-)	LMK (+)
EDU (-)	INN (+)	

Additionally, we have an endogenous variable, GDP per capita (depends on GDP growth rate), which relates to the supply side and has a negative relationship with entrepreneurial intention emergence.

To test our propositions, we first study the behaviour of our baseline model (*scenario 0*) with standard settings, and then compare it with two alternative scenarios.

In the *first scenario*, we model the behaviour of the baseline system with increased supply. In the model, the supply can be increased by growing the share of adult population, decreasing the level of higher education, or by economic downturn. Taking into account that during peace time, dramatic changes in national population structures are quite unlikely to occur in a short period of time (1-2 years), we do not introduce any alterations in adult population dynamics. At the same time, the adoption of a policy to intentionally decrease the level of higher education seems counter-intuitive, thus we also do not change the level of the variable EDU. In order to change the supply, we modify the rates of GDP growth. In particular, we model a situation when the GDP growth rate becomes negative (i.e. we introduce a sudden drop of -200% of the current value) for a one-year period (see Table 6). This pattern resembles the situation in many European countries during the economic meltdown in 2008. It is interesting to examine how fast the system recovers after the shock and what level the main indicators reach by the end of simulation period.

The *second scenario* is similar to the first scenario, but this time, we aim to model governmental intervention. Thus, in the second year after the initial GDP growth decrease, we improve the external factors (innovation and labour market efficiency) by 10%. In the first year of "crisis", the variables remain unchanged. The idea is to emulate the lagged reaction to sudden economic shock and to perform measures aiming to eliminate the effect of the shock. Therefore, we are interested to see whether such intervention provides any noticeable improvement to the system condition, and how we can compare it to the unchanged, baseline model behaviour.

All simulation runs start with the same initial conditions, such as population, GDP, and GDP growth rate, which allows us the comparison of the system state by the end of the simulation period.

The basic assumptions of the scenarios are summarised in Table 5.

Table 5. Scenario assumptions

Simulation period	20 years
Time units	years
Starting period	2011
Country of analysis	Norway
Initial conditions (at time=0) Equal for all scenarios	Population: 2011 level GDP: 2011 level; GDP growth: 2011 level
GDP growth rate	Scenario 0: no external changes, fully endogenous Scenarios 1, 2: time steps 0-4: fully endogenous time step 5: -200% from the initial rate time steps 6-20: fully endogenous
Innovation and labour market efficiency	Scenarios 0,1: no changes, remain constant for the whole simulation period (set at the level 2011-2012) Scenario 2: time steps 0-5: set at the level 2011-2012 time step 6-20: 10% increase (the level reached by time step 7 remains the same until the end of the simulation period)

4.2 Simulation Results

The baseline model behaviour (Scenario 0) is presented in Figure 5. In spite of positive rates of GDP growth, for most of the simulation period, the system experiences a decrease in GDP per capita. This happens because population growth at the beginning of the simulation outpaces the growth of GDP (Figure 6). However, later, when the population growth rate becomes lower than GDP growth, the system is able to start growing. However, that late growth does not change the pattern for TEA. In our model, TEA experiences constant decline. Moreover, the rate of the decline increases. Such behaviour can be explained by the decline in the adult population share, resulting in a decrease in the supply of potential entrepreneurs.

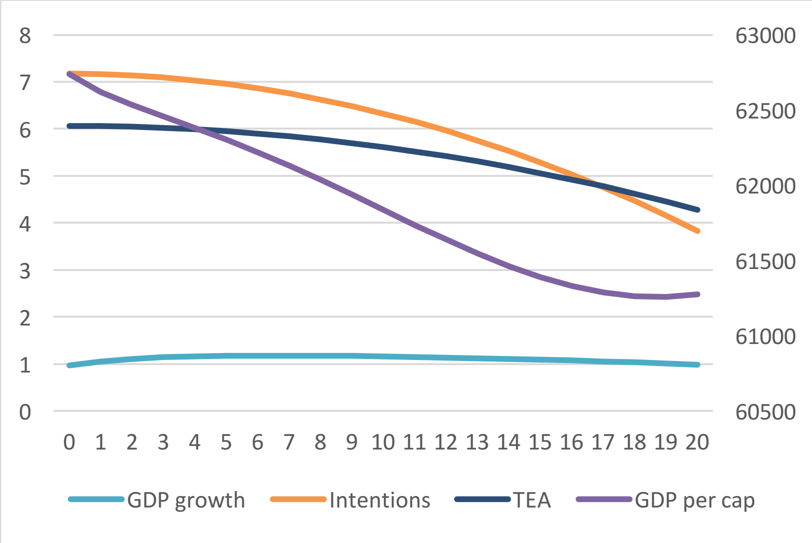

Fig. 5. The baseline model behaviour (Scenario 0)

Another interesting phenomenon occurs at the end of the simulation period, when TEA overcomes the entrepreneurial intentions. The increased share of necessity-driven entrepreneurship could account for this. Such people may not necessarily have strong intentions towards entrepreneurship careers (that is why we do not have an increase in intention rates), but are rather forced to become self-employed due to the absence of viable alternatives.

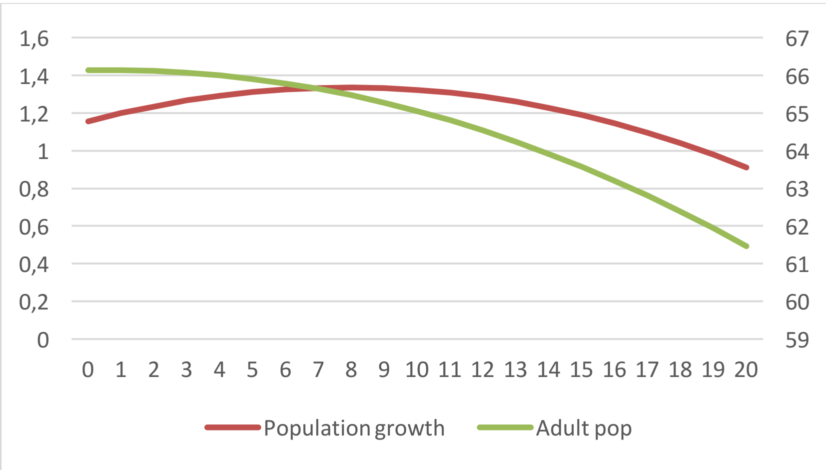

Fig. 6. The demographic trends in the model (valid for all scenarios)

Comparing the baseline model with the conceptual scenarios, we see that even a model without governmental interventions (Scenario 1) demonstrates quite a short recovery period (Figure 7). Thus, the system demonstrates positive growth rates already 1.5 years after the initial shock. The full recovery time is longer; only by time step 14 does the system reach the same growth rates as the baseline model. Interestingly, after that, the system in scenario 1 continues growth at higher rates than the baseline model. The increase in growth rates reaches almost 3% (1.017% for scenario 1 versus 0.987% for scenario 0) by the end of the simulation period.

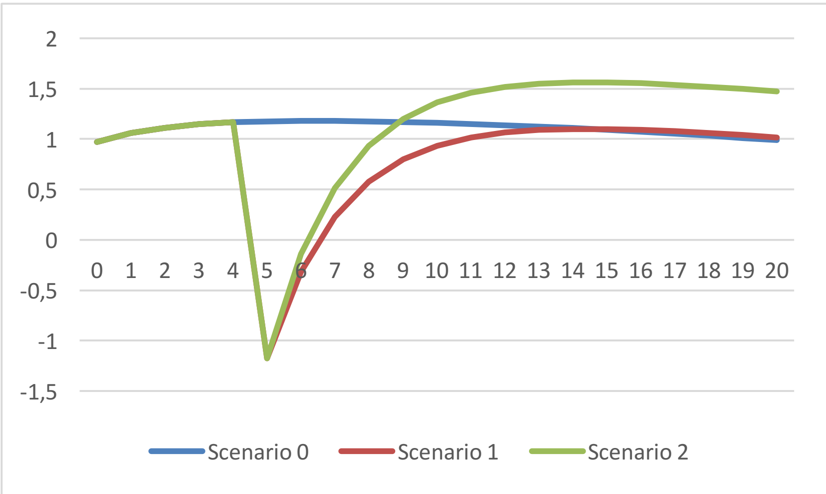

Fig. 7. GDP growth rates

Scenario 2, with governmental interventions, demonstrates even better results (faster recovery time and higher GDP growth rates by the end of the period). The overall advantage over scenario 1 reaches 31% in the final simulation year. However, in spite of an advantage in absolute numbers, all three scenarios demonstrate the tendency towards a decrease in GDP growth rates. Furthermore, even though scenarios 1 and 2, by the end of the simulation period, showed growth at higher rates than scenario 0, that is not enough to generate the same level of GDP per capita (Table 6), although the differences are relatively small (less than 1% for scenario 2 and 5.9% for scenario 1).

Interestingly, scenarios 1 and 2 also demonstrate higher rates of TEA and entrepreneurial intentions than the baseline model. However, only scenario 2 is able to maintain rates of entrepreneurial intentions exceeding TEA.

Table 6 Simulation results summary

	Scenario 0	**Scenario 1**	**Scenario 2**
GDP per capita* (PPP, USD)	61276	57639	61023
GDP growth (%)*	0.987	1.017	1.473
TEA (%)*	4.282	4.504	7.527

	Scenario 0	Scenario 1	Scenario 2
Entrepreneurial intentions (%)*	3.83	4.246	7.986
Time to reach positive GDP growth (after shock)	na	1.5 years	1.2 years
Recovery time (time to reach baseline model GDP growth rates)	na	10 years	4 years

**Results by the end of the simulation period*

4.3 Discussion of the results

In the discussion, we first consider the issues that occurred during the model-building process, and then continue with the discussion of the simulation results. Thus, although our model captures a number of important relationships, we were not able to identify the impact of different types of entrepreneurs on the economy. These results are expected for factor-driven and efficiency-driven economies, while for innovation-driven economies, improvement- and opportunity-driven entrepreneurs, as well as high-expectancy entrepreneurs, are believed to have a greater positive impact (Valliere and Peterson, 2009, Wong et al., 2005).

On the other hand, we consider the causality problem – that is, whether the prevalence of necessity-driven entrepreneurs provides a negative effect on economic growth or vice versa, so that the economic slowdown causes an increase in the number of such individuals. The results of the simulation (scenario 0) demonstrate that under defined conditions (a decrease in economic growth rates, as well as overall GDP per capita) overall TEA may be greater than the entrepreneurial intention level. This means that the number of people involved in entrepreneurial activities is greater than the number of people considering an entrepreneurial career. This extra input is attributed to the growing share of necessity-driven entrepreneurs - people who may not have strong entrepreneurial intentions, and so are not counted at the initial stage of the model, but appear only at the TEA stage.

Moreover, considering the entrepreneurial impact on the economy, we should not exclude non-innovative entrepreneurs. First, the impact of radical, “equilibrium disturbing” innovation developed by the Schumpeterian type of entrepreneur may not always be positive (Agarwal et al., 2007). At the same time, taking into account the relative scarcity of such entrepreneurs, we should not neglect low-innovation or even replicative ventures (also created by necessity-driven entrepreneurs), which, though they are less likely to have a significant impact on economic growth, are present in greater numbers and may eventually produce a similar effect (Levie and Autio, 2008; Shane, 2003).

However, considering the actual impact delivered by entrepreneurship, we have to accept that it is relatively limited (thus, the regression coefficient in the equation is small). Moreover, the significance level is not appropriate for commonly applied standards. Analysis with the data for different years results in even more confusing outcomes when the impact of entrepreneurship is significant for one year and not significant for others. Compared with the previous research findings, we see a confusing picture, in which one author finds a positive impact of entrepreneurship

(Cummings et al., 2014), while others provide some notions critical of that effect (Veciana and Urbano, 2008).

Moreover, it seems that an entrepreneurial system is susceptible to external factors. While isolated, it can recover from a shock quite fast (scenarios 1 and 2), but in real circumstances, the behaviour might be different (consider the case of Finland). The expected positive effect cannot eliminate the negative effect from other factors affecting the country's economy. This explains the over-optimistic predictions of GDP growth rates for Finland.

Interestingly, not all the proposed factors appeared to have a significant impact in our model. Thus, we were able to identify only three external determinants, which are directly affected by policy regulations: innovation, labour market efficiency, and higher education. On the other hand, the impact from cultural variables appears non-significant, which contradicts other findings (Linan and Fernandez-Serrano, 2014; Petrakis, 2014). We may attribute this confusing result to the relatively small sample size. However, although excluding these factors from the model should not provide a bias for the general behaviour estimation (as well as a comparison of countries with similar cultural characteristics), the possible unobserved effect may play a role in the evaluation of policy measures results. Therefore, we propose the necessity of the impact of cultural variables on entrepreneurship and their interconnections with other external factors for further research (see, e.g., Misra et al., 2012).

The first proposition holds true, and the eventual growth rates are even higher than in the baseline scenario, although we cannot consider scenario 1 better because the overall figures for GDP per capita are lower. Furthermore, in a real situation, such an economic downturn will also influence other factors, which are not included in the model. Therefore, the actual recovery time might be longer. In this situation, the government interventions modelled in scenario 2 are necessary measures. However, it might be questionable whether it is possible to achieve such noticeable improvements in a relatively short time. Moreover, taking into account a controversial finding regarding the economic impact of entrepreneurship, we might also question whether such measures should be of primary importance.

We should also consider a possible increase in necessity-driven entrepreneurs. For them, lacking the necessary experience and networks, the additional support becomes especially important. At the same time, even people with high intentions towards entrepreneurship are subject to failure in the harsh economic conditions. Therefore, the improvement of external conditions, provided by direct support for entrepreneurs by means of, for example, business incubators, may result in sufficient improvement in the system conditions and faster recovery from an economic recession.

Regarding our third proposition, we found that demographic characteristics might play a significant role in the long-term development of the entrepreneurial system. Although the population demographic indicators are a well-recognised determinant of entrepreneurship (Bowen and Clerq, 2008; Shane 2003, Verheul et al., 2002; Wennekers et al., 2005), their long-term impact on entrepreneurial activities is understudied. Our model reveals that, in spite of favourable external factors, the population decrease and, more importantly, the decrease in the adult population share will negatively affect entrepreneurship activities and, consequently, to some extent, economic growth rates.

At the end of the simulation (scenario 0), population decline led to certain growth in GDP per capita, but combined with an even more severe decline in the adult population share, this eventually resulted in an increased decline in TEA. A discussion of demographic policy goes beyond the scope of this paper. It seems that policy-makers aiming to improve entrepreneurial conditions also need to take into account the current demographic situation and further trends.

5 Conclusion

This paper demonstrates the dynamic macro-level model of entrepreneurship. The main feature of the model is the combination of external determinants of entrepreneurial activities with the economic effect of entrepreneurship. Therefore, the model is able to capture the complex non-linear behaviour generated through the feedback loop. We constructed model equations based on regression analysis of multi-country data, which improves model applicability in different institutional settings and enables country comparison.

The secondary data used in model equation building comes from open sources such as the Global Entrepreneurship Monitor, Global Competitiveness Index, and World Bank databases. The model was validated using historical data for 2011-2014. For this purpose, we used data from Finland and Norway. The reason for that choice is that both countries are developed economies (and consequently have high levels of entrepreneurship determinants) and demonstrate low levels of entrepreneurial activity (below the average level for innovation-driven economies). Both countries also have similar cultural values, which limits the risk of possible bias due to the unobserved effect of cultural variables, which we excluded from our model.

We aimed to explore the behaviour of the entrepreneurial system model and test the research propositions. The main outcome is that, although isolated from other external factors affecting the economic state, the system is able to generate positive economic growths rates and even recover after a sudden shock. The long-term system behaviour depends on factors such as overall country population development and especially the proportion of the adult population. Indeed, these macro-level factors affect numerous aspects of the national economy, and entrepreneurship is dependent on them.

Moreover, the study raises the question of the proper understanding of the role of entrepreneurship in a country's economic growth. Even though the positive role of entrepreneurship is a fact, the actual contribution to the economy may vary. Thus, a simplified understanding of entrepreneurship as a universal solution for economic problems may not provide the desired outcomes. Moreover, we found that considering entrepreneurship as the only economic growth factor may produce over-optimistic results, which do not correlate well with the real situation.

The results of this work have several academic implications and raise some questions for further discussion. It is clear that there is a need for a comprehensive model of entrepreneurship, which would include not only the determinants of entrepreneurship, but would consider the impact that entrepreneurial activities have on the national economy and overall society. In other words, to better understand the entrepreneurship phenomenon and its importance, we need to capture the feedback loop between the factors that have an impact on entrepreneurship, and the impact that entrepreneurs have on these factors.

The policy and managerial implications lie in the need to understand the system complexity. The improvement of one factor may have a direct effect, but may be unable to change a long-term trend caused by, for example, national demographic development. Furthermore, the external determinants may have different effects on entrepreneurship and other economic and societal factors. Thus, the level of higher education has a negative impact on the emergence of entrepreneurial intentions. However, it seems strange to recommend decreasing the higher education rate in order to stimulate entrepreneurial activity. Entrepreneurship is just one part of a complex economic system; therefore, all the measures aiming to alter the level of entrepreneurship require a holistic approach.

The major limitation of the developed model lies in the compromise between accuracy and complexity. The application of multi-country data, although it enables the application of the model to various countries, inevitably results in increased error rates, compared to a tailored model based on one country's time-series data. Another limitation, which prohibited us from creating more precise tailored models, is data availability. Being limited to open databases, we did not have enough historical data to conduct a meaningful statistical analysis for each specific country. Small sample size might be also a reason for confusing results regarding the impact of entrepreneurship as well as non-significant coefficients for cultural variables.

A valuable direction for further research can be an expansion of the system dynamic model, aiming at the more accurate capture of overall national economic behaviour. The development of specifically tailored country models will undoubtedly increase the precision of predictions and enable better understanding of national specifics, when different factors may be of different importance for each specific economy.

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Appendix

Table A1. Descriptive statistics

Variable	Mean	Std Dev	Minimum	Maximum
GDP growth	2.423	3.558	-15.262	9.322
GDP growth lagged	2.140	3.418	-6.572	10.247
GDP	4.250	0.364	2.893	4.817
POP	7.263	0.753	5.454	9.133
POP growth	0.814	1.022	-1.283	3.336
POP adult	65.345	5.324	49.185	73.094
UNP	10.454	7.420	0.770	29.650
TEA	13.799	8.804	3.428	39.905
OEA	46.969	13.453	18.378	76.034
NEA	25.280	11.547	4.000	60.981
EIN	23.861	15.459	2.595	66.689
INN	3.761	0.905	2.1	5.8
TEC	4.342	1.074	2.4	6.2
LMK	4.326	0.567	2.9	5.8
GMK	4.383	0.518	3	5.6
FIN	4.288	0.727	2.4	5.8
INS	4.195	0.808	2.8	6.1
EDU	4.553	0.900	2.1	6.3
PDA	61.102	19.827	13	100
IND	43.186	23.219	6	91
UA	65.966	23.137	8	100

Table A2. Correlations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
GDP growth	1.000																				
GDP growth lagged	0.732*	1.000																			
GDP	-0.426*	-0.429*	1.000																		
POP	0.319*	0.205	-0.153	1.000																	
POP growth	0.439*	0.489*	-0.619*	0.271*	1.000																
POP adult	-0.326*	-0.259*	0.567*	-0.024	-0.714*	1.000															
UNP	-0.293	-0.424*	-0.089	-0.237	-0.328*	0.059	1.000														
TEA	0.425*	0.562*	-0.657*	0.028	0.595*	-0.532*	-0.078	1.000													
OEA	-0.074	0.083	0.376*	-0.074	-0.077	0.180	-0.560*	-0.157	1.000												
NEA	0.253*	0.001	-0.512*	0.152	0.075	-0.075	0.531*	0.151	-0.604*	1.000											
EIN	0.522*	0.453*	-0.785*	-0.027	0.613*	-0.566*	0.046	0.786*	-0.252*	0.341*	1.000										
INN	-0.258*	-0.222	0.644*	0.074	-0.229	0.180	-0.161	-0.429*	0.415*	-0.430*	-0.587*	1.000									
TEC	-0.508*	-0.404*	0.831*	-0.171	-0.514*	0.356*	-0.025	-0.562*	0.385*	-0.500*	-0.734*	0.852*	1.000								
LMK	-0.059	0.130	0.272*	-0.125	-0.103	0.041	-0.133	-0.030	0.435*	-0.366*	-0.224	0.628*	0.556*	1.000							
GMK	-0.134	-0.041	0.518*	-0.048	-0.241	0.226	-0.167	-0.271*	0.385*	-0.377*	-0.475*	0.800*	0.724*	0.728*	1.000						
FIN	0.025	0.226	0.261*	0.004	-0.013	0.087	-0.305*	-0.035	0.355*	-0.313*	-0.207	0.632*	0.483*	0.713*	0.777*	1.000					
INS	-0.249*	-0.147	0.565*	-0.188	-0.245*	0.171	-0.070	-0.308*	0.419*	-0.458*	-0.448*	0.838*	0.775*	0.698*	0.850*	0.726*	1.000				
EDU	-0.519*	-0.428*	0.854*	-0.117	-0.643*	0.567*	-0.091	-0.618*	0.372	-0.427*	-0.758*	0.804*	0.931*	0.461*	0.677*	0.430*	0.715*	1.000			
PDA	0.461*	0.393*	-0.536*	0.252	0.293*	-0.109	-0.028	0.284*	-0.289*	0.410*	0.340*	-0.572*	-0.614*	-0.349*	-0.403*	-0.267*	-0.545*	-0.564*	1.000		
IND	-0.486*	-0.427*	0.578*	-0.047	-0.328*	0.115	0.049	-0.520*	0.157	-0.285*	-0.572*	0.550*	0.639*	0.357*	0.417*	0.292*	0.526*	0.592*	-0.695*	1.000	
UA	-0.207	-0.210	0.170	-0.094	-0.210	0.014	0.081	-0.195	-0.179	0.068	-0.103	-0.224	-0.003	-0.502*	-0.370*	-0.429*	-0.352*	0.012	0.204	-0.119	1.000

**Significant at least 5%*

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Exploring Digital Service Innovation Process Through Value Creation

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Abstract. Value is generated through the whole service innovation process in a complex collaborative networked ecosystem. This study aims to enhance understanding of value generation in digital service innovation process with an emphasis on information technology by developing an extended value generation process framework and evaluating on how it is applicable in a real-life networked retail service innovation context. The findings of the study suggest that multiple information technology (IT), process and business related factors affect value creation during the digital service innovation process. The role of information technology is multifaceted, providing both new opportunities and challenges in the service innovation context. The extended framework for exploring the service innovation process provides a more structured way to examine the complex, networked, service innovation ecosystems.

Keywords. Innovation, Value co-creation, Service industry, Retail selling.

1 Introduction

The rapid development of information and communication technologies has introduced a whole new array of possibilities for creating novel digitally enabled services that enhance peoples' daily lives and create new business opportunities for companies. Consequently, the focus of companies' innovation activities has shifted from closed good-centric to open and service-centric. As companies have become more and more service oriented, service innovation has gained increasing interest also in research and the scope has evolved from the traditional product innovation view to the multidimensional and all-encompassing view to service innovation (see e.g. Carlborg et al., 2014; Biemans et al., 2015). A network or an ecosystem centric view (see e.g. Chesbrough, 2006) emphasizes the collaborative nature of service innovation. The importance of information technology as an enabler and a driver of ecosystem based service innovation have also received notable attention in the research community. For example, Maglio and Spohrer (2008) suggested that technology is an integral part of innovation in service systems. Lusch and Nambisan (2015) develop a service dominant (S-D) logic based framework which emphasizes an ecosystem centric view of value co-creation and the role of information technology in the service innovation process.

According to Lusch and Nambisan (2015), behind the design and development of new digitally enabled service innovations, there is a network of actors with a wide range of resources that can be used in the value co-creation. This stresses the importance of efficiency of resource integration processes. It is necessary to identify how resources are integrated between different companies and the customers and what the possible challenges are in resource integration and related value creation activities. From the perspective of the service provider companies, the main challenge is twofold. On one hand, they must manage the efficient inter-firm resource integration activities with other companies. On the other hand, they must adjust their value generation processes and service delivery mechanisms to enable the participation in the customers' value creation process in a meaningful and economically efficient manner.

Because of the two megatrends, digitalization and servitization, driving the economic development of our societies, the ability to solve the above twofold challenge is becoming crucial to more and more companies. Hence, there is a clear need for further research and development of analytical tools that on one hand address the value generation process from the customer-centric perspective, and on the other hand tackle the challenges related to resource integration from an ecosystem perspective.

In this study we attempt to address this need by developing a research framework which draws on two intertwined major marketing research themes, value creation and service innovation. The developed framework approaches the innovation process from the value generation viewpoint, by combining the service logic (SL) value generation process model (see e.g. Grönroos and Gummerus, 2014) and the service innovation framework introduced by Lusch and Nambisan (2015). In this framework, value is determined as value-in-use, which is the central value definition in both service-dominant logic (SDL) and service-logic (SL). Value-in-use is the value for the customer and it is created by the customer during usage of resources instead of being inherent to the product (see e.g. Woodruff and Gardial, 1996; Vargo and Lusch, 2004; Grönroos, 2006). As value is always created by the customer, the company's activities are related to the facilitation of creation of value-in-use (creation of potential value-in- use) and direct interaction with the customer (co-creation of value-in-use).

This study utilizes experiences from a pilot case in the retail sector to examine the suitability of the developed framework for analyzing the innovation process of a real-life digital service. Especially we are interested in whether the developed framework can be used for a) identifying the crucial factors in the digital service innovation process from the value generation viewpoint and b) assessing the role of information technology (IT) in the process. The retail sector was chosen because of its potential of benefitting from the emerging digitalization and related new ways of customer engagement. The importance of positive shopping experience and integrated multichannel customer engagement is highlighted in recent retail studies (e.g. Verhoef et al., 2009; Rigby, 2011; Grewal et al., 2011; Shankar et al., 2011; Gallino and Moreno, 2014; Herhausen et al., 2015). The multichannel utilization trend has forced retailers to find new ways to enhance the shopping experience and to reinvent the service concept of the traditional physical store (Brynjolfsson et al., 2013; Herhausen et al., 2015). These studies highlight the multifaceted nature of innovation in the retail context. The innovation process within the pilot case is examined using the developed framework. Through our framework, we are able to map the value generation activities of different actors during the service innovation process to the extended value generation process framework, which provides a service-oriented customer-centric approach with an ecosystem actor perspective to examine value creation.

This paper is structured as follows. Section 'Value generation process in service innovation' provides the theoretical background of the research and the research questions. It introduces the approaches that provide a basis for the developed extended value generation process framework. The following 'Research methods' section provides an overview of the research approach and includes a description of the data collection methods used in the study. The fourth section describes the process of digital shopping service innovation mapped with the extended value generation process framework. The fifth section discusses the findings of the study and presents answers to the research questions raised within this study. The sixth section presents concluding remarks, brings out limitations of the study and outlines potential directions for future research.

2 Value generation process in service innovation

Lusch and Nambisan (2015, p. 161) define service innovation as "the rebundling of diverse resources that create novel resources that are beneficial (i.e., value experiencing) to some actors in a given context." Hence, service innovation can be interpreted as a change in the roles and the composition of the actor network involved in the value creation processes. Consequently, the fundamental prerequisite in succeeding with new service development is identifying key actors, their roles and understanding the value creation processes.

2.1 Value creation

The concepts of value and value creation have gained increasing attention in marketing research since the focus of the majority of research shifted from goods to services. One of the most significant contributions was the introduction of service-dominant logic (SDL) by Vargo and Lusch (2004, 2008, 2016), which provides a conceptual framework for value co-creation. An analytical view to value creation, value co-creation and the value generation process was taken in service logic (SL) (Grönroos and Voima, 2013; Grönroos and Gummerus, 2014). SL is based on an explicit definition of value as value-in-use, and describes the value generation process (see Figure 1) including all provider and customer activities. The value generation process framework consists of three spheres: provider, joint and customer sphere (Grönroos and Voima, 2013).

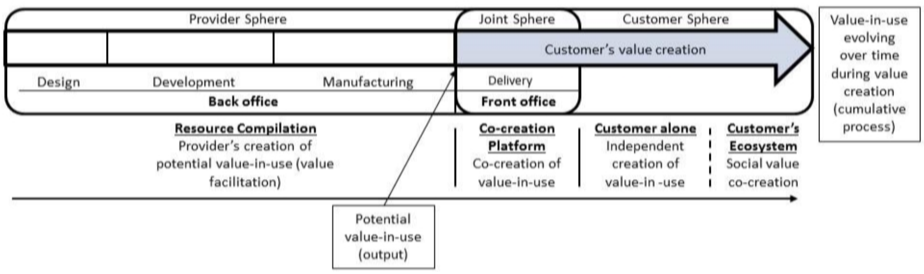

Fig. 1. SL based value generation, process model. Source: Grönroos and Gummerus (2014, p. 218).

The provider sphere is closed to the customer, and in it, the firms' activities are facilitating customers' value creation by compiling resources and thus producing potential value-in-use. In the joint sphere, a direct interaction between service provider and customer takes place. This direct interaction creates the co-creation platform, which enables the service provider to participate in and contribute to the customer's value creation process. The customer sphere is closed to the service provider. In this sphere, customer creates value-in-use either alone (independent creation of value-in-use) or as a part of his/her social ecosystem (social value co-creation). Social value co-creation has similarities with the concept of value-in-social context introduced by Edvardsson et al. (2011), who suggests that value perceptions are relative in nature as customers compare themselves with others. As stressed by Grönroos and Gummerus (2014), the process is not necessarily linear and static. Different spheres can be intertwined, for example, a co-creation platform (i.e. joint sphere) can be seen to have already emerged in the design phase if customers are involved in the service design and ideation.

The value generation process model gives customer-centric and service-oriented approach highlighting, for example, the customer's social ecosystem, but it does not cover a broader view to service ecosystems and resource integration activities from a B-to-B viewpoint. It highlights position and role of an end customer (e.g. customer of a store) as the creator of value-in-use and emphasizes direct interactions between the customer and the service provider in the platform of co-creation, but it does not explicitly deal with the network perspective, which includes back office activities incorporating resource compilation and value facilitation between multiple business actors.

2.2 Service Innovation

During the past decade, the research on service innovation has also undergone major changes. One of the main changes has been the opening of firm boundaries, i.e. shifting the focus from internal innovation resources and capabilities into a network or an ecosystem centric view (see e.g. Chesbrough, 2006). The importance Inter-firm collaboration in service innovation is highlighted in e.g. Schilling and Phelps (2007), and Tsou and Chen (2012). Furthermore, studies have also shown the benefits of integrating customers in innovation activities (e.g. Chen et al., 2011; Tsou and Chen, 2012). According to a broadened view of Lusch and Nambisan (2015), service innovation is a collaborative resource rebundling process in an actor-to-actor-network highlighting value experienced by the beneficiary. This broadened view is based on a definition of services "as the application of specialized competencies (knowledge and skills) through deeds, processes, and performances for the benefit of another entity or the entity itself (Vargo and Lusch, 2004)". This view highlights the importance of enhancing resource density, e.g. by providing interfaces and extending access to appropriate resources or resource bundles in order to support the collaborative innovation process and improve the opportunities for service innovations.

The aforementioned conceptualizations emphasizing service innovation as a collaborative, networked process include several aspects that are used when exploring this real-life case to achieve a better understanding of the nature of service innovation, value creation and the role of information technology in a complex network of diverse actors. Lusch and Nambisan (2015) introduced a service innovation framework with three inter-related elements: 1) a service ecosystem, an organizing structure for a network of actors, 2) a service platform that serves as the venue for innovation, and 3) value co-creation, processes and activities that underlie resource integration and incorporate roles of ecosystem actors. The service innovation framework is grounded in SDL and used to define the concept of value as value-in-use. Figure 2 illustrates the simplified service innovation framework including three identified inter-related key elements. In addition to emphasizing the network aspect of innovation, the framework by Lusch and Nambisan (2015) provides fruitful insights into the role of IT in service innovation. In recent studies, a role of information technology is considered an operand (static, tangible and enabling) and operant (dynamic, intangible and triggering) resource in the context of services and service innovation (Nambisan, 2013; Akaka and Vargo, 2014; Lusch and Nambisan, 2015).

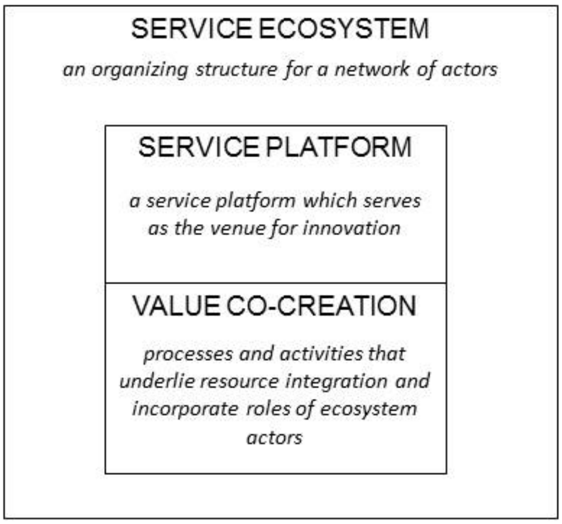

Fig. 2. A simplified version of service innovation framework. Source: Adaptation of Figure 1 from Lusch and Nambisan (2015, p. 162). Copyright © 2015, Regents of the University of Minnesota. Reprinted by permission.

One of the key issues related to service ecosystems is the architecture of participation, i.e. the way in which the interactions between network actors are coordinated (Lusch and Nambisan, 2015). A sound architecture of participation is the main antecedent of a well-balanced combination of structural flexibility and structural integrity. Structural flexibility refers to the actor network's ability to adapt to changes in business, societal and technological environments. Structural integrity can be considered as ties or relationships that hold the diverse actors together in a network (Lewicki and Brinsfield, 2009). The optimal mix of structural flexibility and integrity leads to efficiency in the resource integration process, which is also defined as resource density (Lusch and Nambisan, 2015). The central elements of participation coordination are clear and transparent rules of interaction, orchestration of the service innovation process and value capture structure, which creates adequate incentives for network participation. Lusch and Nambisan (2015) identified three supporting issues for value co-creation: facilitating interaction among actors, adapting internal processes, and transparency of activities, which can be seen as linked with the aforementioned elements of participation coordination and have an impact on the balance between structural flexibility and integrity.

In Lusch and Nambisan's service innovation framework, service platforms play a central role as they define a service platform as "a modular structure that comprises tangible and intangible components (resources) and facilitates the interaction of actors and resources (or resource bundles)" (Lusch and Nambisan, 2015, p. 166). In the context of the value generation process model, service platforms can emerge in both the provider sphere and the joint sphere, i.e. they can facilitate both business network interaction closed to the end customer, hence co-creating potential value-in-use and service provider-end customer interaction thus creating a co-creation platform which facilitates the co-creation of value-in-use.

To explicitly include the network aspect into the value creation analysis and to enhance understanding regarding resource integration and value creation in larger service innovation ecosystems consisting of diverse network of actors, the following extended value generation process framework (see Figure 3), which considers the closed sphere as a part of a B-to-B (business-to-business) innovation ecosystem, is proposed. With this framework we attempt to seek answers to our first research question:

> *RQ1: What kinds of crucial factors can be identified in the innovation process of digitally enabled service from the value generation viewpoint?*

Through this combined framework, it is possible to map the value generation activities of different actors during the service innovation process. In the extended framework, the principle of a direct interaction concept (see Grönroos and Voima, 2013; Grönroos and Gummerus, 2014) for identifying when co-creation of potential value-in-use occurs through B-to-B focused resource integration processes especially in back office phases is applied.

This assumes the service provider as the focal company, which as the result of the service innovation process (including resource pooling and integration of different network actors), provides the retail service to the end customer in the joint sphere. Again, it must be noted that this framework is not linear and static. For example, if end customers are involved in the design phase of the service innovation, then the joint sphere already emerges at that stage of the process.

The extended framework provides a foundation to examine more systematically activities and processes underlying value creation in a large service ecosystem and through that makes it easier to identify possible challenges and opportunities.

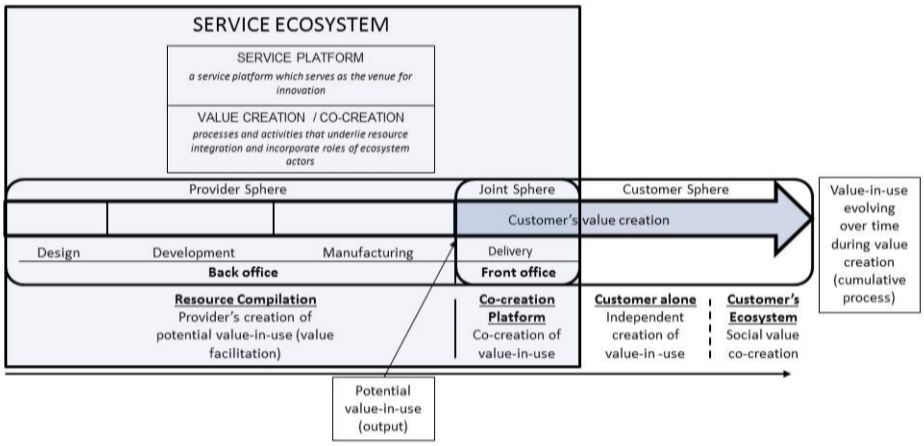

Fig. 3. The extended value generation process framework. Source: Adaptation of Grönroos and Gummerus (2014, p. 218) and Figure 1 of Lusch and Nambisan (2015, p. 162). Copyright © 2015, Regents of the University of Minnesota. Reprinted by permission.

2.3 Digitally enabled services

The rapid development of information and communication technologies has been one of the enablers and drivers in digitalization of different industries and introduced a new array of possibilities for creating novel digitally enabled services. It has been also suggested that technology is one integral part of value-creation configuration in service systems (Maglio and Spohrer, 2008). Technologically oriented approach that emphasizes commonly tangible technological aspects of the innovation is one of the common approaches to study the innovation. However, it can be seen that there are also a wide range of technology related intangible elements playing a substantial role within service innovations and value creation. Hence, a broader view is needed in order to achieve a deeper understanding of IT and value creation in digital service innovation.

Examining the role of IT from operand/operant and service platform aspects can provide a foundation for a deeper understanding of IT's role in the service innovation context. In terms of operand and operant resources the former refers to resources that enable or facilitate value creation. These types of resources are typically tangible and static, such as a digital infrastructure or devices. Operant resources are typically dynamic and intangible resources, which act on other resources in the value creation process. These operant resources are for example, people's skills and expertise. Basically, in traditional manufacturing environment materials can be seen as operand resources and employees as operant resources. Traditionally technology has been treated as an operand resource that is an outcome of human actions highlighting material characteristics of technology, but it can be also viewed as a dynamic and intangible operant resource (Akaka and Vargo, 2014). As noted in Lusch and Nambisan (2015) IT has a dual role in digital service innovation – as an operand resource and as an operant resource. In addition to examination of service innovation from operand and operant resource perspectives, a definition of service platform can give a starting point for more extended examination of the IT and service innovation as it highlights service platform's modular structure and role as a venue for innovation (see Lusch and Nambisan, 2015). Referring to the aforementioned views our second research question is:

> *RQ2: What is the role of information technology in the service innovation process?*

Finally, as this research presents a new research framework and applies it to a real-life digital service innovation case in the retail sector, we scrutinize the suitability of the developed framework as a tool for service innovation analysis. Our third research question is:

> *RQ3: How suitable is the extended value generation process framework for exploring service innovation?*

3 Research methods

The research questions call for a holistic approach to the phenomenon under analysis – the value generation during the service innovation process. Hence, use of the case study approach was appropriate as it enables researchers to gain an in-depth understanding of a complex issue by scrutinizing the phenomenon using multiple data sources. Yin (1984) defines a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used. Yin (1984) further states that the case study's unique strength is its ability to deal with a wide variety of evidence - documents, artefacts, interviews and observations. One benefit of a case study is that it allows for use of quantitative data. Yin (2003) makes a distinction between case study and qualitative study by acknowledging the use of quantitative evidence in the former.

Data for the analysis was collected through observation and interviews. Collected and analyzed data was mainly qualitative. In addition, quantitative customer behavior related data was collected by using a depth sensor tracking system. That data was used for analyzing customer behavior in proximity to the customer PC in the store.

Observations were done by actively participating in different innovation activities during different phases of the pilot case. Researchers involved in the case took notes regarding different face-to-face and telco meetings. Notes were also used to support the analysis of the case. In addition, ecosystem business actors involved in the pilot case were interviewed after deployment of and during a working pilot service. Semi-structured interviews were arranged as face-to-face and phone interviews. All interviews were recorded and transcribed by researchers for later analysis.

Semi-structured interviews of ecosystem business actors focused on various themes, such as actors' interests, aims, roles and practices in the shopping service innovation context. In the analysis, the main goal was identification of the different value related assets and their associations between different actors. In addition, the goal was to identify possible challenges and opportunities regarding the pilot case and innovation activities, and in particular, to examine them from the perspective of generation of potential value-in-use and value co-creation of value-in-use. Table 1 illustrates the group of interviewed ecosystem business actors. Nine of these ten interviews were individual interviews while one retail personnel interview in the first additional pilot store was conducted with two interviewees. In addition to the first interview with a store manager in the original pilot store, this manager was later contacted several times by phone to receive information on the usage of the new shopping service and the opinions of sales personnel of the service.

In addition to interviewed business actors, store customers were interviewed and observed in the store, which provided premises for the pilot shopping service. At the beginning of the interview, the concept of the new digital shopping service was introduced to the customers; however, they did not actually directly interact with the service. A total of 35 store customers were interviewed and nine of them participated in a usability test in a real store environment. In addition, a brief survey was administered to all end customers who placed a product order through the shopping service. A primary goal of the end customer interviews was to gain an understanding of the customer's value-in-use regarding retail services, by collecting data about online and offline shopping behavior and to clarify the customers' attitudes towards the digitally enabled shopping service as well as how useful they felt it to be. The main goal of the usability test was to collect data for refining requirements for further service development with a central focus on the customer PC's user interface.

An analysis phase of the study consisted of multiple stages. In the analysis transcribed verbal statements from different ecosystem business actor interviews and meetings were systematically gone through in order to identify common themes and discrepancies, which were then coded and categorized. In addition, analyzed data from the customer interface was reflected and compared with data from business actor interviews and meetings. When the shopping service was deployed in two additional pilot stores later on, representatives of these stores were also interviewed and collected data analyzed jointly with previously collected data. As researchers (including the first author of this paper) were involved in the service innovation process activities and especially in the ideation, concepting and deployment phases of the innovation process, their observations through the process provided also support for the analysis phase.

Table 1. Interviewed ecosystem business actors.

Interviewee	Organization	Interview type
Concept development director	Digital signage service provider	Face-to-Face
Director in retail area	Retail management	Face-to-Face
Store manager	Retail personnel/Store management (original pilot store)	Phone
Project director	E-commerce development company	Phone
Division manager	Store chain management	Face-to-Face
Development manager in retail	Retail management	Face-to-Face
Marketing manager	Sales and marketing in the retail company	Phone
Store manager and sales person	Retail personnel (1st additional pilot store)	Face to Face
Store manager	Retail personnel (2nd additional pilot store)	Face to Face
Sales person	Retail personnel (2nd additional pilot store)	Face to Face

As a process grounded framework, the extended value generation process framework naturally steers us to examine value generation in service innovation through phases of the innovation process. The pilot case is explored based on the extended framework by the five identified phases with the main focus being on the service innovation process, more precisely on resources and their integration activities and related value generation. The exploration especially emphasizes the three support areas of co-creation and the efficient resource integration views that are highlighted in the service innovation framework defined by Lusch and Nambisan (2015). As noted earlier, the central elements of participation coordination are clear and transparent rules of interaction, orchestration of the service innovation process and value capture structure, which creates adequate incentives for network participation. These participation coordination elements can be seen as connected with the three following areas of supporting a favorable environment for resource integration activities and consequently for value co-creation: 1) facilitating interaction among actors, 2) adapting internal processes and 3) transparency of activities.

Table 2 sums up the focus areas that are used for exploration of value creation in the pilot case. The role of IT is also discussed in different phases of the innovation process.

Table 2. Focus areas for examining value creation in the pilot case.

Focus	Viewpoints for examination
Resource integration and creation of potential value-in-use	How is potential value-in-use generated through resource integration? What kind of roles, activities, processes there are behind resource integrations and value creation between business actors? What kind of challenges can be identified in creation of potential value-in-use?
Co-creation of value-in-use with the end customer	How does the end customer value (value-in-use) generation occur in the co-creation platform through direct interactions? What kind of roles, activities, processes there are behind resource integrations and value creation between actors? What kind of challenges can be identified in resource integration activities in co-creation platform?
Facilitating interaction among actors	Mechanisms provided for interaction among ecosystem actors
Adapting internal processes	Capability to adapt existing or adopt new internal processes
Transparency of activities	Enhancing the transparency of resource integration activities in the service ecosystem

4 Mapping the innovation process of the real-life pilot case with the extended value generation process framework

The target of the retail service provider was to provide a wider selection of goods from a store for customers living in a rural area with limited shopping opportunities. An initial assumption was that the new digital shopping service might especially support shopping activities of the elderly customers of the store. The pilot store was selected based on these thoughts from the rural area in northern Finland, where a number of special stores is limited and the proportion of older people is relatively high. The basic idea was to seamlessly combine different physical and digital channels so that customers could more facilely do their shopping in a retail store. The customers were also provided with the possibility of placing their orders online outside the store, e.g. from their homes and then collect the ordered products from the store. The shopping service innovation was realized over several stages. In general, the stages of the innovation process usually include all steps from idea generation to commercialization (Baregheh et al., 2009). This section describes the innovation process, ecosystem actors, their roles and activities, and the pilot solution as a service platform in the context of the shopping service pilot case. In addition, the case is explored through the extended value generation process framework.

4.1 Innovation process and service ecosystem actors

The shopping service was realized through several process phases. The primary goal of the service innovation was to improve the customer's value-in-use experience by providing a seamless shopping experience for customers in the store and better selection of goods. This required development of new processes and the configuration of technological components. The innovation process of the case consisted of process phases from ideation to a working pilot service. During the phases of the innovation process, different ecosystem actors were active in order to provide their knowledge and skills for creating a novel shopping service solution. The innovation process was iterative in nature and identified phases had overlapping activities.

When the identified innovation process phases of the pilot case were positioned with the value generation process model (see Figure 4), the first four of these phases (ideation, concepting & design, development and deployment) could be considered to be back office activities (i.e. provider sphere) and the fifth phase (pilot service) referred to delivery activities of the front office (i.e. joint sphere), when a service is available for usage. As mentioned before, the joint sphere can emerge in earlier process phases, which in this case was within the provider's sphere. For example, this can occur through close co-design activities with the customer. In the pilot case; however, customers of the store were not involved in the innovation process prior to the front office activities (pilot service phase).

The pilot case required active and close collaboration, and direct interactions between actors in different phases. Different actors were actively involved in resource integrations and influenced potential value-in-use that is realized as a value-in-use through experiences of the end customer. According to Grönroos and Gummerus (2014), collaborative and dialogical joint processes evoke co-creation platforms for reciprocal co-creation of value. When innovation process phases and related resource integrations between business actors of the pilot case are examined against that statement, it can be observed that the innovation process phases of the pilot case are grounded on value co-creation.

A diverse set of actors with a range of different roles and resources participated in the innovation process. Table 3 describes the service ecosystem actors, their main role and involvement in different phases of the innovation process in the pilot case.

Table 3. Ecosystem actors, their key resources/roles and participation in the innovation process (*) part of the service provider organization).

Service ecosystem actor	Key resource/Role	Ideation	Concepting & Design	Development	Deployment	Pilot service
Research organization	Knowledge and skills to build digitally enabled service concepts in the retail domain and experience in designing research and conducting pilot studies.	x	x	x	x	x
*Management of the retail company	Knowledge about retail business and processes and digital roadmap	x	x			
*Sales and marketing unit of the retail company	Design and implementation of different marketing material and digital service content		x	x	x	
*E-commerce development company	Design and implementation of retail online solutions	x	x	x	x	x

Service ecosystem actor	Key resource/Role	Ideation	Concepting & Design	Development	Deployment	Pilot service
Web service development company	Design and implementation of the digital service user interface		x	x		
3D visualization company	Design and implementation of 3D visualizations		x	x	x	
Digital signage service provider	Design and implementation of digital signage solutions	x	x	x	x	
*Store/Retail service provider	Knowledge about the practical activities and daily operations/processes in the store environment				x	x
Customer	End customers of the shopping service involved in the testing activities					x

Figure 4 illustrates the elements of the shopping service pilot case mapped in the extended value generation process framework covering end customer and inter-firm connections through the shopping service innovation process.

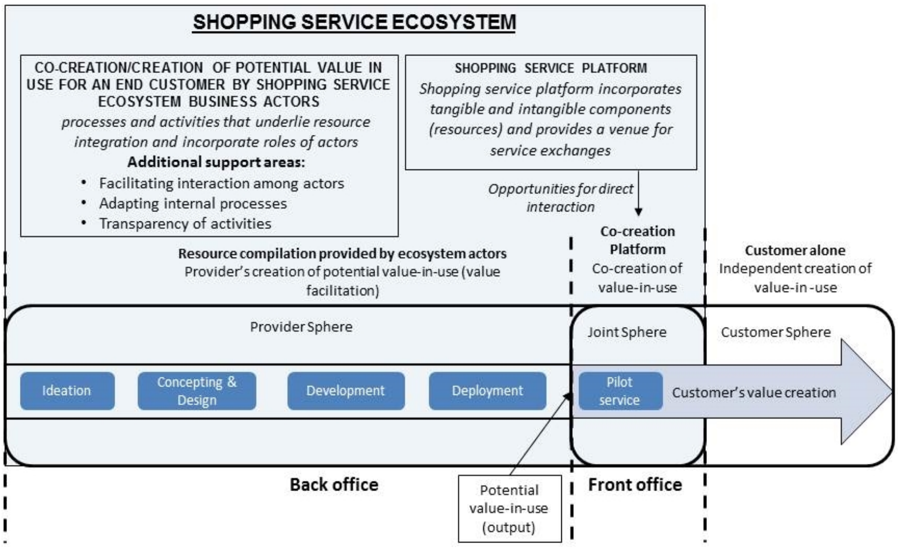

Fig. 4. Shopping service elements of the pilot case mapped with the extended value generation process framework. Source: Adaptation of Grönroos and Gummerus (2014, p. 218) and Figure 1 of Lusch and Nambisan (2015, p. 162). Copyright © 2015, Regents of the University of Minnesota. Reprinted by permission.

4.2 The new shopping service

Next sub-sections scrutinize service innovation process in the pilot case by using the extended value generation process framework.

Ideation. The first phase in creating a way towards the working pilot service was the *ideation*. The core of the selected idea was based on integrating (existing and new) online services and digital features with a physical grocery store. A need for a novel operational model regarding digital services had already been identified by the retail company management a couple of years earlier.

Key resources used in the early ideation phase were intangible in nature. The management of the retail company provided knowledge of the business and the division manager of the retail company brought knowledge of the processes in the store environment. The e-commerce development company provided information on the current e-commerce solutions and their earlier experiences with e-commerce services in public spaces. The research organization's role was to study new trends in retail and contribute the ideation based on the omnichannel retail approach (see e.g. Frazer and Stiehler, 2014; Rigby, 2011) and provide information about technological possibilities. In addition, the research organization coordinated the ideation activities by arranging and leading ideation workshop meetings. The above-mentioned group of ecosystem actors constitutes a key group in creating the foundational idea for a new digitally enabled shopping service.

Ideation continued later in the innovation process, focusing more on greater detail and was, in part, parallel to and interactive with the concepting and design phases. Overall, ideation and concepting activities were rather closely connected. First drafts of the concept description raised discussions and acted as a starting point for modifications and additional ideas that could be utilized in concepting and design. In practice, a general level idea was taken to the more concrete and detailed level by describing it through different techniques (e.g. sketches, service blueprints, customer journeys), which created a foundation for new ideas focusing more on details. A digital signage service company was also active in this more detailed ideation, primarily focusing on integrating digital resources seamlessly into a shopping service and providing ideas for digital visualization.

Store personnel and end customers of the store were not directly involved in the ideation activities. Information about the store processes was essentially provided by the division manager and upper management of the retail company. The division manager acted as a link between the "offerings" of different actors and the numerous different processes in a store (e.g. payment processes, customer service processes, product collection processes). The division manager provided valuable information on store processes together with the upper retail management in the ideation phase. However, the store manager was of the opinion that it might have been beneficial in the early phases of the innovation process to have greater collaboration with the store personnel, who directly interact with the end customers on a daily basis. The following comment of the store representative illustrates this point:

"It would have been good, if the whole thing had been thought more from a store level and from a different perspective, so that we [store personnel] would have a possibility to think how it should be implemented and what is the smartest way to do it." (Store manager)

In the ideation phase, communication was done through face-to-face/telco/video meetings and emails. However, there were no face-to-face meetings in which representatives from all organizations would have been in attendance at the same time. Resource integrations were transparent as actors' roles and goals were clear, and the number of active actors was relatively small in the ideation phase. The retail company was also willing to develop new internal processes (e.g. a supported product ordering in the store).

Concepting and design. To summarize, the aforementioned group of ecosystem actors brought their resources to the ideation phase, resulting in the idea that was viewed as feasible from business, process and technological aspects. In addition, more detailed ideation was interactively done with concepting activities. The roles of key actors were clear, and necessary additional ecosystem actors were identified for the innovation activities. During the *concepting and design* phase, the identified service idea was brought to a more concrete level. The main objective of this phase was to create a good starting point for different development activities (e.g. SW development, visual content creation) in the following phase. In this phase, activities continued in collaboration with several ecosystem actors.

A new service concept was described using different techniques. The research organization had a leading role in the early phase of concepting, and created descriptions on the service based on the information received from different actors. The main results of this phase was the concept description (including e.g. use cases, service blueprints, service processes descriptions and definitions of underlying design elements) for the digital shopping service. At this phase, background processes related to the shopping service (e.g. delivery, storage) were also discussed and defined at a detailed level and necessary additional resources were identified for the shopping service. Discussions were started and actively continued with "indirect" actors (e.g. Internet service provider, retail company's IT unit), whose resources were identified to be essential for the new shopping service.

When the shopping service concept was taken to a more concrete level, research activities to study customer behavior in the context of new shopping service were also planned at a more detailed level by the research organization. A general plan was to study customer behavior through interviews and a depth sensor, customer tracking system. Concrete descriptions with spatial dimensions of the store were required for tracking system related algorithm development. The pilot store sent information about the store (e.g. images) to support the research organization's research planning and depth sensor system configuration for the store.

Concepting and design were partially done parallel to the development phase. Based on the design sketches from the research organization and the ideas from the digital signage service provider, the retail company's sales and marketing team was able to design and generate more finalized versions of service user interface (UI) visualization templates including content for info screens. The web service development company used different versions of UI layouts during their software development activities. In general, key actors collaborated actively and interaction was done through multiple channels including face-to-face meetings and there were no visible challenges in collaboration between actors. However, as in the previous ideation phase, store personnel and end customers were not involved in the activities of this phase.

Development. A *development* phase mainly consisted of the implementation/integration activities and setting up of the pilot systems. Separate online stores were integrated through the common UI layer, which was developed based on a finalized UI design. Online and offline content for the service (e.g. ultra-resolution images) was generated for the service. The system was also tested in order to ensure that all parts of the system were working properly before setting up the pilot service in the store environment. Technical implementations and system integrations between different IT based system suppliers were highlighted, especially in this phase.

During the development phase, some challenges emerged in the resource integration related activities. The digital signage service provider did not have direct visibility for digital UI development done by the e-commerce development company and the web service development company. The initial idea of technical integration between customer PC UI and the digital signage system was abandoned, which was not communicated clearly enough for all ecosystem members. This situation was commented as follows by one of the technology providers:

"The challenge was that we did not know much about the e-commerce side…not even an exact schedule. We did not know what they have been thinking about and what they are developing." (Technology provider)

The main reasons for leaving out the technical integration during the pilot case were a relatively tight schedule and the lack of appropriate, available resources in the pilot project. However, if the digital signage service provider would have been more closely connected to the integration activities, it is possible that initial specifications for future enhancements regarding digital signage integration with other IT components could have been done.

The research organization developed algorithms for the analysis components of the customer behavior tracking system. Spatial dimensions of the store and location and physical dimensions of the service UI were needed for development of the analysis algorithms. In addition, questions for customer and store personnel interviews and usability tests to be conducted in a real store were planned at the same time.

The ultra-resolution image content was also integrated with the UI implementation of the customer PC. The e-commerce development company, the web service development company and the 3D visualization company collaborated closely in order to develop a coherent implementation. There were some challenges in generation of ultra-resolution pictures in order to provide a possibility for richer visualization. The initial goal was to provide product images that could be viewed from different angles by the end customer. However, at that time the actors did not have readiness to generate the required images, which resulted in the use of still images. There was clearly a lack of appropriate resources in the service ecosystem for generating visualization that could provide additional functionalities for the user of the service and initially planned richer visualization was not used in the shopping service. This can partly be seen as a challenge of adapting one's own processes in order to create a more supportive environment for value co-creation of potential value-in-use.

Deployment. After the development/integration of different service elements, it was time to set up the pilot service in the store environment including system installations. Key technology enablers of the service and depth sensor tracking system, as tangible components (resources) of the shopping service solution, were set up to the pilot store. Figure 5 illustrates tangible components of the physical interaction layer installed in the pilot store. As a part of the *deployment* phase, the sales personnel were also trained and external communication was done through media.

One of the key issues in the deployment phase was ensuring adequate bandwidth for data transfer regarding digital content of the customer PC. In particular, the ultra-resolution images required high data transfer capacity. As the pilot store was located in a rural area, high capacity network connections were not available at a reasonable price. 10/2 Mb network connection installed in the pilot store was adequate for ultra-resolution images. If richer visualizations would have been used as initially planned, it might have required a faster connection.

The new shopping service solution was generally well received by the store's sales personnel; however, the amount of new devices was questioned by the store personnel. For example an, additional payment terminal and a printer were installed in the store along with the new shopping service solution. In addition to the existing IT system for package management, they received a new separate package management IT system with the pilot shopping service. The additional devices and systems made the store environment more complex to manage and thus more challenging to maintain good customer service. The following two comments from interviewees illustrate the use of parallel systems in the store:

"If we think about systems…technical and that kind of systems…there are some overlapping things. If we are going to extend [the service], they should be solved in some way." (Retail chain presentative)

"A separate payment terminal feels a bit strange. If she/he [a customer] would pay the product directly to the cash register, it would also felt that the product is bought from the own local store." (Store manager)

The e-commerce development company's view was that it would have been beneficial if their personnel had been present in the store when the new customer PC was installed in the store. That way they could have directly seen if there were any previously unidentified challenges in a real usage context of the customer PC, and they could have reacted faster to these potential challenges. In addition, the sales and marketing personnel of the retail company highlighted that marketing and communication for end customers and the store personnel is extremely important regarding the new service. Furthermore, management highlighted the role of the store personnel in adoption of the new service as they are in direct contact with customers.

Pilot service. After the service related installations and deployment activities, the *pilot service* phase that also included testing the service in a real store was initiated. Data was collected from the sales personnel and the customers of the store. The primary goal of the user study was to examine customers' online and offline shopping behavior and to clarify their attitudes towards the digitally enabled shopping service. In addition, a usability test was conducted in the pilot store with the customers to collect digital UI related data for future development requirements of the shopping service solution. The digital shopping service concept was validated through data analysis.

In general, the new shopping service was not an immediate financial success, as customers did not use the service for shopping in the store to the expected extent. Usability related issues in the customer PC could partially explain the relatively low degree of usage of the shopping service. The main issues decreasing the value-in-use experience that emerged from the usability test were related to problems in the sensitivity of the touch screen, an unintuitive order process through the common UI layer and the lack of privacy when using the customer PC for product browsing. Depth sensor based data pointed out that the store's customers did not spend much time in front of the customer PC, which indicated for the most part, that the customer PC was not used for placing product orders. Instead, it was used for taking a quick glance at the service. The detailed results of the user study, including end customer and store personnel experiences, are presented in Ervasti et al. (2014).

In addition to challenges in a customer interface, there were also business related factors that affected the digital service innovation process and the outcome. As the service provider role can partially be considered to be shared between two ecosystem business actors (a retail company and an e-commerce development company), there should have been clearly defined rules on how financial benefits could be shared between the two actors. In the pilot case, this was not a major problem as it was experimental in nature. However, if this kind of service would be put into wider use, sharing of financial benefits should be carefully considered to ensure that they are adequately beneficial and motivating for all actors in a service provider’s role. Moreover, according to one of the interviewees, if benefits are clearly defined and communicated, they might also increase the commitment of the operational level employees to the newly deployed services.

In addition, the e-commerce development company approached the pilot case from the scalability viewpoint. An interviewed project director of the e-commerce development company viewed the scalability as a crucial aspect in new services. As the pilot case consisted of a single service point, scalability was not concrete challenge yet. However, if the service would be scaled up to cover a wide range of stores, scalability issues should be carefully considered. In particular, scalability raises new requirements for technical solutions so that instead of managing numerous separate and fragmented digital shopping services, there should be a possibility to manage digitally enabled services in a more centralized and effective way, e.g. through a common digital service platform.

Even though the new shopping service was not an immediate financial success, based on experiences from the pilot shopping service, revised versions of the service were subsequently adopted in two additional stores. Both of these stores are also located in rural areas with limited shopping opportunities. In the first additional pilot store, the deployed shopping service was nearly identical to that of the original pilot shopping service, including the same service processes in the store. The only clear difference was that there was not an info screen above the customer PC. According to store personnel, the use of online stores among customers was increased by the new shopping service. The second additional store utilized a “lighter” service solution, which was based on a tablet PC usage without a separate payment terminal or printer.

The findings from the two additional stores support earlier findings in the original pilot store setting and, for example, found that most of the product orders were done outside of the store. The finished service solution was installed in the stores and the personnel were trained to use the new service without involvement in the early phases of the innovation process. In general, the new digital shopping service was perceived to be an advantageous additional service in both stores, and employees were generally satisfied with the new service. In addition, according to the store personnel, the store customers perceived the shopping service as positive. Despite generally positive perceptions of the new service, there were also some service related challenges mainly related to the service process in the store and inadequate privacy.

Overall, the retail company considered the shopping service as a long-term strategic initiative and they were satisfied with the pilot shopping service. The goal for the future is to simplify the usage process of the service through tailored shopping service solutions, which are deployed in other stores.

4.3 Shopping service platform

As noted earlier, Lusch and Nambisan (2015) delineate a service platform as a modular structure consisting of tangible and intangible resources that facilitates interaction of actors and resources or resource bundles in the service ecosystem. They also suggest that "service platforms serve as a venue for service innovation because many interacting actors will seek or discover novel solutions to problems; that is, their resource exchanges may lead to innovative, scalable solutions" (Lusch and Nambisan, 2015, p. 166). Simply, the service platform can be seen as a venue that serves actors in their efforts to find relevant resources for resource integration by providing easy access and interfaces for service innovation. That reflects to resource density of the service ecosystem. As the pilot case service innovation is approached from the service platform perspective, a structure consisting of a wide range of different tangible and intangible components can be identified. Figure 5 illustrates the structure of the pilot service solution from the IT or digital component based viewpoint. In addition to a tangible dimension of these components, there is a broad scale of IT related intangible resources, for example, on design and development of the software (SW) components for the shopping service. As this study shows, digital components have a crucial role in shopping service. The upper part of Figure 5 represents the IT based service platform components in the service front end and the lower part incorporates back end components. Here, the front end refers to the service interface between the user in the role of end customer and store personnel and the shopping service. Basically, front end components, which were installed in the physical pilot store, constitute an IT based physical interaction layer, whereas back end components are part of the digital processing layer of the shopping service. From a technical viewpoint, these layers can be seen as constituting a digital infrastructure of the shopping service solution.

When exploring the pilot shopping service from the service platform perspective, it can be identified that it is structured from a wide range of tangible and intangible components, and it facilitates B-to-B and B-to-C (Business-to-Customer) interactions between different actors within the service ecosystem. As the shopping service is scrutinized in greater detail through the extended framework (see Figure 4), the physical interaction layer, as a part of the service platform, can be seen to have the potential to create a co-creation platform by enabling direct interaction and thus, can provide a venue for co-creation of value-in-use for the end customer and the service provider. In terms of direct interaction in the pilot case, store personnel also had an essential role in the shopping service. The shopping process related to the new service incorporated several phases where end customers and store employees interacted directly. Browsing service content via a customer touch screen PC with the help of store personnel and payment activities by cash register are examples of the shopping process phases in which direct interaction occurred between the sales person and the end customer. These activities naturally also included the use of a set of different tangible IT based resources of the service platform. In sum, the intangible resources of store personnel together with tangible IT based resources in the physical interaction layer served as a setting for direct interactions and enabled co-creation of value-in-use between the end customer and the service provider. For example, in the pilot case two tangible IT based components, the info screen and the touch screen customer PC, created a co-creation platform.

The service platform perspective also sheds light on value creation related activities between business actors as a part the shopping service ecosystem. There is a wide range of different intangible IT related components (e.g. design and engineering related resources) behind all tangible IT based resources illustrated in Figure 5. These resources and combinations of resources were preconditions for developing the new shopping service based on the initial idea about the service. In addition, these IT based components potentially provide the foundation for future innovations that can enhance the shopping service with new actors and their resources.

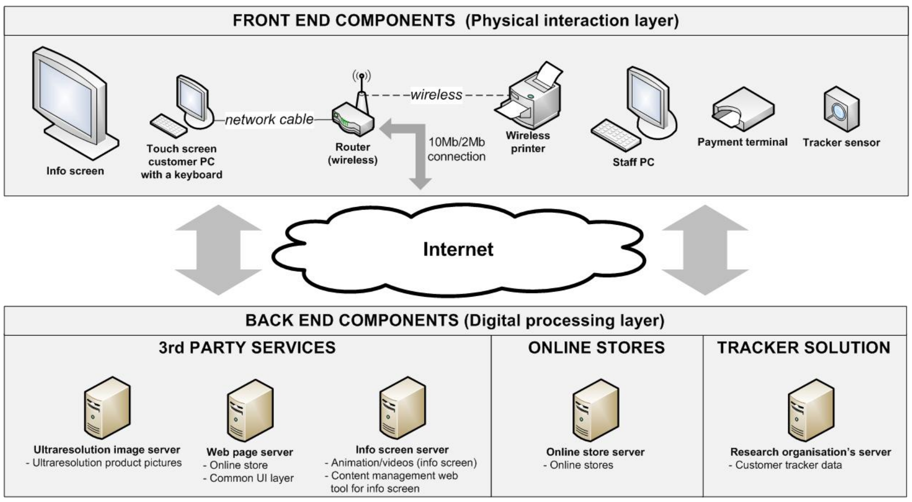

Fig. 5. IT based tangible digital components (resources) constituting a digital infrastructure of the shopping service solution.

In order to achieve a more holistic view to value creation in the pilot shopping service it is also necessary to explore other than IT based resources impacting resource integration activities behind the value creation. As a part of the shopping service platform, these non-IT resources can hinder or set the scene for service exchanges among actors and resources, and provide good ground for innovations. For example, expertise in retail business logic and operational level support activities in a store are related to intangible non-IT resources that are needed for the working pilot service. In addition, actors responsible for transportation of ordered products with respected resources are needed to deal with the delivery process of the ordered product. The physical store premises can be seen as a tangible non-IT resource in the service platform.

5 Discussion

According to our study multiple information technology, process and business related factors affect value creation during the digital service innovation process and the role of information technology is multifaceted, providing both new opportunities and challenges in the service innovation context. In addition, the extended framework for exploring the service innovation process provides a more structured way to examine the complex, networked, service innovation ecosystems. In order to answer the research questions, activities and processes behind resource integration between service innovation ecosystem actors were examined and applied to an extended value generation process framework in a real-life pilot case. The three research questions are answered in this section. The first research question was formulated as:

> *RQ1: What kinds of crucial factors can be identified in the innovation process of digitally enabled service from the value generation viewpoint?*

Based on the findings from the pilot case, three layers of service innovation were identified. These include information technology, process and business layers. All of these layers incorporated resource integration related factors that affect the value creation or co-creation. The information technology layer consists of elements related to IT resources in the shopping service innovation. The process layer incorporates back end and front end operations and processes related to the shopping service. In addition, a marketing and communication process was identified to be an important factor in the service innovation. The business layer covers business related factors that emerged during the shopping service innovation process. Table 4 presents identified crucial factors that were found to have an impact on the different layers of the service innovation. Based on the experiences from the pilot case, recommended actions that could tackle the potential challenges resulted from factors identified during the service innovation process were also formulated. Even though some of these factors did not have a major impact on the experimental pilot case, if this service were to be scaled up to include a greater number of stores and customers, the significance of the identified factors should be increased.

Examination of the innovation process phases from the viewpoint of the identified factors revealed that early phases of the service innovation process are critical. Furthermore, our findings stress the importance of the customer-centric approach highlighted in SL (Grönroos and Gummerus, 2014). Store personnel and end customers were not directly involved in the early phases of the innovation process. There was no direct interaction and consequently a co-creation platform did not emerge between the end customers and the shopping service provided by the service provider prior to the pilot service phase. Direct involvement of store personnel first occurred in the deployment phase of the innovation process. Involving end customers and store personnel already in the design phase of the service innovation process could have paved the way for more user-friendly and acceptable service. This could be achieved, for example, through the co-design approach that has roots in the participatory design (Sanders and Stappers, 2008). New innovative methods and dedicated resources are needed for collaboration, as there can be challenges in integrating collaboration activities with the effective and busy daily operation of a store, as mentioned in interviews.

All in all, based on the findings of the case study, communication and interaction related factors in the service ecosystem were the most impacting factors in the creation of challenges during the innovation process. In addition to a lack of direct interaction between the service provider and end users (i.e. end customers and store personnel) in the early phases (back office activities) of the service innovation process, there were also some deficiencies in the communication and interaction between business actors in different phases of the innovation process. This highlights the importance of participation coordination and creation of a supportive environment for the service innovation.

Reviewing the pilot case in terms of the three areas that impact support of value creation identified by Lusch and Nambisan (2015), it was noted that interaction facilitation among actors, internal process adaptation and transparency of activities were relevant and apparent in the pilot case. In all three areas, some challenges and needs for improvements were identified during the pilot innovation process.

Table 4. Summary of identified factors and recommended actions that should be taken into consideration during a service innovation process.

Layer	Identified factor	Recommended practical actions
IT	Parallel IT components in the service environment	Early back office phase exploration of existing IT systems (IT architecture) with service provider's IT experts and integration of service components with existing IT systems.
	Digital UI related challenges in the customer interface	Early involvement of end users from early back office phases to later front office phase in order to iteratively identify user requirements for the user interface.
	Inadequate transparency of IT development activities	Close collaboration and active communication between ecosystem actors through different channels.
	Network and device requirements for the service	Early phase exploration of context specific technical limitations with IT experts of the service provider organization.
	Fragmented point service solution related challenges in scalability and maintenance	Focus on designing and developing an interoperable system (e.g. a common digital service platform), which provides effective content management features and enables service enhancements in the future.
Process	Adaptation of a new service with the back end processes in a store (e.g. storage and delivery)	Exploration of existing back end processes and definition of requirements in a new service context. Close collaboration in process definition between different actors.
	Adaptation of a new service with front end processes (e.g. payment	Exploration of existing front end processes and definition of requirements in a new service context.

Layer	Identified factor	Recommended practical actions
	and customer support) in a store	Close collaboration in process definition between different actors including end users.
	Marketing and communication processes	Active communication with store personnel and potential customers in early phases of the innovation.
	Integration of service innovation process related activities with service provider's daily operational level activities	Allocation of dedicated operational level resources for service innovation related activities in order to facilitate effective collaboration during the innovation process.
Business	Clear understanding of the possible effects on business process requirements between actors in a new service context	Negotiations in the early phase of service innovation process about the business logic behind the service between different actors
	Service innovation processes and outcomes as a part of the service provider's business	Defining service innovation processes and outcome as a longer term initiative, which does not necessarily offer immediate financial benefits, but is more a part of strategic aims.

The second research question was formulated as:

RQ2: What is the role of information technology in the service innovation process?

IT resource focused elaboration of service innovation in the pilot case provides concrete real-life examples how operant and operand resources discussed in earlier research (Nambisan 2013; Akaka and Vargo, 2014; Lusch and Nambisan, 2015) emerge in a networked service innovation context. The analysis of the case study through resource classification enhances understanding about a role IT resources in the service innovation context.

Overall, tangible IT components and intangible IT resources (e.g. IT related design and development competence) were naturally pivotal to the service innovation process as a central target was to integrate retail processes and digital service elements. When exploring the service innovation process and the digital infrastructure from an information technology viewpoint through operand and operant resource classification, it can be perceived that both types of IT resources existed in the pilot case. As stated in earlier research, operand resources are more static, tangible and enabling in nature and operant resources are more dynamic, intangible and triggering in nature (Nambisan 2013; Akaka and Vargo, 2014; Lusch and Nambisan, 2015).

Upon closer examination of the IT based resources in the pilot case, the common UI layer can be seen to be an example of an enabler of innovation, emphasizing an operand nature of the resource. In general, the common UI layer supports the integrations of different resources at different levels. On a higher level, it enables integration of physical store environments with online stores. On a lower service level, the common UI layer creates opportunities for value creation by facilitating integrations between different online stores and equalizing the usage processes of online stores in the physical store environment.

A depth sensor system installed in a store and used for data collection can be seen as an example of an IT resource that is operant in nature and creates novel opportunities for resource integration and innovation. The depth sensor solution triggered initial ideas for further service innovations in the store environment. A common factor for these ideas was that depth sensors could be used for supporting interaction between the elements in the physical store environment and the digital service content. The basic idea was that the enhanced depth sensor system would "scan" the environment and changes in the environment would be reflected as digital content of the service and physical store elements (e.g. lights). In addition, the depth sensor system can be seen as an independent service platform that provides interfaces for resource integrations and innovations and thus improves the resource density of the service innovation. In general, the depth sensor system could provide a way to bridge physical and digital elements of the shopping service more tightly together. Intangible IT resources are crucial in terms of the depth sensor system as specialized knowledge and skills are needed in design and development activities of the novel depth sensor based systems for retail environments. These activities can include, for example, research and development of context specific SW algorithms and fusion methods for real-time analysis of shopper movement, action and mood.

Although the depth sensor system installed in a store can primarily be identified as operant resource, it might have a more operand nature in the future. It can be postulated that the depth sensor system will become an everyday solution with numerous connections between the system and the surrounding digital and physical retail environment. This extends current research related to a role of technology with a view, whereby a nature of certain resources is changing over time and a line between operand and operant is not necessarily distinct.

The third research question was formulated as:

> *RQ3: How suitable is the extended value generation process framework for exploring service innovation?*

In general, the extended value generation process framework provided a structured way to explore the service innovation process and related value creation activities from a service ecosystem perspective with a special focus on the end customer role. The service platform view gave an organizing structure for the resources behind value creation. It made it easier to form a holistic and clear understanding of the service infrastructure through IT based resource identification and description; areas of support for value-creation that were pointed out to be relevant when exploring the pilot case. Three areas of value co-creation provide a foundation for estimating how supportive the environment is for potential value-in-use. In summary, the extended framework provides a good tool for exploring the role of the end customer in the service innovation process from a value creation perspective. In addition, the extended framework gives tools for exploring B-to-B emphasized resource integrations and observes the potential challenges in the service innovation process in value creation related activities between business actors.

6 Conclusions

Examination of the pilot case through the extended value generation process framework elicited a wide range of factors that were different from each other in terms of their nature. Based on these factors, three main layers (information technology, process and business) were created to which the identified factors were assigned. The findings revealed that the three layers identified in this study, together with the extended value generation process framework, could provide a good reference point for examining resource integrations and value creation/co-creation in digitally enabled service innovation processes in the future. These layers are intertwined with each other, and elements in different layers can be seen as being connected to the innovation process phases and impacting on value creation and consequently the success of the service innovation outcome.

A role of IT was elaborated through the operand/operant classification in the pilot case. According to findings of our study different kinds of IT related resources can be found in different levels of service innovation impacting widely on value creation, and exploration of the service innovation process indicated that some IT elements are operand or operant in their nature. However, it can be seen that a difference between operant and operand is not always necessarily distinct. Further research is needed for achieving a deeper understanding on operand and operant resources and the role of IT in the service innovation context. Long-term case studies would provide a good starting point for further research focusing on different resource types in the service innovation context.

Earlier research emphasizing IT related aspects in value creation/co-creation could also provide useful insights for enhancing understanding of the role of IT in the service innovation. For example, Grover and Kohli (2012) have focused on the role of IT in inter-organizational settings and studied the value of IT in networked firm interactions. Lempinen and Rajala (2014) approach value creation from an organizational viewpoint by studying multi-actor value creation in IT service processes. Tuunanen et al. (2010) have created a framework for the development of digitized services focusing on value co-creation in consumer information systems and emphasizing system value propositions and customer value drivers. Even though many of these IT related studies discussing value creation are not directly focused on innovation research, they might provide fruitful ideas for positioning different aspects of information technology into the service innovation context in future research.

The findings from the pilot case highlight the importance of involving operational level employees and end users in the service innovation process already in early back office phases. This is important for achieving a successful front office phase. Especially employees working on the frontline close to the end customers have an integral role in the service innovation. Hasu et al. (2015) have also identified user-employee interaction as a crucial element in the context of service innovation and highlighted the interactive process between the service provider and the user, and its impact on the use value. Review of the findings indicate that communication and direct interaction are also important in B-to-B relationships in order to avoid setbacks in the innovation process, and create a supportive environment for resource integration and value creation in the service ecosystem. Overall it can be postulated, that although the technology has a central role in digitally enabled service innovations, a service innovation process should be considered to be primarily driven by people not technology. Based on the experiences from the pilot case, the goal should be to reach a human centric service innovation process, which emphasizes the role of people in the process of the service innovation.

In this study the principle of a direct interaction concept was applied, which is primarily discussed in the context of B-to-C interactions. Basically, the concept of direct interaction is based on the view that collaborative and dialogical joint processes evoke co-creation platforms for reciprocal co-creation of value (Grönroos and Gummerus, 2014). Further research in B-to-B context is suggested as it would contribute to service innovation research by focusing on interactions between business actors. This then could lead to a better understanding of the business actors' roles in the service innovation process. In addition, examining different value dimensions affecting value creation in a B-to-B context can provide an interesting direction for the future research. For example, in addition to traditional economic values, other customer value dimensions (e.g. emotional value) have recently been highlighted in B-to-B relationships (Leek and Christodoulides, 2012) and more specifically in the service innovation context (Coutelle-Brillet et al., 2014).

This study aims at enhancing understanding of the factors that are an integral part of service innovation, value creation and value co-creation. Naturally, more research on the topic is needed to achieve greater generalizability, as this study only included one case from the retail sector with a limited sample size. In the future research also other sectors, such as health, energy, banking and financial services, should be covered in order to enhance understanding on potential industry specific characteristics within service innovation. Despite some limitations of the study, we feel that results of this study provide a step toward a more holistic understanding of value creation in a service innovation context and provide interesting directions for future research.

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A Multi-Perspective Performance Approach for Complex Manufacturing Environments

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Abstract. Complexity in manufacturing systems appears under a variety of aspects, namely product, processes and operations and systems. Considering that the manufacturing environment is rapidly and constantly changing, with higher levels of customization and complexity, there is higher demand for flexibility and adaptability from companies. In this context, it seems essential to explore new approaches that can support decision-makers to take better decisions concerning the action plans that they need to launch to achieve the expected strategic and operational performance and alignment goals. Companies should become able to analyse their performance drivers, understand their meaning and the feedback loops that affect them. Therefore, decision makers can look into the future, and act even before these causes affect the transformation systems efficiency and effectiveness. This paper presents an approach oriented to multi-performance measurement in complex manufacturing environments. With this approach it is expected to overcome the gap between the operational and strategic layers of a manufacturing system, in order to reduce time when measuring performance and reacting to unexpected behaviours, as well as reduce errors when taking decisions. Moreover, it is expected to decrease the time necessary to calculate an indicator or to introduce a new one into performance management process, reducing the operational costs.

Keywords. Performance measurement, Complex manufacturing, Proactive behavior, KPI, Key performance indicator, Semantic interoperability, Ontology.

1 Introduction

1.1 Problem Framing

Due to the increasing globalisation process and the current economic situation, the power has shifted from the producer to the costumer, forcing companies to become more aware of the market needs (Wortmann, 1997; de Ron, 1998; Chen, 2008, Hedaa, 2005; Heinonen, 2010). Consequently, aiming to succeed in competitive environments, where all competitors have similar opportunities and surgical improvements can present important competitive advantages, the challenge is to develop solutions capable of supporting companies so that they can continuously improve their core processes in a proactive way, aligning, from the beginning, their behaviour with their goals (Almeida et al., 2012). Only this way can companies become more flexible, manage shorter product life cycles and thus, satisfy their customers by continuously adapting themselves to meet the needs and expectations of the market (Yusuf et al., 2004).

It is recognized that fulfilling the company's strategy implies the capacity of identifying and designing their key business processes, and namely establishing the main multi-perspective objectives for these processes as well as the related key performance indicators (KPIs) and metrics to assess if the objectives are being achieved (Feurer, 1995; Neely et al., 2001; Neely, 2007). It is important to highlight that, the multi-perspective concept in the performance management scope means the capability to assess not only the effectiveness at the end of the process, but also the efficiency and relevance along the entire process execution (Marques et al. 2011; Lauras et al. 2010).

Moreover, in order to become proactive instead of remaining reactive, companies must decrease their reaction time in order to find and solve process bottlenecks in the shortest amount of time possible and thus remain resilient and competitive (Sheffi 2005, Lohman, Fortuin et al. 2002). Hence, companies should explore new solutions that allow them to collect and manipulate data from the shop floor and, consequently, support them so that they can promote a holistic performance monitoring approach capable of measuring performance with high granularity, and identify the causes that are affecting or will have an impact on the system's performance (Gimbert, Bisbe, Mendoza 2010).

However, within complex manufacturing systems, meeting the challenges proposed is not a trivial task due to a number of factors. Firstly, complex systems are by definition environments whose behaviour arises from the interactions (feedbacks) between the different components of the system, and not from the complexity of the components themselves. Therefore, within a complex manufacturing system, there are immense ranges of different feedback processes that interact with each other, as well as different stakeholders with their specific objectives, which may result in paradoxical behaviours. Therefore, it is essential to understand each of the different feedback loops and manage the different strategic objectives in order to assess the dynamics of the global manufacturing systems (Sterman, 2000).

Another difficulty arises from the fact that technology infrastructures make it difficult to obtain the right information to calculate KPIs (Richtermeyer and Webb, 2010). In order to overcome this, companies have sophisticated enterprise systems or extensive legacy systems that can measure operational performance. However, the technology available may make it either too expensive or time-consuming to access the data required for effective performance measurement, and this is due to the complex and sophisticated nature of these systems.

This fact has led to another obstacle, which is the gap between the strategic and operational layers of an organisation. In fact, since decision-makers deeply depend on the performance data extracted from the shop floor and, since they normally are not able to get the data by themselves, it is possible to observe a critical misalignment between strategic and operational layers. In line with this, it is important to explore how to enhance the interoperability between the strategic and operational layers of a manufacturing system. Interoperability is a property of a system, whose interfaces are completely understood, to interact with other systems without any unexpected restricted access or implementation effort. Thus, interoperability should be seen as a key driver for an effective performance management, once it will facilitate the data flow between legacy systems and, consequently, its transformation into information.

Currently, this gap is a critical bottleneck for the reaction time of the company and consequently it prevents companies from acting in a more proactive way.

1.2 Research Objectives

This research aims at improving knowledge and insights on the performance measurement and management area, mainly as part of complex manufacturing environments. In line with this, one of our objectives is to formalize a performance measurement and management reference data model addressing the requirements of complex manufacturing environments and addressing the interoperability issues between the strategic and operational dimensions layers.

Moreover, contemporary decision-makers require a small number of key variables capable of representing a large quantity of information, in a synthesised way, in order to visualise the global system behaviour, identify the causes and take the important decisions in a proactive way. Therefore, it is essential to promote a platform capable of building and maintaining rich and powerful KPIs, in a collaborative way, making it possible not only to assess, but also to drill down a performance disturbance with high resolution. Similarly to the image resolution concept, in our context, high resolution means the ability to increase the level of detail of a manufacturing system's performance picture.

The questions leading this research are the following:

> *Q1 - How should the reference data model be for a proactive performance measurement approach?*

This research question aims at exploring a reference data model for performance measurement that allow companies not only to store performance data, and assessing it taking as reference the strategic goals of the company, but also to share this information with other legacy systems, and make it comprehensible both for machines and humans.

Hence, since issues related to strategic performance data interoperability are still an open subject, this research question aims at exploring an innovative solution based on a semantics approach capable not only of storing information in a structured and formalised way, but also of collecting, combining and inferring knowledge.

> *Q2 – How should the structure of a KPI be and what should be the level of detail of a performance measurement system?*

This research question intends to explore a new approach that supports decision-makers decreasing the number of indicators but maintaining the ability to assess the performance of their manufacturing systems from different perspectives, due to the capability of formalizing aggregated KPIs. With these metrics it should be possible to combine different types of leading factors, from different feedback loops, that can be easily analysed and understood in order to extract the most meaningful information from the performance data, and thus detect critical bottlenecks even before the respective core objectives are affected.

> *Q3 - How should the production system's raw data be fused and related in order to achieve a high-resolution performance measurement in complex manufacturing systems?*

The aim of this research question is to investigate how the architecture of a dynamic performance measurement system should be, capable of integrating not only the raw data existing in the different data sources, but also combining this with the production system's tactical data and information related with the organization strategy. The idea is to present a solution capable of providing performance measurements with high levels of granularity, that can be adjusted for the different stakeholders belonging to different hierarchical layers of the organisation.

The article is organised as follows: the next section presents the literature review and research development that supports this research work. Next, the reference data model for an innovative and integrated strategic performance management approach will be presented. This section is very important since at this stage it will be explored how strategic, tactical and operational data should be structured in order to become comprehensible and reusable by different tools and people. The fourth section will explain the developed platform architecture and its main technical details. Here, a special sub-section is presented dedicated to knowledge database querying and updating process. In order to explain the importance of this performance measurement and management approach in the industry, the implementation efforts performed within a real test case will be documented in the Experiments and Results section. We conclude with a discussion of results achieved, limitations and the conclusions.

2 Literature Review and Research Development

This section provides a review of the literature on performance information, as a key driver for innovation, improvements, and the impact of the performance management systems for the total quality management era. Moreover, since this is an issue that has been broadly explored as a result of the continuously necessity to align the performance management discipline with the organisation's strategy, during this section it will be detailed both the concepts and functionalities explored and defined in the literature that are suitable for proper strategic performance management systems.

2.1 Information Feedback as Key Driver

In 1958 Forrester, founder of the System Dynamics approach for complex and dynamic systems, stated that management was on the verge of a major breakthrough in understanding how industrial company success depends on the interaction between the flows of information, materials, money, manpower, and capital equipment (Forrester, 1958).

Within a complex manufacturing system this is neither a simple nor a straightforward task to be accomplished. In fact, due to the increased intricate relationships and interrelations among the system's elements, characteristic from complex manufacturing systems, along with the stochastic and non-linear nature of the system, characterized by unpredictability, make the system management more and more complex. In line with this, its management critically dependents on the decision makers capability to model the system behaviour, extract the correct information from the real system and, from the merging between model and data, to build his own mind-set about present and future behaviours (McCarthy, Rakotobe-Joel, & Frizelle, 2000). Moreover, this should be seen as a continuous activity, with which decision-makers are capable to maintain their knowledge on the manufacturing system, even when the system's behaviour continually changes.

It is becoming clear that, in order to setup the right measures and the correct analysing methods, aiming to study the manufacturing complexity, it is no longer feasible to simply rely only on the existing traditional approaches (Efthymiou, Pagoropoulos, Papakostas, Mourtzis, & Chryssolouris, 2012). In fact, as systems become more and more sophisticated, in terms of information processing, also the capability to link one form of feedback with future events will be enhanced. From this advantage, it is possible to accumulate experience about every kind of feedback. In fact, this type of information, if well structured and formalized, can be seen as the main pillars of a complex manufacturing model capable to support decision makers to foresee and anticipate decisions in a proactive way. In the scope of these approaches, the information continuously obtained through feedback loops from the system, represents a critical advantage, being seen as a key driver for the complexity analysis of a manufacturing system.

2.2 Strategic Objectives and Operational Performance Alignment

A Performance Measurement System (PMS) aims to support decision-makers by gathering, processing and analysing quantified information on performance and presenting it in a succinct format (Neely, Gregory, & Platts, 2005) (Garengo, Biazzo, & Bititci, 2005). By definition, all performance measurement systems consist of a number of individual performance measures, which can be categorized in different ways, ranging from Kaplan and Norton's (1992) balanced scorecard, Bititci's Integrated Performance Measurement Systems (Bitici et al., 1997) and Lynch's Performance Pyramid Systems (Neely et al., 2000).

Each of these PMS models can be categorized as vertical, balanced and horizontal (De Toni & Tonchia, 2001). Vertical architectures are defined as models that are strictly hierarchical (or strictly vertical), characterized by cost and non-cost performances on different levels of aggregation, until they ultimately become economic-financial. On the other hand, balanced architectures are models where several separate perspectives (financial, internal business processes, customers, learning/growth) are considered independently. Finally, horizontal architectures, also known as by process, are models strictly focused on the value chain and on the internal relationship of customer/supplier.

However, despite the differences between the PMS models previously described, the rationale behind a performance measurement system implementation is that performance measures used need to be aligned with the strategic vision of the organization, as they define the metric used to quantify the efficiency and/or effectiveness of an action. On the other hand, performance measurement may be seen as the standardized process of quantification by which it is expected to stimulate actions and influence people behaviour. Indeed, as pointed out by Mintzberg (1978), it is only through consistency of action that strategies are realized. Finally, a performance measurement system should be seen as the set of metrics used to quantify, in a multi-perspective way, the efficiency and effectiveness of performance of actions.

In line with this vision, Meyer (Meyer, 2002) proposed that performance measures could have seven different purposes. In terms of the time dimension, a measure could either look back (lagging indicator) or look forward (leading indicator). From the organisational perspective, a measure could be summed from the bottom to the top of the company to allow a clear visible linkage between the unit performance and the organisational performance. Likewise, it could cascade down from the centre to individual operating units. It could also be used for performance comparisons among horizontal operating units across the company to facilitate performance comparison. Finally, from the human perspective, a measure could be used for motivational and compensation needs. In the context of manufacturing systems, all seven purposes are required from the operational and control point of view.

In sum, a successful and effective performance measurement system implementation may lead to more than query and reporting capabilities. On the other hand, the purpose of performance management is not just managing but improving performance.

Based on these perspectives, it is important to highlight that when one is specifying a PMS to certain manufacturing system, the rationale behind the methodology applied must be composed by three main stages, as depicted in figure 1 (Neely et al., 2005):

- Analysis of the relationship between the performance measurement system and the environment within which it will operate;
- Specification of the set of performance measures and their relationships – the performance measurement system as an entity;
- And finally the specification of individual performance measures.

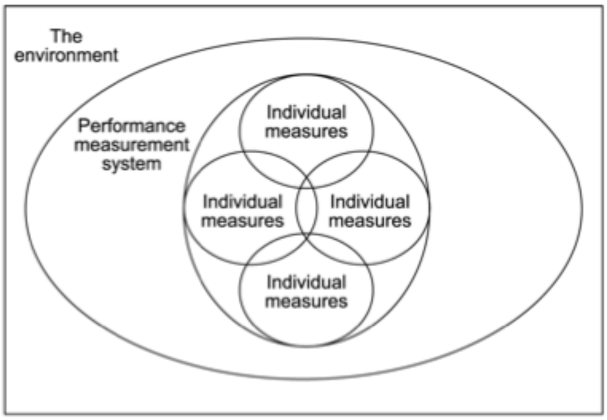

Fig. 1. A Framework for Performance Measurement System Design (Neely et al., 2005)

2.3 Multi-Perspective Performance Measurement

The most significant criticism of the traditional PMSs is the fact that they strictly focus on financial measures. However, as already explained, balanced models (also called multidimensional or multi perspective models) should be explored in order to enhance performance measurement systems with different perspectives of analysis, aiming to manage them in a coordinated way (Chenhall & Langfield-Smith, 2007; Garengo et al., 2005; Lauras, Marques, & Gourc, 2010).

Actually, the innovations in information technology and systems have made it easier to gather and elaborate large amounts of data at a lower cost. Since the dissemination of new managerial concepts and paradigms such as JIT, TQM and others, the role of short-term financial measures within current performance measurement systems is critically impaired. Indeed, the decreased reliance on direct labour, increased capital intensity and increased contribution made by intellectual capital and other intangible resources made it invalid to rely on traditional methods of matching revenue to costs (profit analysis) as a measure of performance. Therefore, it is proposed that a selection of non-financial indicators should be employed in contemporary performance measurement systems, based on the organization's strategy, as well as including measures of manufacturing, marketing and research and also growth and development (Parmenter, 2009).

Dossi and Patelli (2010) underline that against pure financial indicators, non-financial indicators are more forward-looking, better able to predict future performance and more adequate to measure intangible assets. Moreover, in this paper authors studied the importance of non-financial indicators in the creation of strategic alignment within international organisations. According to these authors, when performance measurement systems are empowered with non-financial indicators, these become powerful strategy tools, mainly because they contribute towards the achievement of all strategic objectives defined, through three mechanisms: (i) a better understanding of the linkages between various strategic priorities; (ii) more effective communication of the association between objectives and actions; and (iii) more efficient allocation of resources and tasks.

As previously explained, the 1980s were strongly marked for the rise in the popularity of the "quality gurus", resulting in a resurgence of interest in the measurement of operations performance, especially in terms of the three main clusters: efficiency, effectiveness and relevance. As depicted in the performance triptych (figure 2), the effectiveness assesses whether the output of the process meets the goals for which it was created. Efficiency expresses whether the resources have been used properly to attain the results. Lastly, relevance assess if the means suit the objectives (Marques, Gourc, & Lauras, 2011). This way, it is possible to define a series of indicator types to assess performance from different perspectives, aiming to achieve an optimum balance in the quality, dependability, speed, cost and flexibility dimensions. By taking a number of variables from each of the five dimensions and attributing a weight to each of them it is possible to create a new global and aggregated KPI capable of evaluating the production system according to the expected behaviour, trade-offs and priorities related with the decision-maker's strategy.

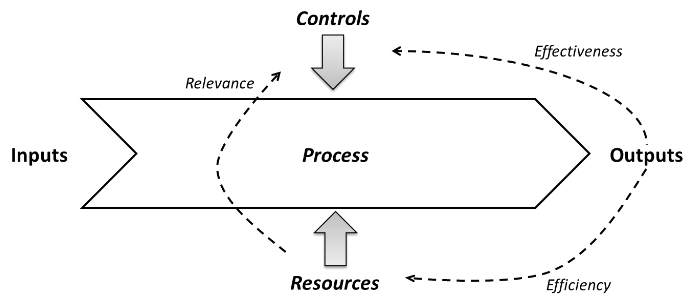

Fig. 2. Performance Triptych (Lauras et al., 2010)

2.4 Dynamic Adaptability

A performance measurement system should include systems for reviewing measures and objectives that make it possible both to adapt the PMS quickly to the changes in the internal and external contexts, and systematically to assess a company's strategy in order to support continuous improvement. Many scholars have studied and defined the dynamic approach (Bititci, Turner, & Begemann, 2000).

2.5 Process Oriented

Performance measurement systems have been explored for a long time. Initially, the most popular measurement system was the so-called DuPont scheme, introduced in 1919 by the DuPont company. However, during the following years the situation changed significantly. In fact, since then it has been observed a considerable evolution concerning performance management approaches, once these are becoming more process-oriented, involving not only decision makers but also process actors (Tupa, 2010).

In general, a process oriented performance measurement system can be seen as an information system that supports organizations so that they can visualize and continuously improve processes performance, controlling its execution by comparing process models with data collected (Kueng & Krahn, 1999).

Due to the fact that more and more process performance management tools and methodologies are considered as being essential for enterprises continuous improvement, new approaches have been developed such as: self-assessments, quality awards, benchmarking, activity-based costing, capability maturity model, balanced scorecard and workflow-based monitoring (Kueng & Krahn, 1999; Melchert & Winter, 2004).

2.6 Causal Relationship

Many scholars have written about the causal relationship between results and their determinants in performance measurement. Kaplan and Norton (1996) underline that identifying a causal relationship between performance indicators and objectives supports the strategy review and learning. Since performance measurement is supposed to support planning and control, a PMS should measure not only the results, but also their determinants and quantify the 'causal relationship' between results and determinants in order to help monitor past actions and the improvement process (Bititci et al., 2000; Neely et al., 2000).

Suwignjo et al. (2000) have analysed different techniques to analyse the relationship between results and determinants, such as cognitive maps, cause and effect diagrams, tree diagrams and analytic hierarchy processes. All these methods can introduce critical advantages when managing and controlling performance.

3 Multi-Perspective Performance Measurement Approach

3.1 Linking Performance Management to Strategy Vision

There is general consensus that, only linking strategic and operational performance, it is possible to improve the overall organizational performance. Despite the fact that strategy and operations are two different and sometimes not associated perspectives, when they are properly aligned the plant is more likely to achieve specific performance goals. Both strategic and operational levels of a manufacturing organization can be defined in terms of the customer-product-process-resource (CPPR) approach (Martinez-Olvera, 2010). In the scope of this model, the strategic perspective of a manufacturing enterprise corresponds to the customer level while the operational perspective corresponds to the process level.

However, in order to approximate both perspectives, a strategic performance management system, covering the entire system's life cycle, should be explored, aiming to link the plant's strategy for the market and operations floor. As inspiration, a strategy management cycle depicted in figure 3 and developed by Morita et al. (Morita, Ochiai, & Flynn, 2011) was used. This model proposes that, initially organizations must clearly define their business opportunity as well as establish their vision about the goals to be achieved. Following, the strategy should be designed, capable to support the organization to achieve the goals defined before. Defined the goals and the strategy, initiatives and operational processes must be designed, in order to materialize and implement the strategy defined. Finally, it is necessary to use a feedback closed-loop approach, capable to measure if the operational layer is satisfying the organizational vision. Indeed, for a performance measure to be considered as a Key Performance Indicator (KPI), it has to be linked to one or more of the organizational critical success factors, more than one balanced scorecard perspective and more than one organization's strategic objectives.

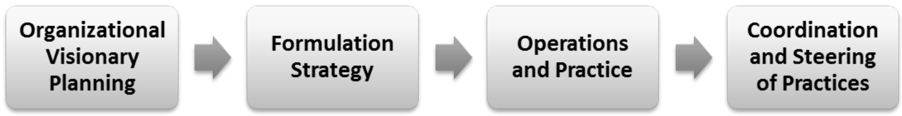

Fig. 3. Strategic Performance Management Cycle

Currently, one of the important paradigms explored within the industrial management scope is strictly related with the idea that a factory is simply a very complex type of product (Jovane, Westkämper, & Williams, 2009), called "Factory as a Product". This innovative way of seeing a factory defines that a factory should be compared with a very complex product, with its own structured and complex life cycle. This means that, similarly to the product development process, factories have to be permanently adapted for changing products, markets and technologies in order to fulfil economic, social and ecologic requirements (Constantinescu & Westkämper, 2010). However, this new kind of product itself is responsible for the manufacturing of other products with a shorter lifetime under the constraint of an ongoing operational, tactical and strategically change and the required adaption to it. Within such an approach is referred as Unified and Sustainable Life Cycles Management and envisions an orchestration or harmonization of the specific life phases of products, production systems and corresponding design methodologies.

Consequently, aiming to explore this paradigm, as well as guarantee the alignment between product and factory life cycles, a functional modelling approach from product design was adapted (Almeida et al., 2012; Jufer et al., 2012; Politze et al., 2010) aiming to model the strategic goals of a factory, called Function Oriented Product Descriptions (FOPD). The FOPD constitutes an approach that combines a requirements model and a functional model. In general, the modelling includes three main steps:

1. Firstly, a functional requirement has to be defined and formulated. By strictly following the rule that it has to be derived from higher goals, a specific stakeholder vision and/or the mission of the company, the rationale behind each functional requirement is captured and may be used later to justify each of the company goals.
2. In a second step, one or several selected KPI that are seen as suitable to assess the intention that stands behind a functional requirement are mapped to them.
3. Finally, a target or reference value has to be provided by the management. This value indicates the intended grade of target achievement and assures its measurability. Moreover, dynamic adjustments may be scheduled which have a direct impact on the target values and allows a dynamic adaptation of the factory goals.

In line with the FOPD paradigm, strategic plans should involve the vision, the mission, the guiding principles and the goals for the business. Therefore, when specifying a manufacturing system, at the strategic level, it is important to define not only the functional requirements, defining the specific behaviours or functions, but also the KPIs that will evaluate these objectives. On the other hand, a tactical plan focuses on methods and processes that support organizations to achieve their strategic goals. Then, at the tactical layer, it is necessary to define the non-functional requirements that specify the criteria that can be used to judge the operation of a system. Finally, the technical layer establishes the connection between the tactical and operational layer in order to define the most granular and detailed production planning.

3.2 Real-Time Performance Measurement and Assessment

As stated by several authors, traditional performance measurement and management approaches are considered unsuccessful, since they mainly use performance data that are extracted after a long feedback period (Figure 4), and only after this time frame – Tf – can the data be analysed in order to promote improvement actions for the next period (Braz, Scavarda, & Martins, 2011; Lohman, Fortuin, & Wouters, 2002). This means that, according to the current approaches, the reaction time is conditioned and increased by feedback and improvement periods. Because of this reason, this approach is no longer suitable. In fact, since the reaction time available is decreasing significantly, if organizations make decisions based on facts that happened on a previous Tf, they are not only losing opportunities during the time in which the problem really occurs until it is identified and solved, but they are also propagating the problem during a Tf, which can definitely compromise the achievement of strategic goals because the time available to achieve the operational excellence is limited (Chen, 2008).

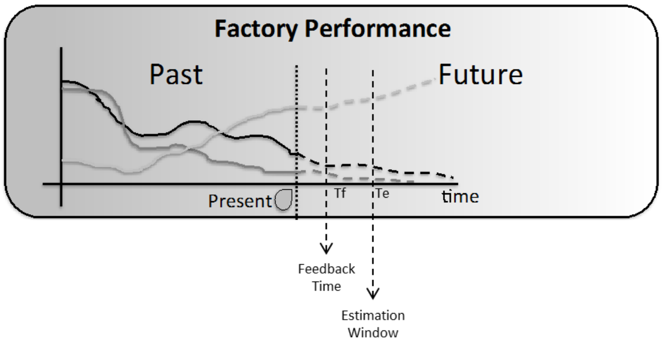

Fig. 4. Performance Management - Time Analysis

Since it is not possible to manage a system if its performance cannot be measured continuously during its entire life cycle, it is necessary to explore a flexible and agile performance measurement and management systems capable to overcome the gaps identified before (Bititci et al., 2000; Braz et al., 2011). Designing a performance measurement model involves a series of important decisions and considerations that should be taken into account since the design stage of the performance measurement system architecture. This means that issues such as the meaning of the measurement, the domain of the calculation and its multi-scale structure, the frequency of the measurement and the source of the data should be considered (Braz et al., 2011).

Based on this premise, Figure 5 presents the main steps of our methodology for a successful performance measurement system implementation, from production network to its locations and sites. Initially, the domain of calculation should be well defined. This means that the boundaries of the system to be managed should be well defined as well as the components of the system that will be controlled and measured individually. Defined the domain of calculation, following, the static assumptions characteristics from this domain should be enumerated and specified. For instance, the effective capacity can be seen as an example of a static assumption. By definition, "effective capacity" is the maximum amount of work that an organization is capable of completing in a given period due to constraints such as quality problems, delays, material handling, etc.

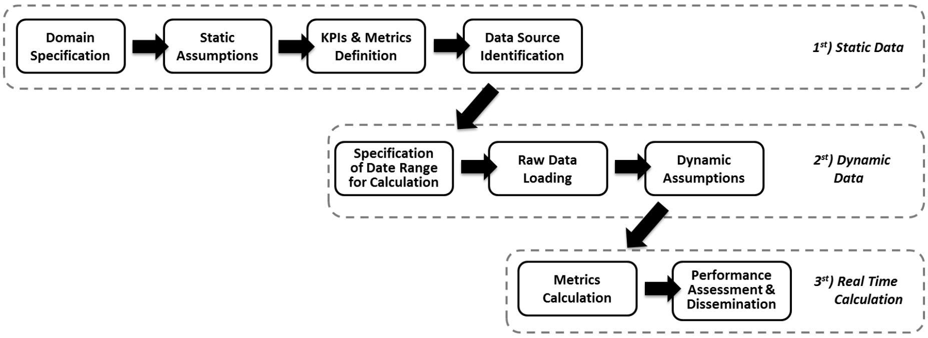

Fig. 5. Performance Measurement System Requirements

The metrics specification is maybe one of the most important steps of this methodology, developed within this proactive performance management concept. Actually, this stage can be performed following two main perspectives: a process-driven or goal-driven perspective. Concerning the process-driven perspective, the system performance manager should start by identifying the core-processes of the system under analysis and, based on the purpose for which each process was designed, select the correct indicators that will evaluate their efficiency, effectiveness and relevance. Contrarily, in the case that a goal-driven strategy is defined, then it is critical to initially define the stakeholders of the system as well as their visions and objectives. Following, the KPIs that will make it possible to evaluate if these objectives are being achieved or not, should be designed. In fact, this is a critical step since it is expected to combine the information desired at the strategic level with the raw data available at the operational level. Consequently, for this proactive performance management concept it is proposed a hierarchical metric definition that support system's performance managers to continuously mould the available raw data scattered throughout the different legacy systems, aiming to respond to the requirements imposed at the strategic level.

At this stage it is already available not only all static and dynamic data necessary to the KPIs calculation but also the mathematical formula, defining how these indicators should be calculated. However, this information is not enough since it will not make it possible to calculate each indicator with the desired level of granularity. Consequently, and taken into account that almost all manufacturing systems produce more than one family of products, that can share or not resources and information, when calculating these indicators it is essential to introduce these variables within the calculation formula in order to calculate each indicator with the higher level of detail as possible. Only this way it is possible to calculate a KPI for each manufacturing system section/department and products perspectives.

Finally, having calculated each of the KPIs defined for the performance measurement system in question, it is essential to compare the obtained values with the target values as well as disseminate this information throughout the entire manufacturing system. From this statement it is important to underline that both dissemination and targeting processes should be competent and efficient. For instance, when broadcasting the performance information it is important to guarantee that an appealing interface is used in order to provide decision makers with a clear, simple and rich visual experience. On the other hand, it is important to respect the fact that each actor involved in the manufacturing system should have access to a personal dashboard where only the KPIs that will support him improving their competences should be available. Actually, this is an important innovation compared with the approaches normally used within current industrial organizations. Indeed, nowadays the performance information is customized according to the necessities and requirements of a limited number of actors, being after that imposed to the entire organization. However, due to the hierarchical construction of the KPIs and its metrics it becomes possible to easily mould the information available aiming to answer to necessities of all the actors involved in the production system.

4 Framework Proposal

If it is true that, in one hand, a PMS should be able to increase the level of accuracy and reliability of the performance information calculated, focusing at the same time on the level of granularity of each key indicator measure, on the other hand the performance measurement component should be flexible enough to gather, whenever necessary, information from multi-data sources, aiming to fuse raw data generated by different functional modules.

Nevertheless, the process related with the combination of raw data should not be performed in an ad-hoc way. This means that both the rules for raw data handling and the KPIs metrics definition should be extended from the strategic objectives defined at the management levels of an industrial organization. Since this research project is not focused on the strategy definition, the performance management framework should be scalable and holistic enough to allow 3rd party modules, strictly related with organization's strategy formalization (e.g. strategy maps, balance scorecard (BSC), and others), to feed this framework with the functional requirements defined as well as the KPIs, metrics and targets that should be assessed.

Due to the levels of complexity characteristic from current manufacturing systems, reading and analysing the performance information is neither a straightforward nor a trivial issue, mainly due to the high number of factors that can hinder the normal behaviour of the system, as well as the trade-offs that can be observed from the synergies between these variables. Therefore, after guaranteeing that performance information is calculated with high levels of reliability and detail possible, it becomes critical to explore new approaches that support decision makers to formulate their mental models about the system, to validate with the different stakeholders, to reuse knowledge for continuous improvement purposes and finally to broadcast this conception about the system behaviour through the organization, aiming to achieve higher effectiveness and homogeneity on the decision making process.

Aiming to fulfil the requirements and gaps previously identified, in figure 6 it is depicted an overview of the multi-perspective performance management approach developed within the scope of this research project, as well as the data flows between the different components. Indeed, one of the key drivers responsible for the flexibility requirements described before is the data model, responsible for the data interoperability not only between the different components of this framework but also with other modules, external to the proactive performance management framework, which can also be interested in absorbing the knowledge developed related with the manufacturing system performance behaviour (Chituc, Azevedo, & Toscano, 2009).

Moreover, it is important to underline that a flexible performance measurement and management system should be capable to read information not only from databases available in the manufacturing system, but also from other functional models applied by decision makers during their planning activities. For instance, if a performance management system is capable to collect the information related with a simulation performed in a specific 3D simulation tool, then it becomes possible to compare if the real system is performing as planned within the virtual world. In the same line, if a performance management system is capable to collect data concerning the layout of a plant, then this information can be used to build a more dynamic and rich domain of calculation, continuously aligned with the reality of the shop floor.

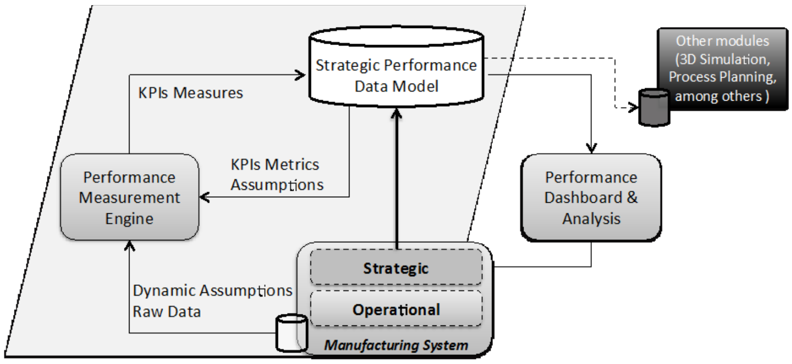

Fig. 6. Proactive Performance Measurement Architecture

Aiming to implement this vision, as showed in the previous figure, the strategic performance data model is the heart of this framework. This is the element responsible by defining which information should be generated as well as the relational model that rule data and knowledge management. Moreover, this reference model defines how data should be stored in order to guarantee that modules, seeking for performance information and with the correct permissions, can gather or even change information (read/write).

Similarly to the data model previously described, the Performance Measurement Engine (PME) is a functional module, developed under the umbrella of a European project called Virtual Factory Framework (VFF), strictly focused on manufacturing system's performance measurement and management. As it is possible to see in Figure 6 the PME mainly relates three types of information:

i. Firstly, due to the continuous necessity to streamline the strategic performance assessment, the PME updates its internal information concerning new/updated KPIs specification, as well as the internal and external static variables that characterize the system in analysis. This kind of information is normally generated at the highest levels of the hierarchical structure of an industrial organization, where do not exist any kind of knowledge or even consciousness about the raw data available at the legacy systems of the organization capable to provide with the raw data necessary to the KPI calculation. Thus, KPIs are usually formulated without specific knowledge about the raw data available to feed them.

ii. Consequently, the second PME perspective is strictly related with the necessity to establish tunnels of communication, from where it will be collected, fused and filtered the correct raw data and dynamic assumptions from the shop floor. This is one of the main functionalities of the overall framework responsible by agile and enhance the linkage between the strategic and operational layers of an organization since it allows decision makers to easily define KPIs metrics, choose the suitable raw data available for its calculation as well as identify the databases where this information is available.

iii. The third most important perspective of this engine is mainly related with the KPIs calculation and information broadcast. In fact, collected all the information related with KPIs metrics, static and dynamics assumptions, domain of calculation as well as raw data location, then it is feasible to calculate with high level of reliability each performance indicator defined at the strategic level. Finally, all the performance information generated through this functional module should be stored at the strategic performance reference model, aiming to make this data available to internal but external modules seeking for this type of information.

Following, it will be provided more detailed information concerning the strategic performance data model and the PME.

4.1 Strategic Performance Data Model

The SPM ontology was developed as part of a European research project (Sacco, 2010) which focused on the need to streamline the introduction of new products within the production system, decreasing the ramp-up, increasing the production system's capability and efficiency. In order to achieve these goals, the "Factory as a Product" paradigm was explored aiming at supporting the implementation of simultaneous/concurrent engineering between products, processes and resources life cycles.

The heart of this European project was the Virtual Factory Data Model (VFDM), mainly responsible by guaranteeing the data interoperability between different functional modules used during the different stages of a factory life cycle. In other words, the development of the VFDM is critical because it not only defines how the data should be exchanged between the different modules involved in the planning and operational stages of a factory, but also clarifies how data should be generated and used.

The VFDM has been decomposed into a series of macro areas, creating a hierarchical structure of ontologies that decompose the problem and reduces its complexity, keeping a holistic approach. As final result, the VFDM is available as a network of ontologies, implemented as OWL files, where each ontology can relate its data with attributes available on others ontologies of the network. This way, the VFDM defines only the so-called Metadata (i.e. the classes, properties and restrictions), whereas the actual instances (i.e. the individuals) will be stored in a Data Repository. However, not all ontologies of the VFDM have been developed from scratch. Therefore, in order to assure reliability and confidence on the reference data model developed, it was taken into account different technical standards available in the state-of-the-art of different domains. For instance, it was taken into consideration the Industry Foundation Classes, STEP-NC (International Organization for Standardization), and ISA-95 (International Society of Automation) (Scholten, 2007).

Nevertheless, in the scope of this research work, the emphasis will be both the strategy and performance management areas of the VFDM. As previously mentioned during the enhanced strategic performance management concept, to make maximum use of the information extracted from the performance measurement system adopted by an industrial company, it is essential to bring together both the strategic and operational perspectives of an organisation's structure, concerning the performance management strategy to be implemented. In fact, while at the strategic layer people define what to measure and the targets to be achieved, at the operational side people are focused on calculating the metrics defined as well as locating the data sources where the suitable information for a reliable KPI calculation is. Therefore, it is critical to define the data model that bridges the gap between the strategic and operational layers of an industrial organization, by formalizing the performance management concept at both the hierarchical layers.

In line with this, a holistic and generalized data model was developed using the semantic concept as pillar. In Figure 7 it is depicted the Ontograf of the SPM ontology. This is a technology developed by the Protégé consortium that allows to, interactively, explore and navigate throughout the relationships of a specific OWL ontology.

It is important to highlight that the SPM ontology here presented results from the merged between the VffStrategy and VffPerformanceManagement ontologies. Thus, when clearly defined the boundaries between these two universes, three concepts gain a higher dimension: measurements, metrics and performance indicators. Despite the similarity between these three concepts, it is important to clarify the main differences between them. A measurement is a number that is quantified at a certain point in time. However, in the performance measurement sphere this value only represents an add-value if it contains a certain meaning associated, which makes it a metric. On the other hand, in the performance management scope a metric only becomes useful if it has a target associated which makes it possible to evaluate these metrics.

In sum, while a KPI is responsible by representing a certain non-functional requirement by a measurable concept, capable to evaluate quantitatively a certain object in a specific scope, a metric is a characteristic of a KPI responsible by formulating it into a mathematical way, with a well-defined objective function.

In line with this, the strategy part of the SPM ontology was developed aiming at modelling the data related to the company strategy, envisioning the alignment between the manufacturing system performance and the market needs. In other words, with this ontology it is expected that the goals envisioned by the stakeholders of the system can be formalised; the KPIs can be mapped with the requirements defined for the manufacturing system and; the information related to the target objectives can be modelled (Dekkers, 2003).

But, how it is possible to map this vision using the semantics and ontologies as pillars? The main premise of the strategy ontology is based on the idea that a manufacturing system (since a supply chain until a micro-factory) is a very complex system, composed by a series of entities (since industrial partners until factory departments, respectively). Each of these entities has a specific reality that can be modelled with the VffScenarioDetail class (Figure 7). Moreover, each of these entities should have a well-defined strategy. Therefore, each manufacturing entity should define its own strategy map, aligned with the entire vision of the manufacturing system.

Consequently, each strategic map is composed by a series of functional requirements. By strictly following the rule that each functional requirement has to be derived from a specific stakeholder's goals, which, consequently, should be aligned with the organization vision, the rationale behind each functional requirement should be captured in order to justify and compose each of the company's goals. Therefore, each of the functional requirements, which should be modelled by the FunctionalRequirement class, may be linked with a criteria (Non-FunctionalRequirement class) and a certain solution (SolutionProperty class)(see Figure 7).

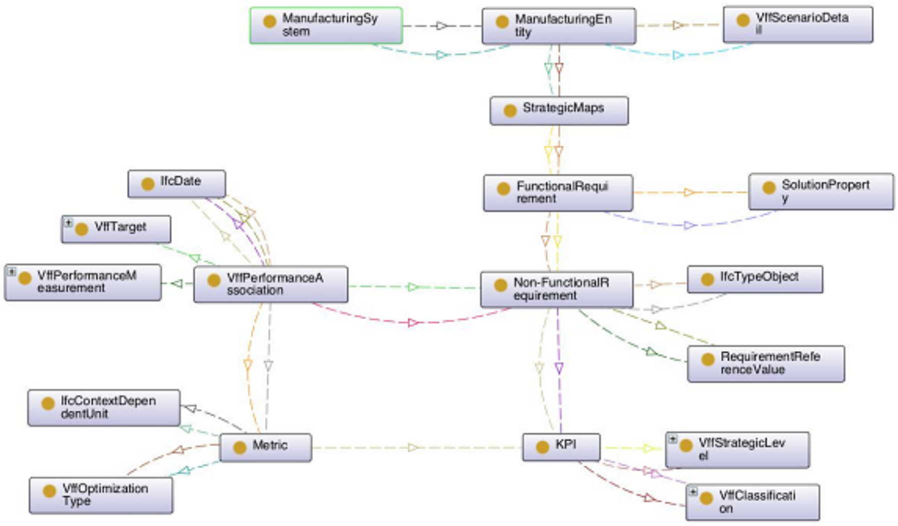

Fig. 7. Strategic Performance Management Ontograf

In a second layer of the ontology, one or several selected KPI/PI, which are seen as suitable to assess the intention that stands behind a functional requirement, should be mapped. The KPI class focuses on storing the main characteristics and specifications of an indicator in order to provide meaning to the measurements obtained. Each KPI must be catalogued according to its classification and strategic level. In the strategic level, the controller must specify if the KPI/PI under analysis is used to evaluate a planning or operational process. In the classification level, it is specified in which terms a KPI/PI evaluates a specific object in the production system: Cost, Quality, Time, Flexibility or Reliability.

On the other hand, the Performance Management part of the SPM ontology aims at modelling the data related to the behaviour of the production system, assessing its performance against the expected targets values. However, the performance measurement should be explored as a dynamic process that alters according to the specific environment that characterises the manufacturing system under analysis. In line with this, the VffPerformanceAssociation class was designed to link a performance target with the performance measurement, calculated with a specific metric, designed to mathematically formulate a certain KPI, for a certain time window.

4.2 Performance Measurement Engine

By definition, a suitable performance measurement and management (PMM) system aims to support decision-makers by gathering, processing and analysing quantified information on performance and presenting it in a succinct format. Strategic performance measurement systems (SPMSs) are a subset of PMM systems. They support the production system stakeholders through a series of distinctive features, such as: integrating long-term strategies and operational goals, providing performance measurements in the area of multiple perspectives, providing a sequence of goals/metrics/targets/action plans for each perspective and presenting explicit causal relationships between goals and/or between performance measurements (Gimbert, Bisbe, Mendoza, 2010).

When designing a SPMs for complex manufacturing systems, there are issues that need to be taken into consideration as this involves gathering multi-disciplinary themes. For instance, it is expectable to find a number of difficulties related to data collection from multi data sources (Jain, Triantis, Liu, 2011). Consequently, during this stage it is important to solve the conflicts that can occur between different performance measurement sources, guaranteeing an appropriate balance between internal and external measures, as well as cataloguing and providing meaning to the data for further use. However, as it is possible to see in Figure 8, issues related with data handling are just the bottom of the pyramid of requirements for a suitable SPMS implementation within complex manufacturing environments. In line with this, since this type of systems presents dynamical behaviours, it is necessary to guarantee the flexible link between tactical manufacturing planning and the different strategy perspectives, which should be formalized by KPI’s metrics and respective measurements.

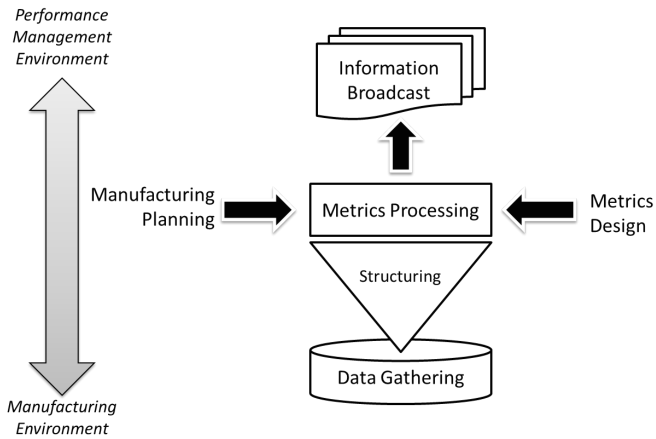

Fig. 8. Requirements Pyramid for Complex Manufacturing Systems

The PME was designed and developed aiming to overcome and simplify all the small details that characterises a dedicated performance measurement solution. Indeed, the main objective was to create a software solution easy to install, setup and maintain but, capable to provide powerful information to stakeholders, shareholders and decision makers. Thus, the biggest contribution of this research work is based on the set of concepts, and respective technological implementations, developed to streamline and boost the performance measurement and management strategy to be implemented in a specific organization. In order to show the main differences between the PME and the solutions currently available into the market, the core features enumerated before for performance management software's will be used as plumb line.

Data Collection: Within complex manufacturing systems, it can be a challenge when the technology infrastructure makes it difficult to obtain or extract the right information to calculate the suitable KPIs in a reliable way. In order to overcome this, there are sophisticated enterprise systems or extensive legacy systems that can help or hinder progress with improving strategic performance measurement. However, the technology in place may make it either too expensive or too time-consuming to access the pieces of data needed for effective performance measurement due to the complex and sophisticated nature of this systems.

Therefore, the PME was developed with the aim of supporting users, during the process of data gathering from the different data sources available in the factory facility. With this in mind, the gathering of data for the calculations was defined in a way that it is possible to combine data from multiple sources, and establish relations between them, so that, more relevant information can be extracted. With this possibility the manufacturing system manager can have more meaningful information without having the hard work of dealing with the data, everything is made through the PME and it is only necessary to define rules and relations using a simple graphical user interface.

Key Performance Indicators: it is critical that an organization defines a number of KPIs capable of measuring its core processes or activities. However, in order to better interpret this important information, sometimes it is necessary to go deeper and study the reason of bad performances behaviours. In line with this, the PME follows an innovative and distinctive approach that defines a KPI according to a hierarchical tree, which enables companies to perform a series of performance management actions and retrieve more information capable to support decision makers.

Moreover, the PME allows production system managers to adapt the performance measurement approach to complex manufacturing environments. In order to simplify the KPIs definition, the PME solution allows the manufacturing system manager to build and store the different KPIs using Drag & Drop functionality. However, it is also possible to define new KPIs to be calculated using other functional modules. To do that, the PME solution has a synchronizing functionality that read formulas stored by other modules in specific data repositories and then presents it to the user so that he can define the data sources for the new KPI. Therefore it is possible to integrate information generated by different functional modules aiming to bridge the gap between the strategic, tactical and operational layers of a manufacturing company.

Generating Information: According to the KPI's metric, the PME solution allows the manufacturing system manager to visualize and analyse the current status of a specific KPI in an interactive way. Using a hierarchical KPI metric definition, where a KPI can be seen as a combination of different indicators, decision makers cannot only assess the KPI value but also all the variables used for its calculation, due to the continuous capability of the measurement engine to power different charts and tables with real performance values. This information can be used not only to better understand the system behaviour, but also to detect bottlenecks.

However, the hierarchical KPI metric definition is not the only concept developed to enhance the quality of performance information generated. If it is true that start analysing a KPI as a function and not as a variable allow decision makers to have a wider view of the system, it is also true that there should be, at the same time, a greater concern in providing a more detailed information about the performance of a complex manufacturing system.

This perception about current necessities of stakeholders of large and complex manufacturing systems led us to another concept called High-Resolution (HR). The HR concept defines that, similarly to the resolution concept of a picture, in the scope of this research, high resolution means the ability to increase the level of detail of a manufacturing system's performance picture. The idea is to present a solution capable of providing performance measurements with high levels of granularity that can be adjusted for the different stakeholders belonging to different hierarchical layers of the organisation. In the application case section an example of both hierarchical KPI metric definition and High-Resolution concepts and its advantage for industrial companies will be presented.

Response to Data Analysis: Following a defined schedule, the PME solution is able to generate performance reports that can be broadcasted through the factory using email services features. The Key Performance Indicators values can be easily consulted, inside and outside the factory, through a web-based application. Permissions were also implemented. Depending on the user logged in, different actions can be performed. Thus, some users might have all the permissions to create and calculate KPIs, while others can only see the calculation results.

Since the PME allows the user to analyse the KPI in a more detailed way, with this performance management system becomes possible to anticipate and prevent low performance behaviours (according the PME approach, the different components of the KPI calculation can be used as leading factors). Therefore, with the PME solution it becomes very simple and quickly to perform "what-if" scenarios activities, understand the reason of low performance rates and predict future performances according to leading factors.

Hierarchical KPI Definition. Aiming to guarantee that operational, tactical and strategic information could be fused within a single but rich aggregated performance indicator, aiming to related different perspectives, a hierarchical KPI definition was explored. Three levels of indicators have been defined for the performance indicator structure: Raw Data, Performance Indicators (KPI0) and Key Performance Indicators (KPI1+).

The Raw Data level gathers the information available on the production system, providing meaning to the measurements obtained from the different sensors available. Therefore, the measurements available in external sources, such as, xls, xlm, csv documents and database tables can be located and modelled to be reused every time this kind of information is required in order to calculate indicators affected by them. Examples of these kinds of data are the data source locations of the following information: order logs and process event logs.

The Performance Indicator level can be seen as a combination of Raw Data to build linear and simple indicators. Indeed, added value information is not expected from these metrics but they do represent critical data that allow key performance indicators to be calculated and analysed swiftly. Examples of this kind of indicators are: elapsed time for the completion of each order type (CET), the number of orders received (NOR), the working duration of each activity in the process (TPA) and the percentage of an order type (POT).

In order to obtain significant and meaningful indicators capable of retrieving a clear and reliable picture of the system's behaviour, it is important to define Key Performance Indicators (KPI). These indicators can be seen as a combination of performance indicators, from different perspectives, and manufacturing system assumptions. In fact, the manufacturing system assumptions are another important variable used by KPIs that should represent the limitations and characteristics of the system.

Architecture. The PME was developed in order to materialise the concept explored by the reference data model as well as provide the right answers to the requirements mentioned before for SPMS. Next, the main layers that compose the PME are presented, from the data extraction and reference models to the KPI calculation and performance management functions.

In order to perform the functionalities already described, the PME solution was designed according to a layered architecture approach (Figure 9). This kind of approach was selected as it makes it possible to share the concerns on the application into stacked groups and, therefore, there is a higher level of flexibility to capture and handle data from different sources and afterwards to calculate the right metrics in order to evaluate the performance of the current strategy. The main components, and respective benefits, of this layered architectural are:

PME WebService: The WebServices connector is at the foundation of the PME structure. This module is responsible for managing all the communications with the semantic repository. Therefore, when it is necessary to read or write any kind of data from the repository, this module selects the suitable SPARQL query template, completes with the missing data and invokes it, using the Suds gateway. The Suds web services client is a lightweight soap-based client for Python that is public available.

Extract Transform Language Layer (ETL): This is a module responsible for collecting data from various sources, transforming the data according to business rules/needs and loading the data into a destination database. Therefore, due to the implementation of this layer it is possible to read data not only from external databases such as Oracle, Mysql, Postgres, SqlServer, but also from diverse file formats (excel, csv, xml and email). An open source technology called CloverETL was used in order to implement this ETL layer.

Raw Data Fusion: For a reliable dynamic KPI calculation it is necessary to gather three kinds of performance data: real-time shop floor data, production system constraints data, and finally strategic data. In line with this, the Raw Data Fusion module is responsible for identifying the data source, selecting the data fields desired, applying filters capable of increasing the performance calculation reliability and expressing the correlation between data available from different sources. After this information is determined, the Raw Data Fusion module retrieves this information to the ETL layer in order to extract the right information with the highest quality possible.

Production System Emulator: After the performance data required to calculate the KPI metric are defined and archived, it is necessary to extract the variables (assumptions/constraints, as well as production system outputs and resources) from the production system. These variables must be taken into account during the calculation process of the indicators since they can influence the detail and reliability of the measurements. In line with this, the production system emulator has the responsibility of characterising each manufacturing agent (collaborative network partner, departments or production sections), organising for each of them the static variables, the main strategic objectives, mapping them with the different manufacturing objects (machines, human resources or products) and respective KPI instances.

KPI Manager: This module intends to manage generic KPIs. In other words, this module is responsible for creating the KPI hierarchical structure and connecting each entity of this structure to the respective Raw Data. However, when dealing with KPIs it is important to integrate in the calculation not only Raw Data but also other indicators. This fact makes this management process more complex, but on the other hand it provides interesting add-value to the production system managers as it simplifies performance assessment.

KPI Calculator: This module is responsible for compiling all the data retrieved from the KPI Manager, Production System Emulator and Raw Data Fusion components, and for calculating the indicators according to the manufacturing system manager specifications.

KPI Analyser and Event Manager: Finally, after the strategic, tactical and operational data are identified, the PME calculates the indicators when necessary (user orders or event triggers), confirms whether the object analysed performs as desired by the different stakeholders, and sends reports (alarms) with charts and possible reasons for low performance rates using KPI Tree analyses.

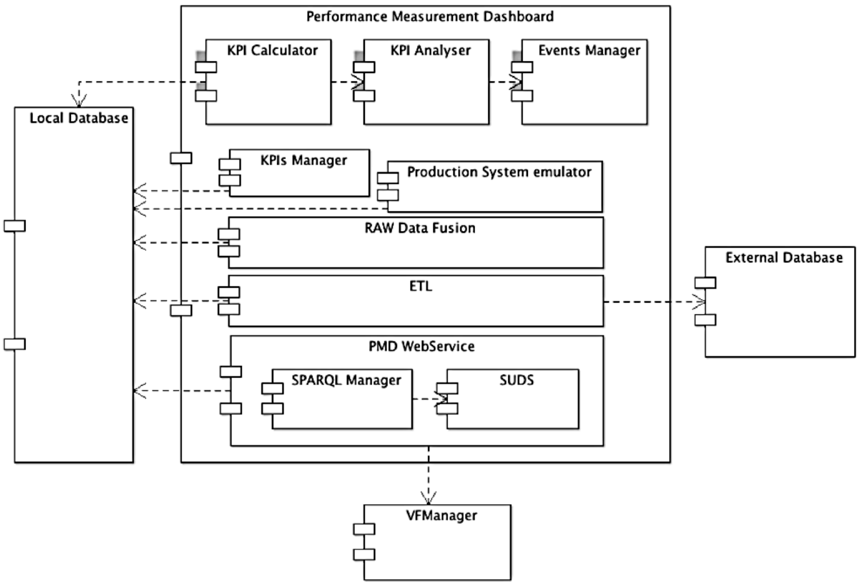

Fig. 9. Performance Measurement Engine Architecture

5 Experiments and Results

5.1 Scope

Aiming to test and validate the PME developed, an industrial partner belonging to the automotive sector was selected to be used as use case. Indeed, the scenario handled at this industrial partner can be classified as a complex system since despite the fact it is composed of a single production line, the truth is that along this production line different families of cars are produced, with different characteristics and requirements (sportive and family cars), sharing processes and resources. Moreover, this production line is divided into the following parts: stamping, painting, body, assembly and quality. Therefore, it is also necessary to calculate each indicator, not only for each product but also according to the structural division of the production system. While some resources are shared between all of the cars, others are shared by a subgroup of families of cars and others are specific to each product. Due to the complexity and time consumption required to perform the KPI calculations and its respective assessment, this presents a very interesting opportunity to evaluate the PME solution.

As illustrated in Figure 10, the PME is located between the strategic and operational levels, aiming to compile raw data according to the KPIs specifications and planning constraints and assumptions retrieved from the strategic level.

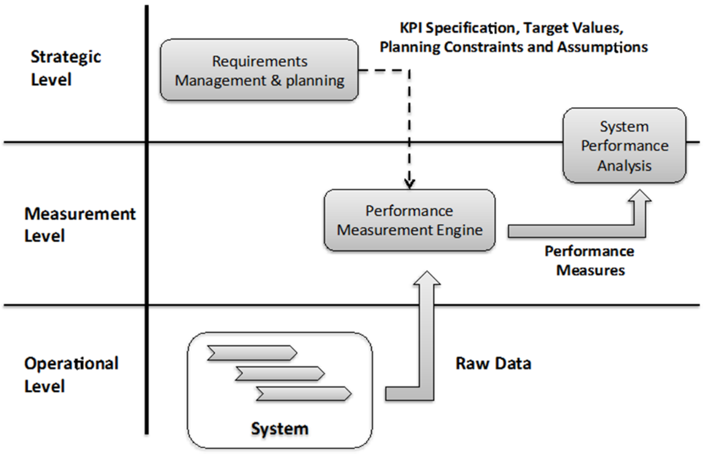

Fig. 10. Integrated Strategic Performance Management

Requirements Management Planning (RMP) tool, at strategic level, supports the design of strategic maps modelling and the necessary alignment with organizations policies and visions. In this pilot case, the Harbour Report was selected as the conceptual pillar supporting the validation of this strategic performance management system. The Harbour Reports, from Harbour Consulting, are relatively standard for empirical research in the automotive industry. Indeed, is one of the most important benchmarking reports aimed not only to ranking automotive plants in terms of efficient but also support organizations involved within this comparison exercise enhancing their manufacturing systems and the entire supply chain.

A relevant KPI related with the manufacturing system productivity, called Hours per Vehicle (HPV), was selected to be included in this pilot case. The KPI HPV takes into account all of the hours worked by the direct plant personnel divided by the number of units produced, with the expected levels of quality, in the time interval defined. This is an aggregated KPI that belongs to the efficiency perspective and is composed of simple indicators from different dimensions, for instance time and quality.

However, the calculation of the variable Manpower is not a straightforward calculation. Thus, in order to calculate this performance indicator it is necessary to know the list of people that directly interact with the production line, the list of people in absenteeism or in training and the list of people that moved from an organizational area to another.

Since the industrial partner's plant produces more than one type of vehicle and the line has five distinctive areas (stamping, body, paint, trim & assembly and quality), the calculation must be performed per car, taking into account the entire line, but also splitting up the production line stages. In other words, the domain/universe of calculation is the production line divided by the five areas and its output, represented by the volume of cars per type. Following a high-resolution paradigm, the more detailed is the calculation of a certain KPI, more information is possible to extract in terms of management issues. Therefore, aiming to automate and increase the level of information extracted from the HPV measure, the PME was used as the engine of calculation of the KPI HPV.

Therefore, the following stage of the pilot case was divided into two main steps: KPIs metrics parameterization and KPIs calculation. While the first stage is mainly responsible by the definition and specification of a certain KPI as an object, during the KPI calculation the main objective is to instantiate the object created in order to answer to the requirements imposed by performance management strategy, such as domain/universe of calculation, static and dynamic assumptions as well as percent of resources allocation per product type.

5.2 KPIs Metrics Parameterization

As previously described, at a first stage of this pilot case, the KPI HPV was specified using the data fusion and metrics formalization capabilities of the PME. Thus, the first task performed was to identify the raw data sources (databases or flat files) available, in order to create the tunnels for data communication. In line with this, initially, all tables containing information about the necessary raw data for the HPV calculation were identified, such as: list of Cost Centres, the payroll table, list of absenteeism, list of people in training and list of people transferred temporarily from one organizational area to another.

Identified the data sources, where the raw data will be available, the following step was strictly related with the KPI0 specification. As previously explained, this type of indicators is mainly responsible by the structuring of raw data through a data fusion approach. For instance, it is possible to merge the list of cost centres with the payroll list in order to obtain the number of persons working in each cost centre. This step is critical, since it is expected to calculate the KPI HPV per organizational areas, which are composed by cost centres. Due to the drag and drop functionality, the user is not required to have any knowledge of SQL language, being only necessary to link the similar attributes from the selected tables.

Identified the data sources as well as specified the KPI0 it is now possible to specify the mathematical formulas for each of the key performance indicators (KPI1+) identified before: Manpower and HPV. In this specific pilot case, the PME was capable to download from a knowledge-based server, where the strategic and performance measurement and management ontology was deployed, the information created by the RMP software concerning KPIs formulas and respective target values. However, if the PME was being used as a standalone solution, then, similarly to the previous step, the formula could be built using the drag and drop functionalities of the PME tool.

It is important to underline that, due to the innovative hierarchical approach explored within this performance measurement engine, it is possible to define KPIs that are composed not only by KPI0 and assumptions but also by others KPI1+. For instance, the KPI HPV is composed by one KPI1+ (Manpower), which, consequently is composed by a set of four PI of level zero (payroll, absenteeism, training and transfers). This hierarchical approach, built according to the metric of each KPI, can be seen in figure 16.

5.3 KPI's Metric Calculation

Specified the metrics of the desired KPIs, the following step of the pilot case is strictly related with the metric calculation. In fact, this is a second process that allows approximating as much as possible the KPI calculation from the real characteristics of the complex manufacturing system.

Therefore, aiming to calculate the KPI HPV, initially the static and dynamic assumptions were defined. Since at the moment that this pilot case was performed it was not possible to establish a direct connection with the data sources where it would be possible to extract the real volume of cars produced, and then this information was manually introduced into the system. At this moment, it is possible to parameterize the day for which it is expected to perform the calculation and, if necessary, update the value of the static assumption "EffectiveTime".

In fact, one of the main advantages of this approach is the capability to calculate a certain KPI with a higher level of detail but with lower effort. Therefore, during the description of the pilot case it was stated that it would be important to calculate the KPI HPV not only per product but also per cost centre. Therefore, the following steps are related with the specification of the performance measurement domain and the percentage of effort allocated for each car family. This means that it is possible to specify for each cost centre selected to make part of the performance management strategy clusters the effort allocated for each car family. In line with this, for each cost centre it is possible to indicate which car family used the resources available and the percentage of usage (in this case human resources). The calculation of this percentage can be done automatically by the PME, through the planned volume of production, or introduced manually by the system's performance manager.

Finally, reports can have different formats: KPI hierarchical trees (Figure 11), charts, tables or pre-defined emails. For instance, the KPI trees represent an innovative approach to analysing and assessing a performance indicator measurement. With this approach, it is not only possible to visualise the entire structure of a KPI (raw data and performance indicators used) but also detect the reasons for low performance rates. Therefore, it is feasible to detect watermelon situations and anticipate possible production system malfunctions. This means that, by using different colour tones from light green/red to dark green/red managers can instantly understand if KPIs are far (darker) from or close (light) to the target. In order to provide managers with more detailed information about the performance behaviour of the system, the possibility of clicking on each of the indicators that compose the KPI in analysis was implemented, so that they could see the real values compared to targets, by domain, and thus providing an even more detailed view of the KPI status.

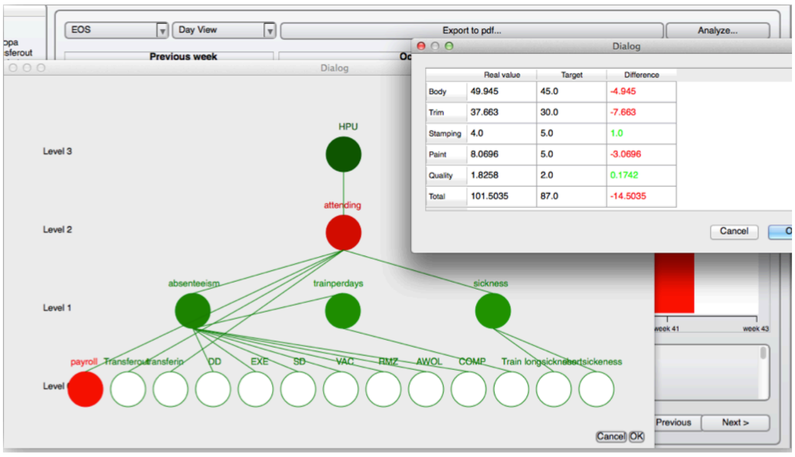

Fig. 11. Root causes analysis through innovative PME drill-down approach

6 Results Analysis and Conclusions

From a literature review, it is possible to confirm that a considerable change has occurred in the managerial culture and rationalisation of the manufacturing systems, which required small and large manufacturing systems to become more and more complex. However, it has been observed that inappropriate research has been conducted in the scope of performance measurement systems in the search for the continuous evolution of manufacturing systems.

For instance, if is true that companies are improving their technical and technological capabilities to meet the market needs, on the other hand this work has had a low impact on the formalisation of holistic and robust performance management models, adopted to deal with this increasing complexity (Garengo, Biazzo and Bititci, 2005).

This research project was developed on the premise that aiming to support decision makers to become more proactive, in terms of performance management strategies, it is necessary to enhance the way in which organizations execute their performance measurement activities, as well as improve the reliability, confidence and granularity on their KPIs metrics and measures.

Due to the simplicity and effectiveness of the technology developed, it was possible to break with the stigma linked to the performance management discipline, where the effort required to obtain interesting performance information neither complies with the added-values obtained nor reinforce the organizational core business processes.

Furthermore, it was demonstrated that based on this approach it is possible to extract more powerful information, envisioning knowledge creation. In other words, providing decision makers with the capability to build multi-perspective and aggregated KPIs, it is possible to decrease, significantly, the number of KPIs necessary to make decisions but keeping, at the same time, a multi-perspective vision of the manufacturing system.

Thus, with the implementation of this application case, it was demonstrated that it is possible to innovate and enhance the way how decision makers interpret this important information, drilling down a problem and study the reason behind a poor performance, in a high resolution way. In this specific case, it was proved that with low effort, it was possible to calculate the KPI HPV for each cost centre, clustered in well-defined organizational units, as well as assess the strategy deployed, and materialized by the manufacturing system performance, per product family. Moreover, by following an innovative approach that structures KPIs in a hierarchical tree, combining multi-perspectives indicators, the PME allowed not only decision makers to analyse the impact of a specific indicator within the KPI structure but also integrate both tactical and operational information, and thus achieving a powerful "what-if" analysis.

In sum, it was possible to evaluate the proposed approach considering three perspectives:

- Time constraints: the time required to calculate each indicator and to broadcast a performance report by the different stakeholders (time constraints) was measured using both the PME method and a traditional method.
- Effort: the number of resources required in both processes was also measured (required effort) taking into account the performance assessment and bottlenecks identification error obtained.
- Learning curve: the time required to train a new performance measurement technician (learning curve). In addition, the time necessary to introduce a new goal and respective KPI(s) was also assessed.

Our study has limitations. The developed approach was tested in the automotive industry, which presents the characteristics stated previously concerning a complex manufacturing system. However, the approach has not been evaluated in other manufacturing environments. Thus, future work should explore the application of proposed approach in multiple industries addressing different operational and markets environments.

7 Acknowledgements

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Determinants of quality management systems implementation in Tunisian firms

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Abstract. This research explores the impact of the firm's internal and external attributes on its degree of implementation of quality management according to the ISO 9000 standard. This econometric study, based on the data gathered from a sample of Tunisian companies certified or in the course of certification in ISO 9001: 2000, reveals that the application of quality management depends on the organizational and environmental context of the company: a motivation rather internal than external to be certified, the application of ISO 9004 standard recommendations, the adhesion of the company to the leveling program, size, investment in new technologies of information and communication and in technologies of analysis and measurement and the importance of innovation and quality criterion for customers.

Keywords. Quality management, NTIC, ISO 9000, Seemingly unrelated regressions.

1 Introduction

In an agitated environment of globalization and to deal with the increased competition in a market where the challenges and issues have become multiple, firms worldwide have adopted new modes of intangible investment and management strategies. Particular attention is given to the model of Quality Management (QM) according to ISO 9000 because it offers the organization a set of best practices allowing the elimination of systemic malfunction risk by appropriate management of resources and processes, monitoring results and promoting continuous improvement of the internal organization. In fact, more and more customers require their suppliers to be certified by this standard. Henceforth, the number of companies certified according to ISO 9001 in the world has increased, dramatically. In Tunisia, the latest statistics from the Agency of Industry Promotion has recorded more than 800 certified companies.

This growing interest devoted to the concept of quality is the result of many economic studies showing the evolution of the quality approach from a simple product characterization to an approach taking an organizational dimension (Gomez, 1996; Debruyne, 2001; Mazé, 2003; Hajjem, 2011). Several empirical studies showed that quality is a key factor of competition between firms (Scotto, 1996; Solis and al, 1997; Duane and al., 2009; Legros and Galia. 2011). Others analyzed the relationship between innovation and quality and indicated that for great innovation performance improvement well established quality system is needed inside the firm (Sanja, and Galia. 2009).

However, little work has been done to show that the adoption of QM practices depends

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on the organizational context and the firm's environment (Fahmi, 2000; Wardhani, 2008; Anand and Prajogo, 2009;Prajogo, 2011). Our study is in this research field. It specificallyconcentrates on the impact of the firm's internal and external attributes on the level of QM implementation. Our paper is organized as follows: First, the theoretical assumptions from the literature review are presented. Then, our econometric method based on simultaneous equation model are explained. Finally, the different results and the prospects for future research are presented and discussed.

2 Conceptual framework and research hypotheses

The interest by the QM model according to ISO 9000 and the growing number of companies seeking certification have led many researchers to make contributions on the empirical determinants of this new type of strategic management adoption. Thus, several studies have been conducted to examine the effect of motivation to get certified. Others have studied the impact of environmental and organizational context of the firm (internal and external factors) on the achievement of quality management practices and business performance in general.

2.1 The challenges and limitations of the certification ISO 9001: 2000

Several studies have been conducted to identify the motivations that may induce firms to engage in a process of ISO 9001 certification. For example, Solis and al. (1997) indicated that certified firms registered a higher degree of leadership, information analysis, quality strategic planning, human resource development, quality assurance, good customer-supplier relationships and quality results. Others have studied the effect of certification on business performance. Thus, it turned out that the ISO 9000 adoption positively affects customer satisfaction (Avery and Babel, 1996; Duane and al., 2009), competitiveness, profitability (Scotto, 1996; Hajjem, 2011) and product and service quality (Zelealem and Solomon, 2002).

Indeed, the certification founds the company's reputation by improving the market transaction thanks to the trust built between buyers and sellers. It aims to reduce the quality uncertainty for both the buyer confident in the reliability of the service offered and the seller assured of reliable and regular finding (Debruyne, 2001). So, in addition to the assurance of maintaining the product or service intrinsic quality, ISO 9001 ensure customer satisfaction by his positive evaluation regarding all the contacts that he may have (home phone, on-time delivery, customer service). It also helps to develop a quality management system eliminating the failure risk by a suitable management of resources and processes, monitoring results and promoting continuous improvement of the internal management.

Other studies have revealed that certification should not be a finality in itself. Gongxu (1999) concluded based on extensive investigations in 10 Chinese companies, that being ISO 9001 certified implies only that the degree of Total Quality Management (TQM) has reached a new starting point. Thus, Hongyi (2000) made the recommendation that ISO 9001 should be incorporated with the philosophy and methods of TQM. In addition, Rahman and Sohal (2002) showed that, except the process control factor, there is no significant difference between the impact of total quality management practices on organizational performance of Australian SMEs with and without ISO 9001 certification.

In fact, certification has also several deficiencies related as much to its inclusion in the firm's competitive evolution, as to the difficulty of its socio-organizational implementation (Debruyne, 2001). The commitment of a company in a certification approach may be encouraged by rational mimetism: the company is obliged to adhere to the standard to deal with the increased competition. Moreover, in the race for ISO certification, it is very difficult for the final consumer to evaluate the benefit he may take from a certified product or service against another that is not certified.

Certification can also be a factor of rigidity and an obstacle to innovation because the internal organizational radical change encourages the lack of questioning about the new structure by the direction. Thus, anticipatory and adaptive capacity of the firm maybe impaired face to the market permanent evolution. In addition, the introduction in the company of too many and detailed written procedures inhibits creativity and personal initiative. The certification in this case is a source of disqualification and return to Taylorism.

Henceforth, some studies (Lee and Palmar, 1999; Pytlak, 2002; Wardhani, 2008) have conditioned the positive impact of certification by the nature of the company's motivation to become certified. The three main cited reasons are direct pressure from customers, indirect pressure from competition and the desire to conquer new markets. In fact, when the leader's motivations to certification are internal (process improvement, work organization, product and service quality, preserving the know-how), not external (direct pressure from customers and / or group, indirect pressure from competitors), the company is more likely to subsequently implement a quality management system at an advanced level (Pytlak, 2002, Anand, and Prajogo, 2009;Prajogo, 2011). All these studies and findings lead us to formulate our first hypothesis:

> *H1: The internal motivations for the certification decision have a significant positive effect on the QM implementation degree.*

Another line of research is to study the effect of the firm's internal and external attributes on the adoption degree of QM practices.

2.2 Impact of the firm's characteristics

Some original research works have shown that the quality management does not generate the same value for all firms and that its implementation depends on organizational context and the firm's environment (Wruck and Jensen, 1994; Fahmi, 2000; Wardhani, 2008, Prajogo, 2011). In the light of these studies, we will formulate our research hypotheses concerning the internal and external factors determining the implementation degree of quality management practices.

Effect of size. Lee and Palmer (1999) have shown that unlike large companies, the use of ISO 9001 certification by small businesses is due more to external than internal factors, and they have little intention of making an extension of their quality program beyond the certification.

Furthermore, the examination of small (<50 employees), medium (50-200 employees) and large (> 200 employees) firms showed significant differences in the contribution of certification on the implementation degree of QM items especially for human resources management, process management, relationship with suppliers and customers (Gotzamani and Tsiotras, 2002). The improvement of these practices was significantly lower for large firms. The authors explained this result by the fact that these companies have a higher level of quality management even before certification. In fact, unlike large firms, small and medium enterprises have limited managerial skills, ambitions and resources. Quazi and Padibjo (1998) showed that the lack of managers' experience and knowledge, human and financial resources and time required for the implementation of quality management are the major problems faced by SMEs when adopting a quality approach.

Indeed, Quality Management is an approach enabling efficient use of specific information. It gives more autonomy and power to the organization's lower levels and increases their direct responsibilities. This value is generated through timely and appropriate treatment of information and better use of specific knowledge. Therefore, the QM is economically profitable for large firms with significant informational challenges, and where over-centralization would lead to making sub-optimal decisions (Wruck and Jensen, 1994).

Increasing the company size generates the complication of its organization which makes the efficient decision-making impossible in a limited time or in a centralized manner. In addition, the production process requires a lot of information and specific skills, widely distributed among staff which requires employee involvement and teamwork. Moreover, the larger the size, the greater the communication costs are high. Crossing the hierarchy, the transmitted orders can be disturbed and an offset may exist between the implementation of corrective actions and the perception of problems and malfunctions. Under these conditions, if large companies cannot find efficient solutions to these issues of information overload and organizational costs, their performance will inevitably decrease (Fahmi, 2000). The optimal way to organize the activity of these companies is therefore to decentralize responsibilities and to encourage better human knowledge management through the adoption of QM practices. Hence our hypothesis 2:

> *H2: The increase of the firm size has a positive effect on the quality management adoption.*

Role of Investment in New Information and Communication Technologies and in Technologies of Analysis and Measurement. To facilitate the implementation of QM, the firm must establish appropriate means allowing the consistent treatment of information available to agents located at different levels of the hierarchy and making the right decisions at appropriate times. In this regard, the use of new information and communication technologies (ICT) is essential to promote the flow of information and enable the development of more decentralized organizational structures (Harris, 1995; Wardhani, 2008, Prajogo, 2011). Indeed, the role of ICT consists in the compression of time, reducing response deadlines of the company, improving the capacity of information processing and of employees' control.

On the other hand, decentralization of decision making can lead to opportunistic behavior among some employees who are assigned new responsibilities. They will rationally try to benefit from their informational advantage and pursue their own interests instead of the maximization of corporate value. The existence of analysis and measurement technologies (AMT) facilitates the control of these agents and the coordination of decisions. Thus it is a principal determinant of the QM implementation (Wruck and Jensen, 1994; Fahmi, 2000). This is because these technologies allow reducing control costs related to the decentralization of decision making and the reduction of uncertainty and asymmetric information existing between agents (internal and external partners). These arguments allow us to formulate our third hypothesis:

H3: Investment in new information and communication technologies and in measurement and analysis technologies has a positive effect on the implementation degree of QM.

Role of the interdependence between units. The QM provides continuous improvement across all interdependent units of a company (Fahmi, 2000). In fact, the recourse to quality improvement teams encourages sharing of information regarding quality and malfunctioning. Besides, this promotes cooperation links and communication between the firm's different units. Thus, there is a decrease in internal conflicts and a limitation of individualistic practices. Henceforth, more units are interdependent, more the incentive to mutual control is high, since a low level of effort (high) at a unit may penalize (improve) the performance and the reward for all units (Barua, Lee and Whinston, 1995).

On the other hand, organizational change engendered by the company commitment in a QM calls the establishment of horizontal coordination between units. The process of communication and information exchange are therefore accelerated which allows units to react and quickly find solutions to problems that arise. Furthermore, the implementation level of this approach would be more advanced if staff is polyvalent which promotes flexibility and interchangeability of employees between the units.

Given these arguments, we conclude that the QM return will be more interesting in firms characterized by a high level of interdependence between the units. Hence our hypothesis 4:

H4: The degree of interdependence between units has a positive effect on the quality management adoption.

Impact of the firm's environment. Due to the constant change and uncertainty of the environment, firms are obliged to be informed about changes in customer needs, competition and situations of all their external partners in order to better manage these changes (Cyert and Kumar, 1996; Wardhani, 2008, Prajogo, 2011). This aim requires operating a large amount of information difficult to obtain and manage and developing new skills to interpret and process the data.

Milgrom and Roberts (1988) reported that under such conditions, a company must either increase the amount of information to treat or reduce the need to process information. In fact, a centralized firm may face some incompleteness of data due to the multiplicity of sources and the difficulty to collect everything. QM guidelines such as the decentralized modes of organization promoting skill sharing, teamwork, methods of problem resolution and encouraging employees to respond independently to new situations, all these elements increase organizational capacity to adapt to unpredictable fluctuations in the market and new technologies (Hackman and Wageman, 1995).

Moreover, the importance of innovation for customers is seen as another external factor favoring the adoption of QM. Indeed, the relationship between innovation and quality has been the subject of several empirical research (Galia and Legros, 2003; Prajogo and Sohal, 2006). The main conclusion of these studies supports a positive relationship between these two constructs. In fact, according to evolutionary theory, the QM can promote competencies and encourage initiative and creativity. Hence, the adoption of QM in this case is encouraged by the willingness of the company to strengthen its innovation capacity in order to follow the evolution of customer expectations (Benezech and al., 2001; Reverdy, 2005).

In addition, the importance of the quality criterion for customer is also an external factor encouraging firms to review and rationalize their internal processes in order to satisfy the needs of their customer increasingly demanding. All these findings lead us to state our fifth hypothesis:

> *H5: The adoption of quality management is positively related to the increased uncertainty of the environment and the importance of innovation and quality criterion for customers.*

Thus, we identified the factors determining the implementation degree of QM practices. We will test these research hypotheses in the following thanks to a survey among a sample of Tunisian firms certified or undergoing certification according to ISO 9001: 2000.

3 Econometric study

3.1 Data collection

Data were collected through a questionnaire addressed in 2006 to Tunisian firms certified or undergoing certification according to ISO 9001: 2000, since we are interested in the QM model according to this standard. The design of the items was made on the basis of the literature (Saraph and al. 1991; Wruck and Jensen, 1994, Solis and al. 1997; Fahmi, 2000; Pytlak, 2002). Finally, the questionnaire was sent to 115 companies and we have received 47 usable returns (a response rate of 40.87%).Industrial companies present 83% of our sample; the majorities are chemical (25.53%) and electrical (21.27%) companies. The percentage of service companies is much lower (17%) as there are still a minority of Tunisian companies in this sector that are engaged in a quality management process.

3.2 Operationalization of variables and model design

Given the increasing number of items related to our issue, we first performed a principal component analysis (PCA) to construct variables measuring QM practices. In fact, this method is the most appropriate to deal with an increasing number of ordinal variables in front of a small number of observations (Evrard and al., 1997). Thus, we have built seven quality management practices: communication of quality policy and direction commitment (P_1), taking into account the clients' needs (P_2), employee involvement (P_3), process control (P_4), developing close relationships with suppliers (P_5), involvement of suppliers (P_6) and integration of environmental requirements (P_7). We note an equivalence between these practices and principles of QM according to ISO 9000 (*Customer-Focused Organization, Leadership, Involvement of People, Process*

Approach, Continual Improvement, Factual Approach to Decision Making and Mutually Beneficial Supplier Relationships) which shows the validity of our factor analysis. We used these constructed variables to determine the factors explaining their level of implementation in Tunisian companies. On the other hand, based on the literature and our research hypotheses, we considered the following firm's internal and external attributes as determinants of the QM implementation degree:

Table 1: List of variables[1]

Variable	Label	Measure
Type	Firm type	Nominal variable (manufacturer / service)
PMN	Involvement in the leveling program	Binary variable (yes / no)
Ann_lance	Starting Year of the quality approach	Ordinal variable (less than 5 years, 5 to 10 years, more than 10 years).
Cert_94	Certification ISO 9000 : 1994	Binary variable (yes / no)
Type_94	Type of the ISO 9000 :1994 Certification	Nominal variable (ISO 9001/ 9002/ 9003)
ISO_1994	Implementation of the l'ISO 9004	Binary variable (yes / no)
I_NTIC	Investment in new technologies of information and communication	Binary variable (yes / no)
I_TAM	Investment in analysis and measurement technologies	Binary variable (yes / no)
F_motiv	Motivation factor that most influenced certification	Nominal variable (competitors, customers, group, financial performance, internal organization, product quality).
Size	Size	Number of employees in 2005
Conce	Intensity of competition	Likert scale from 1 to 5
Chg_socio Chg_tech Chg_regl	Environmental uncertainty	3 items (socio-cultural, technological, legal and regulatory changes). Likert scale from 1 to 5
Innov_clt	Importance of innovation for customers	Likert scale from 1 to 5
Q_clt	Importance of quality criterion for customer	Likert scale from 1 to 5
Interdep	Interdependence between units[2]	Likert scale from 1 to 5

For the model specification explaining the adoption of each QM practice, we conducted a stepwise forward multivariate regression (Stata software).

In fact, the difficulty in multivariate regression is to construct a regression model with high explanatory power and at the same time having the smallest number of explanatory variables as possible. So, the choice of variables to consider is usually done using heuristic methods for selecting variables based on sequential procedures such as the

[1] All the variables are considered based on the literature review and our research hypotheses presented in section 2. Almost of them are binary (yes/no) or nominal variables obtained directly from the response of the frims'quality managers to the questionnaire items.
[2]A unit may correspond to the company headquarters, division, subsidiary,department, office, factory, workshop, service, institution etc.

stepwise forward method that starts from the regression including all variables then successively removes each variable less decreasing the explanatory power of the model, until getting a model composed of significant variables (Hamilton, 1992).

The results of a regression are valid unless there are significant correlations between these variables. This is to avoid the phenomenon of multicollinearity that appears when one or more variables are linear combinations of other variables. Multicollinearity is detected by studying the tolerance (equal to the inverse of the variance inflation factor) of each variable in the regression, means its part of variance not shared with other explanatory variables. In practice, the tolerance of each variable must be greater than 0.20 to obtain acceptable results (Hamilton, 1992).

The required criteria for valid results (Hamilton, 1992; Evrard and al, 1997) are:

1. Residues should be distributed according to a normal distribution with zero mean.
2. The variance of the residuals should be constant for all levels of the dependent variable. When this is not the case, heteroscedasticity will be detected.
3. Residues should be independent of each other (no autocorrelation phenomenon).

Moreover, the model significance is determined using a test based on the F statistic of Fisher-Snedecor. Its explanatory power is measured by the square of the multiple correlation coefficient R^2 (determination coefficient) and the adjusted coefficient of determination R^2_{aj} which is a correction of the R^2 coefficient performed to take into account the sample size opposed to the number of variables . We should ensure that it is near the R^2.

After performing for each regression (Appendix) the tests of global (F statistic) and individual (Student t) significances of variables and tests of heteroscedasticity (Breusch-Pagan test) and normality of residuals (Skewness / Kurtosis test), the equations retained are as follows:

$$P_1 = \beta_{10} + \beta_{11}\,type + \beta_{12}Innov\_clt + \beta_{13}ann\_lance + \beta_{14}Conce + \beta_{15}\,ISO\_9004 + \beta_{16}\,size + \varepsilon_1.$$

$$P_2 = \beta_{20} + \beta_{21}F\_motiv + \beta_{22}\,I\_TAM + \beta_{23}Innov\_clt + \beta_{24}chg\_socio + \beta_{25}\,ISO\_9004 + \varepsilon_2.$$

$$P_3 = \beta_{30} + \beta_{31}\,type + \beta_{32}Conce + \beta_{33}ann\_lance + \beta_{34}Innov\_clt + \beta_{35}ISO\_9004 + \beta_{36}F\_motiv + \beta_{37}\,I\_TAM + \varepsilon_3.$$

$$P_4 = \beta_{40} + \beta_{41}F\_motiv + \beta_{42}Q\_clt + \beta_{43}ann\_lance + \beta_{44}\,I\_NTIC + \beta_{45}\,ISO\_9004 + \varepsilon_4.$$

$$P_5 = \beta_{50} + \beta_{51}ann\_lance + \beta_{52}F\_motiv + \beta_{53}size + \beta_{54}Q\_clt + \beta_{55}\,I\_TAM + \varepsilon_5.$$

$$P_6 = \beta_{60} + \beta_{61}type + \beta_{62}\,PMN + \beta_{63}Conce + \beta_{64}\,I\_NTIC + \varepsilon_6.$$

$$P_7 = \beta_{70} + \beta_{71}\,ISO\_9004 + \beta_{72}chg\_regl + \beta_{73}Innov\_clt + \beta_{74}Q\_clt + \beta_{75}\,I\_NTIC + \varepsilon_7.$$

Thus, these seven multiple regressions allowed us to clearly specify the models explaining the implementation degree of each QM practice. However, this method does not highlight the interdependence and complementarity between these practices to form a model of consistent and interactive management. Hence, it would be interesting to estimate the system equations by the method of seemingly unrelated regressions (SUR). In fact, the correlation matrix of the equation residuals is as follows:

	P_1	P_2	P_3	P_4	P_5	P_6	P_7
P_1	1.0000						
P_2	0.6169	1.0000					
P_3	0.7436	0.6305	1.0000				
P_4	0.6481	0.6239	0.7192	1.0000			
P_5	0.3638	0.3640	0.2592	0.4225	1.0000		
P_6	0.2365	0.3291	0.3118	0.3885	-0.0574	1.0000	
P_7	0.4091	0.3384	0.5141	0.5859	0.1726	0.6149	1.0000

Breusch-Pagan test of independence: chi2 (21) = 192,501, Pr = 0.0000

Thus, it appears that our use of SUR model is relevant since the equations of QM practices are dependent by their disturbances. Indeed, we see from the correlation matrix of the residuals and the Breusch-Pagan statistic that there is a highly significant correlation (with a risk of 0% error) between the disturbances of equations which proves their simultaneity and therefore inefficiency of the estimation by OLS equation by equation (Green, 2000).

3.3 Estimation results of the system equations by the SUR method

The matrix form of our equation system is:

$$\begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_7 \end{bmatrix} = \begin{bmatrix} X_1 & 0 & \cdots & 0 \\ 0 & X_2 & \cdots & 0 \\ & & \vdots & \\ 0 & 0 & \cdots & X_7 \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_7 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_7 \end{bmatrix} = X\beta + \varepsilon.$$

X_1 = (1, type, Innov_clt, ann_lance, Conce, ISO_9004, taille) ; $\beta_1 = (\beta_{10},..., \beta_{16})'$.

X_2 = (1, F_motiv, I_TAM, Innov_clt, chg_socio, ISO_9004) ; $\beta_2 = (\beta_{20}, \beta_{21},..., \beta_{25})'$.

X_3 = (1, type, Conce, ann_lance , Innov_clt, ISO_9004, F_motiv, I_TAM) ; $\beta_3 = (\beta_{30}, \beta_{31},..., \beta_{37})'$.

X_4 = (1, F_motiv, Q_clt, ann_lance, I_ NTIC, ISO_9004); $\beta_4 = (\beta_{40}, \beta_{41},..., \beta_{45})'$.

X_5 = (1,ann_lance, F_motiv, taille, Q_clt, I_TAM) ; $\beta_5 = (\beta_{50}, \beta_{51},..., \beta_{55})'$.

X_6 = (1, type, PMN, Conce, I_NTIC) ; $\beta_6 = (\beta_{60}, \beta_{61},..., \beta_{63})'$.

X_7 = (1, ISO_9004, chg_regl, Innov_clt , Q_clt , I_NTIC) ; $\beta_7 = (\beta_{70}, \beta_{71},..., \beta_{75})'$.

The estimation by the method of seemingly unrelated regressions (Stata) gave the following results:

Table 2. Regression by the SUR method

Equation	R^2	Chi2
P_1	0.3558	***28.75****
P_2	0.4430	***36.16****
P_3	0.4902	***55.49****
P_4	0.3618	***31.81****
P_5	0.3755	***25.85****
P_6	0.3150	***24.42****
P_7	0.3634	***31.17****

	Coefficient	S.E	z
P_1			
type	**-.4140**	.2430	***-1.70****
Innov_clt	**.1521**	.1091	***1.39****
ann_lance	**.3383**	.1347	***2.51****
Conce	**-.1874**	.0855	***-2.19****
ISO_9004	**.6247**	.2166	***2.88****
size	**.0002**	.0001	***2.16****
cons	-.4128	.6817	*-0.61*
P_2			
F_motiv	**.1017**	.0477	***2.13****
I_TAM	**.6313**	.1767	***3.57****
Innov_clt	**.3289**	.1018	***3.23****
chg_socio	-.0693	.0738	*-0.94*
ISO_9004	**.3583**	.1943	***1.84****
Cons	**-2.0918**	.4855	***-4.31****
P_3			
type	**-.4042**	.1768	***-2.29****
Conce	**-.1899**	.0674	***-2.82****
ann_lance	**.2125**	.1087	***1.95****
Innov_clt	**.3811**	.0875	***4.35****
ISO_9004	**.5830**	.1959	***2.98****
F_motiv	**.0645**	.0378	***1.70 ****
I_TAM	**.3776**	1360	***2.78****
Cons	**-1.5093**	.5674	***-2.66****
P_4			
F_motiv	**.1317**	.0447	***2.94****
Q_clt	**.5276**	.1221	***4.32****
ann_lance	**.2875**	.1144	***2.51****
I_NTIC	.1476	.2081	*0.71*
ISO_9004	**.3001**	.1931	***1.55****
Cons	**-3.6630**	.6778	***-5.40****
P_5			
ann_lance	**.4420**	.1549	***2.85****
F_motiv	**.1640**	.0620	***2.64****
size	**-.0002**	.0001	***-1.86 *****
Q_clt	**.4945**	.1641	***3.01****
I_TAM	**.3343**	.2119	***1.58 ****
Cons	**-3.7938**	.8671	***-4.37 ******
P_6			
type	**.6440**	.2661	***2.42****
PMN	**.8638**	.2294	***3.76****
Conce	**-.1753**	.0941	***-1.86****

	I_NTIC	**.5363**	.3223	***1.66****
	_cons	**-1.2299**	.6448	***-1.91*****
P_7		**.7669**	.1915	***4.00******
	ISO_9004	**-.2229**	.0773	***-2.88******
	chg_regl	**.2142**	.1094	***1.96*****
	Innov_clt	**.3473**	.1511	***2.44******
	Q_clt	**.5723**	.2916	***1.96*****
	I_NTIC	**-2.4713**	.6814	***-3.63******
	_cons			

* : Significant at 10 % ; ** : Significant at 5 % ; *** : Significant at 1 %

3.4 Interpretation and hypothesis testing

The results of the SUR estimation method show that the equations' R^2 are mostly average. We also note that all the system equations are globally significant ((pr> chi2) <1%). We will now analyze the effect of each factor on the adoption of QM practices which will ultimately allow us to test our research hypotheses.

Effects of the motivation to get certified and use of quality labels. We find that the motivating factor most influencing the certification decision has a significant and positive effect on the implementation degree of 4 practices: P2, P3, P4, P5. So it appears that QM is implemented at an advanced level when the most important firm motivation (as perceived by quality manager) is oriented towards improving internal organization and product and service quality. This result is very interesting since it highlights the organizational orientation of the conception of the certification role. Indeed, the strengthening in the 2000 edition of ISO 9000 in terms of process approach, continuous improvement and employee involvement leads companies to integrate more internal motivations for certification. External motivations (direct pressure from customers and / or group, indirect pressure from competitors) lead the company to assimilate the certification to a simple signal sent to external partners and not as a means of creating an internal dynamic of continuous improvement (Pytlak, 2002).

On the other side, the implementation of ISO 9004 recommendations (or "guidelines for performance improvement") has provided significant assistance to companies in strengthening the involvement of top management (P1) and staff in the quality process (P3), taking into account the needs of customers (P2), process control (P4) and the integration of environmental requirements (P7). In fact, compliance with this standard requirement enables organization to develop a quality management system eliminating the failure risk by a suitable management of resources and processes, streamlining procedures, monitoring results, and continuously improving internal management. Moreover, the interdependence of the QM practices reflects the systemic approach of the QM model according to ISO 9000 which considers the firm as a sequence of interactive and consistent processes.

Finally, the Tunisian label role is materialized by the positive effect of the leveling program participation (PMN) on the degree of supplier involvement (significant at 1%). So, this restructuring has prepared the participating companies to set up a QM system marked especially by developing mutually beneficial relationships with suppliers. Hence, government should intensify this type of consolidation program.

Effects of the company's internal attributes. According to the regression results, we find that the firm's activity type significantly affects three QM practices: P1, P3 and P6. In fact, giving the complexity of their production processes, industrial enterprises are marked by greater involvement of direction and staff in the quality process (this variable coefficient is significantly negative in the equation of P1 and P3). While service companies tend to favor greater involvement of suppliers (P6). This can be explained by the fact that the suppliers' product and service quality and their respect of deadlines are reflected more clearly on the quality level offered by service companies. However, for the other practices, the effect of activity type is not significant. This result is in favor of the generic nature of QM i.e. that most of its practices can be applied both by service and manufacturer companies.

In addition, our study highlights the importance of time factor to establish quality culture in the organization and especially to assess the commitment of its employees and the degree of process control and development of close relations with suppliers, since the coefficient of the variable ann_lance (launch year of the quality approach) is significantly positive for these practices.

Furthermore, the effect of firm size is significant for two QM practices: P1 and P5. The coefficient of this variable is positive (low but significant at 5%) for the direction commitment to quality policy and negative (low but significant at 5%) for the development of close relations with suppliers. The QM allows large companies more efficient use of specific information widespread within the organization (Wruck and Jensen, 1994). Thus, managers of these firms are more easily convinced of the utility of a QM policy promoting decentralization of responsibilities and allowing better use of competencies. However, it appears that small firms tend more than large ones to maintain strong relationships with suppliers. Henceforth, considered by many researchers as a determinant factor (Gotzamani and Tsiotras, 2002; Quazi and Padibjo, 1998), the size seems to be a little determinant factor (but significant) of the QM implementation degree by Tunisian companies (consistent with the study of Fahmi (2000)). Thus there is mixed evidence with respect to size.Our hypothesis about the positive effect of size on the QM adoption cannot be confirmedbecause of the weakness of this coefficient and its negative sign for P5.

On the other side, it follows from the estimation by the SUR method that the impact of investment in new information and communication technologies is significantly positive on the involvement of suppliers and the integration of environmental requirements. This is due to the fact that these technologies facilitate communication between the company and its external environment and dissemination of the firm's efforts, results and planned improvements. Hence, our hypothesis about the positive effect of ICT investment on the level of QM adoption is accepted.

Finally, we find that investment in analysis and measurement technologies is in favor of the customer focus, employee involvement and establishing mutually beneficial relationships with suppliers. In fact, these technologies enable the company to organize and control exchanges with its internal and external partners (Wruck and Jensen, 1994), for example through the establishment of customer satisfaction surveys, regular evaluation of skills and the use of scientific indicators for suppliers' selection and evaluation ,reducing control costs generated by asymmetric information. Thus, our hypothesis about the positive effect of investment in analysis and measurement technologies on the QM implementation degree is confirmed.

Nevertheless, this study using Tunisian companies' data was unable to highlight the role of the interdependence degree between units on the QM adoption as the results show that this factor was not significant for all the practices. Thus, our hypothesis about the positive impact of this interdependence is contested.

Effects of external attributes. Our results support the view according to which there is a strong relationship between innovation and quality management (Galia and Legros, 2003) since the coefficient of the variable importance of innovation for customers (Innov_clt) is significantly positive for P1, P2, P3 and P7.This factor incites the firm to enhance its innovation capacity by integrating this goal among the quality objectives in order to follow the evolution of customer expectations. In addition, the firm's ability to innovate cannot be improved without encouraging the sense of initiative for employees which has a positive effect on their reflection and creativity capacity as well as their degree of involvement in the quality process (Bénézech, Lanoux and Lambert, 2001; Lin and Wu, 2005; Loukil, 2005).

Similarly, the importance of quality criterion for customers has a significant and positive effect on the degree of process control, development of close relationships with suppliers and integration of environmental requirements. Indeed, this external motivation factor is classified second (after the improvement of internal organization) among the motivating factors most critical for the certification decision (mentioned by over 31% of respondents). This element encourages firms to review and rationalize their internal processes in order to meet their customers' needs becoming increasingly demanding in terms of quality. It also encourages them to better select their suppliers and subcontractors whose quality of products and services directly affects the company's product and service quality.

Finally, it appears that Tunisian firms are not yet able to internalize the constraints of their environment through the recourse to the QM as a competitive advantage in order to manage uncertainty and confront competition. These environmental changes represent for them factors limiting (case of increased competition and regulatory changes) the progress level of QM. Our assumption about the positive effect of environmental uncertainty on the degree of QM implementation (Cyert and Kumar, 1996; Hackman and Wageman, 1995) is thus contested.

4 Conclusions

To determine the factors influencing the adoption or the implementation degree of quality management practices by Tunisian companies, we have used a variety of analytical and econometric tools. Thus, the principal component analysis allowed us to summarize the items related to QM practices in seven consistent dimensions equivalent at a large extent to the QM principles according to ISO 9000: 2000. Next, we used stepwise forward multivariate regression for each practice which allowed us to significantly reduce the number of explanatory variables and formulate valid linear models. However, the interdependence of QM practices and the existence of a correlation between their equations' residuals led us to estimate the system of simultaneous equations using the method of seemingly unrelated regressions.

It turned out that the majority of our hypotheses are confirmed. Indeed, several internal factors promote the QM adoption degree by Tunisian firms: implementing the recommendations of ISO 9004, an internal rather than external motivation to get certified (H1), adherence to the leveling program, firm's size (H2) and investment in new technologies of information and communication and in analysis and measurement technologies (H3). External attributes, are linked to the importance of innovation and quality criterion for the customer (H5).

We have shown that the application of quality management depends on the company's organizational and environmental context (Bénézech et al., 2001; Lin and Wu, 2005; Wardhani, 2008, Prajogo, 2011). As implications of our results, the Tunisian companies are invited to invest more in new information and communication technologies. This investment is essential to allow them promoting the flow of information between their internal and external partners and developing more decentralized organizational structures. Besides, the ICT will help those companies to implement the international QM standards by reducing their response deadlines, improving the capacity of information processing and of employees' control. In fact, those technologies allow reducing control costs related to the decentralization of decision making and the reduction of uncertainty and asymmetric information existing between agents. Thus giving the importance of such investment, the State should pursue policies to promote the adoption of quality management by providing subsidies encouraging those expenses and by modernizing local labels and leveling programs.

Moreover, the Tunisian firms are invited also to well define their internal motivations to get certified.In fact, we have found that when the leader's motivations to certification are internal (process improvement, work organization, product and service quality, preserving the know-how), not external (direct pressure from customers and / or group, indirect pressure from competitors), the company is more likely to subsequently implement a successful quality management system at an advanced level (Pytlak, 2002; Anand, and Prajogo, 2009; Prajogo, 2011). This implication is very important since in case of lack of real internal motivations certification can also be a factor of rigidity and an obstacle to innovation. In fact, anticipatory and adaptive capacity of the firm maybe impaired face to the market permanent evolution because the internal organizational radical change will reduce questioning about the new structure by the direction. In addition, the introduction in the company of numerous and detailed written procedures inhibits creativity and personal initiative. The certification in this case will be a source of disqualification and return to Taylorism rather than a source of promoting competitiveness for Tunisian companies.

The importance of our findings shows the richness of this research axis and the relevance of our model. However, our study suffers from a main limit which consists of the very small size of our sample. So,its extension will be a very interesting research perspective in order to generalize the results.

Indeed, the establishment of quality management as an organizational change is not an easy process and has often disappointing results. Hence, it is very interesting to study success factors determining the contribution of QM process to value creation and promotion of organizational performance.

Finally, taking into account the evolution of QM systems over time through the use of panel data and the integration of a spatial variable to see the impact of the geographic location of the company on its level of QM implementation and organizational performance are also attractive research opportunities.

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Appendix

Regression of P_1:

R^2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.3795	***7.49****	***3.86****	3.39

P_1	Coef.	Robust S.E	t	Tolerance (1/vif)
type	**-.6135**	.2658	***-2.31****	0.7594
Innov_clt	**.2742**	.1370	***2.00****	0.9479
ann_lance	**.4260**	.2420	***1.76 ****	0.9292
Conce	**-.1974**	.1023	***-1.93 ****	0.9469
ISO_9004	**.7547**	.2923	***2.58****	0.8965
taille	**.0003**	.0000	***3.42****	0.7553
cons	**-.8861**	.9463	*-0.94*	-

* : Significatif at 10 %; ** : Significatif at 5 %; *** : Significatif at 1 %

Regression of P_2:

R^2	Adjusted R^2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.497	0.436	***8.12 *****	*1.11*	*0.92*

P_2	Coef.	S.E	t	Tolerance (1/vif)
F_motiv	**.1689**	.0666	***2.54****	0.8653
I_TAM	**.9495**	.2605	***3.65****	0.7653
Innov_clt	**.4804**	.1485	***3.42****	0.8653
chg_socio	**-.1907**	.1123	***-1.70****	0.7911
ISO_9004	**.4652**	.2432	***1.91****	0.8141
cons	**-2.8497**	.6597	***-4.32****	-

Regression of P_3:

R^2	Ajusted R^2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.540	0.4574	***6.54****	*0.66*	*1.61*

P_3	Coef.	S.E	t	Tolerance (1/vif)

type	**-.5627**	.2984	***-1.89****	0.9178
Conce	**-.2445**	.1162	***-2.10*****	0.9043
ann_lance	**.3129**	.1685	***1.86****	0.9254
Innov_clt	**.4780**	.1323	***3.61*******	0.9398
ISO_9004	**.6554**	.2515	***2.61*******	0.7326
F_motiv	**.1498**	.0661	***2.27*****	0.9344
I_TAM	**.6140**	.2514	***2.44*******	0.7908
Cons	**-2.2228**	.9096	***-2.44*******	-

Regression of P_4:

R^2	Ajusted R2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.439	0.371	***6.43*******	*0.13*	*0.95*

P_4	Coef.	S.E	t	Tolerance (1/vif)
F_motiv	**.2436**	.0709	***3.43*******	0.9406
Q_clt	**.7217**	.1975	***3.65*******	0.8270
ann_lance	**.4286**	.1812	***2.36*****	0.9276
I_NTIC	**.5849**	.3363	***1.74****	0.9336
ISO_9004	**.5432**	.2610	***2.08*****	0.7889
Cons	**-5.7206**	1.0702	***-5.35*******	-

Regression of P_5:

R^2	Ajusted R^2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.389	0.315	***5.23*******	*0.91*	*0.41*

P_5	Coef.	S.E	t	Tolerance (1/vif)
ann_lance	**.4966**	.1844	***2.69****	0.9753
F_motiv	**.2135**	.0729	***2.93****	0.9700
taille	**- .0003**	.0001	***- 2.04***	0.9408
Q_clt	**.5461**	.1915	***2.85****	0.9576
I_TAM	**.4538**	.2537	***1.79****	0.9800
Cons	**- 4.3694**	1.0208	***- 4.28****	-

Regression of P_6:

R^2	ajusted R^2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.335	0.272	***5.30****	*0.05*	*0.92*

P_6	Coef.	S.E	t	Tolerance (1/vif)
type	**.6473**	.3637	***1.78****	0.8287
PMN	**1.0624**	.3258	***3.26****	0.8706
Conce	**- .2448**	.1327	***-1.84****	0.9300
I_NTIC	**.7884**	.3746	***2.10****	0.8703
Cons	- 1.3428	.8612	*-1.56*	-

Regression of P_7:

R^2	Ajusted R^2	F	Chi 2 of Breusch-Pagan	Chi 2 of Skewness/Kurtosis
0.3887	0.3141	***5.21****	*1.35*	*0.60*

P_7	Coef.	S.E	t	Tolérance (1/vif)
ISO_9004	**.9698**	.2723	***3.56****	0.7902
chg_regl	**-.2200**	.1208	***-1.82 ****	0.8140
Innov_clt	**.2808**	.1698	***1.65****	0.7208
Q_clt	**.4766**	.2251	***2.12****	0.6941
I_NTIC	**.7316**	.3660	***2.00****	0.8594
Cons	**-3.5524**	.9790	***-3.63****	-