CROSS-BORDER ASSESSMENT OF THE BUSINESS ECOSYSTEM SPECIALIZED IN ADDITIVE MANUFACTURING

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DOI: https://doi.org/10.52152/D11385 | Received: 19/dec/2024 • Reviewing: 19/dic/2024 • Accepted: 07/abr/2025

To cite this article:

RODRÍGUEZ-MARTÍN, Manuel; PRIETO-SÁNCHEZ, Carlos-Javier; GARCÍA-MARTÍN, Roberto-José; LORENZO-FERNÁNDEZ, Miguel-Ángel. CROSS-BORDER ASSESSMENT OF THE BUSINESS ECOSYSTEM SPECIALIZED IN ADDITIVE MANUFACTURING. DYNA. July August Vol. 100, n.4, pp. 314-320 | DOI: https://doi.org/10.52152/D11385

ABSTRACT:

In this paper, a prospective investigation is conducted using open sources on organizations benefiting from additive manufacturing in the cross-border region between western Spain and northern Portugal. This work aims to assess business specialization within the framework of this Industry 4.0 technology in two areas affected by depopulation and deindustrialization processes. The adopted methodology includes a systematic search based on predefined criteria, followed by a quantitative analysis based on three stratification factors: company size, business objectives, and geographic location. Additionally, a qualitative and heuristic analysis of open information from key organizations and their relationship with regional socio-economic development is carried out.

Keywords: Smart Specialization, Additive Manufacturing, Regional Development, New Materials.

FUNDING

The following work has been funded by the Interreg-POCTEP call within the European Naturfab project (0049_NATUR_FAB_2_E).

1. INTRODUCTION

Additive manufacturing is enhancing production processes by contributing to improved efficiency, customization, and sustainability [1]. At the same time, its various benefits are increasingly being consolidated within the business sector [2–3].

1.1. Additive manufacturing as a pillar of Industry 4.0 and 5.0

The integration of additive manufacturing is closely linked to the implementation of disruptive technologies characteristic of Industry 4.0 and Industry 5.0 [4–6]. Moreover, additive manufacturing is not a single technology but rather encompasses a variety of processes (recently codified in [7]) tailored to specific applications [8], thereby enabling the adaptation of the technology to diverse contexts and technical requirements. In addition, additive manufacturing is not limited to polymers; there are additive technologies capable of printing components using metallic materials, composites, ceramics, and even biological tissues and food products.

From a sustainability and circularity standpoint, the adoption of additive manufacturing supports cleaner and more efficient production, acting as an enabler of the circular economy through its three Rs: reduce, reuse, and recycle [9]. Consequently, the integration of this technology into production processes fosters stronger alignment with the European Union's decarbonization and sustainability objectives, as well as with the United Nations Sustainable Development Goals (SDGs) [10].

1.1. Additive manufacturing as a smart specialisation strategy

The Regional Innovation Systems (RIS) approach has an important weight in the scientific debate regarding the uneven distribution of innovation, as well as the factors that influence knowledge creation and innovative capacity in different regions [11]. Additive

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

manufacturing fits perfectly within the framework of smart specialization (RIS3) of the European Union [12], a strategic approach that promotes the development of regional capabilities based on local strengths and competitive advantages. This concept drives innovation by identifying priority areas in which each region has the potential to create value. In the context of the European Union (EU) industrial policy, additive manufacturing is seen as a key tool to drive digital and green transformation, two fundamental pillars of the European Green Pact [13], contributing directly to these objectives, promoting energy efficiency, waste reduction and the use of sustainable materials and, in addition, it does not generally require a large infrastructure or high initial investments for its integration within the productive processes of companies.

1.2. Development of additive manufacturing in Spain and Portugal

These countries have identified additive manufacturing as a key technology for smart specialization and for enhancing their industrial competitiveness, particularly (though not exclusively) in regions with a strong orientation toward the automotive industry, such as Catalonia and the Basque Country in Spain, and the aerospace sector in other regions such as Andalusia and Madrid.

However, there exists a significant asymmetry in the assimilation of the benefits of 3D printing across regions, both in Spain and Portugal. For instance, in the region of Castilla y León, depopulation and the weakening of the industrial fabric represent critical challenges that are not experienced in the same way in other, more industrialized Spanish regions such as those mentioned above [14]. Moreover, the common market fosters cross-border collaboration with other countries, such as Portugal, with which Castilla y León and other bordering regions share the aforementioned challenges and a greater geographical proximity than other regions within the same country. For this reason, the implementation of 3D printing solutions in these regions of Spain and Portugal appears to be at a less advanced stage of development compared to other Spanish regions and to more industrialized regions of the European Union.

To address these disparities and to leverage the geographical proximity of both countries as well as European cohesion, various initiatives (such as the Naturfab project [15], funded under the Interreg-POCTEP call [16]) provide viable solutions. These initiatives apply smart specialization strategies to harness the endogenous resources of the Castilla y León region and the Northern region of Portugal to develop new materials and 3D printing processes that promote the circular economy.

2. - Methodology

First, the search criteria were established. To this end, companies related to additive manufacturing in any of its forms were prioritized, these being grouped into:

- Large company: A company that meets the following criteria established in European Commission Recommendation 2003/361/EC [17]: more than 250 employees, turnover of more than 50 €million, and an annual balance sheet of more than 43 million euros.
- Small and Medium-sized Enterprises (SME): Following the same criteria as the previous point, only on the contrary, micro, small, and medium-sized enterprises were considered in this section.
- Association: Associations and companies in the technological or business field were considered about additive manufacturing in any of its forms, provided that they have different legal forms from the previous two. Although these associations may not have a productive purpose, they are considered important agents for innovation in additive manufacturing, as a novel and disruptive technology that is amid technological consolidation [5-6].
- Sectoral federation or business grouping: Entities that group different companies or federated companies by sector were considered.
- Technology centre: It includes private or mixed R+D+i centres that undertake research or innovation tasks within the framework of additive manufacturing exclusively or as part of their catalogue of services and/or *capabilities*.

To set the criterion of zone of influence, the area established in the European Commission's interregional programme Interreg-POCTEP [16] was used, which determines the area of influence indicated in Figure 1.

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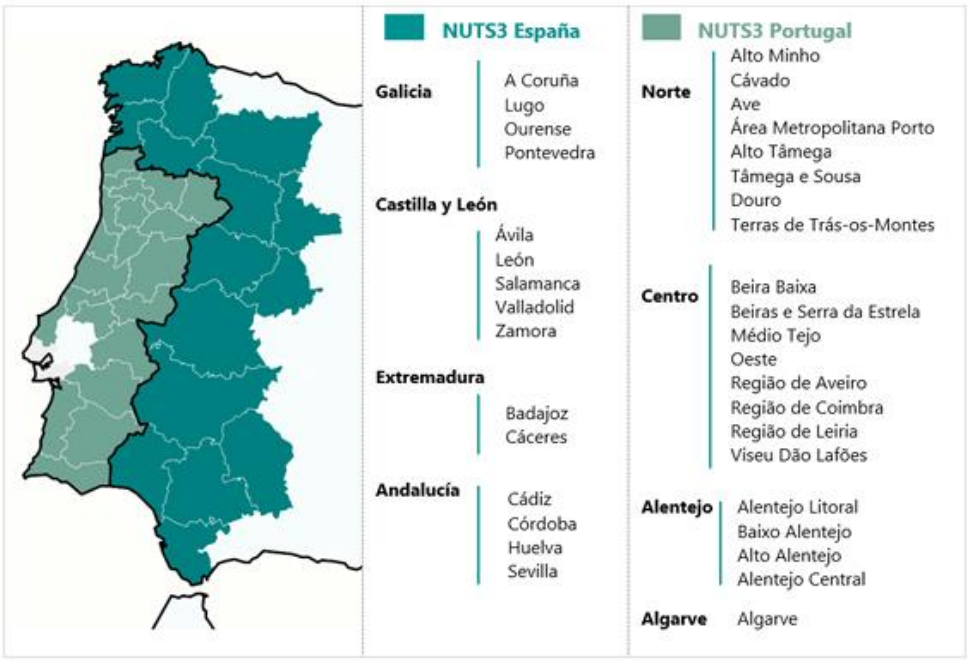

Figure 1: Cross-border area established as a geographical criterion for the analysis carried out. Retrieved from [16]

Regarding the objectives of the companies analysed, and considering the heterogeneity of applications and interests related to the supply of services and/or products in the field of additive manufacturing, it has focused on four types of companies whose objectives are defined in Table 1.

Tabla 1: Classification of companies by objectives used as a stratification criterion.

Type	Description
1	Technology consulting service providers that apply additive manufacturing as a technology in their workflows and/or provide their customers with solutions based on the value of this technology.
2	Companies that supply supplies for 3D printing, mainly material filaments, but also other material formats such as pellets and/or additional chemicals.
3	Companies that supply hardware in the field of additive manufacturing, mainly 3D printing machines and their components and elements, but also additional equipment for pre- and post-processing tasks (curing, filament drying, surface finishing, cleaning, heat treatment, machining, priming, testing, etc.)
4	Direct manufacturing service providers that use additive manufacturing in any form in accordance with ISO/ASTM 52900 [7] to manufacture parts on demand or in batches.

For the identification of relevant companies and the collection of information, an exhaustive and heuristic search was carried out, restricting the results by using the following sources of information (Figure 2):

- Companies and entities associated with ADDIMAT, the "Additive Manufacturing AFM Cluster" [18].
- Companies and entities participating in the conferences organized within the framework of the “Programa de Capacitación y Apoyo a la I+D+i Empresarial Centr@Tec” of the Agency for Business Innovation, Financing and Internationalization of Spain (ADE), in collaboration with Technology Centers of Castilla y León [19].
- Companies and entities participating in the cross-border 3D Printing workshop organized by NERBA in Bragança on April 11, 2024, in the context of the European Naturfab project [15].

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- Companies and entities adhered to FACYL, the "Automotive and Mobility Cluster of Castilla y León" [20].
- Orbis Europe Database. Bureau Van Dick with information from the Mercantile Registers of Spain and Portugal
- Other companies that are participating in conferences and conferences organized within the framework of the project.

Preference was also given to those companies located in the area of influence of the project, i.e. in the cross-border area between Castilla y León and the north of Portugal.

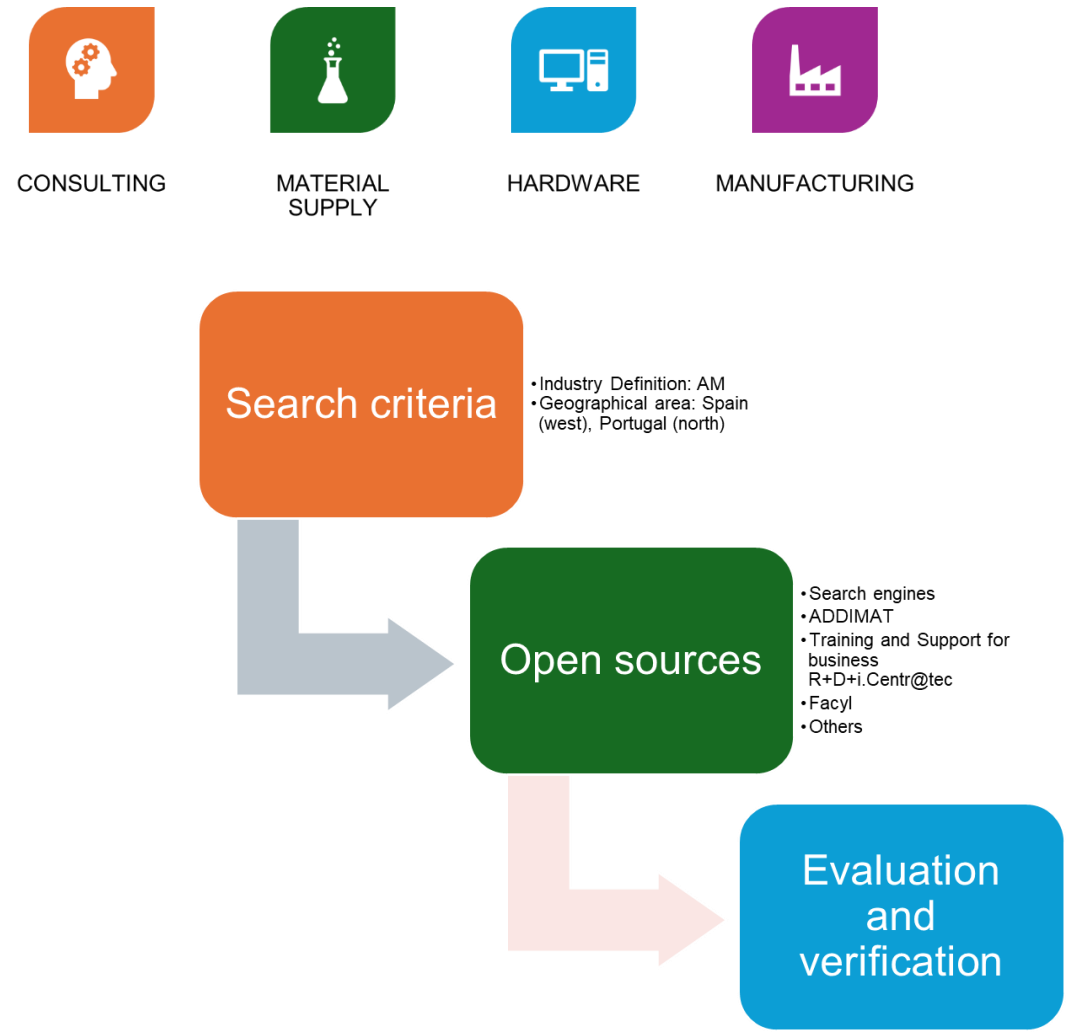

Figure 2: Process applied for searching for information based on open sources.

After collecting the data corresponding to the identified companies, a quantitative analysis was carried out based, firstly, on the calculation of absolute and relative frequencies for each of the previously established criteria, covering both the nature of the entities and their business objectives and, secondly, on the information on operating income and on the number of employees collected in the databases of the Commercial Registers of both countries.

The quantitative approach was complemented with a qualitative analysis based on the evaluation of aspects such as the services offered, the scope of the activities, the corporate objectives, using the corporate information of the entities analyzed, and the technologies used by the companies.

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4. - RESULTS

4.1. Quantitative analysis

Based on the search carried out and the established criteria (Figure 2), a total of 36 entities were located: 20 from Spain and 16 from Portugal (see Annex). Without being able to say that this sample is exhaustive, it can be said that rigorous criteria have been followed to guarantee the relationship between the business objectives and the subject matter of additive manufacturing. Of the 36 companies, it was possible to obtain complete information on operating income (turnover in USD) and on the number of employees (for the last year available in the database) for 25 of them.

Regarding the nature of the companies, it was possible to corroborate that Small and Medium-sized Enterprises (SMEs) are the main constituents of the industrial fabric in the field of additive manufacturing and account for 69.00% of the entities located (Figure 3). However, this percentage is slightly higher than the Spanish average (99.8%). It is worth noting the low representation of large companies, with 3.00% of the total (Figure 3). However, this figure is higher than the percentage of large companies in Spain in general terms (0.20% according to [21]).

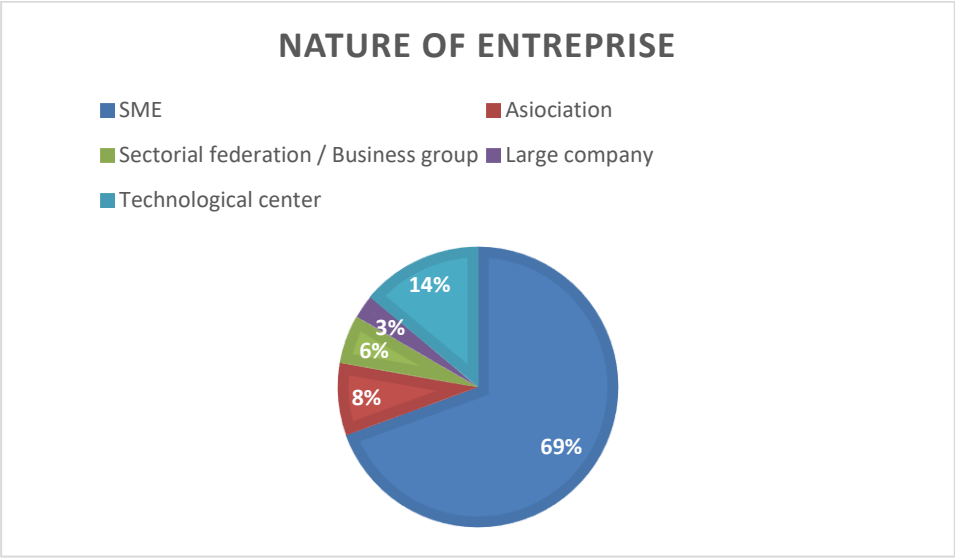

Figure 3: Classification of companies by nature of enterprise.

Applying a stratification by country (Figure 4), certain asymmetries were detected in terms of technology centres, which had a notably greater weight in Portugal (18.75%) compared to Spain (10.00%) and to associations (none found on the Portuguese side).

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

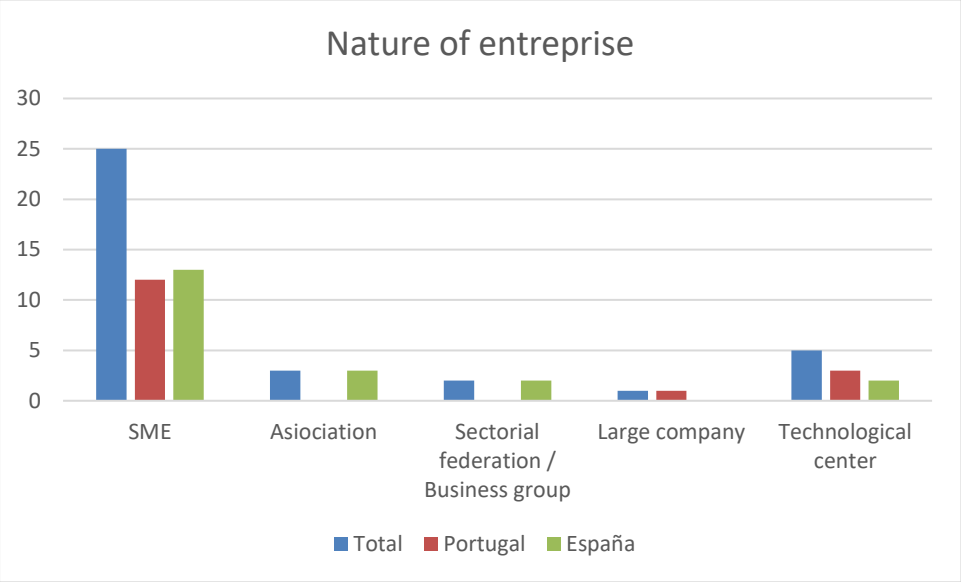

Figure 4: Classification by nature of companies. Stratification by country.

As can be seen in Figure 5, Type 1 companies were the ones with the highest absolute frequency, reaching 38.89% of the total. This was followed by Type 4 companies with a percentage of 25.00%, then Type 3 companies with a percentage of 19.44%, and finally Type 2 companies with 16.67%.

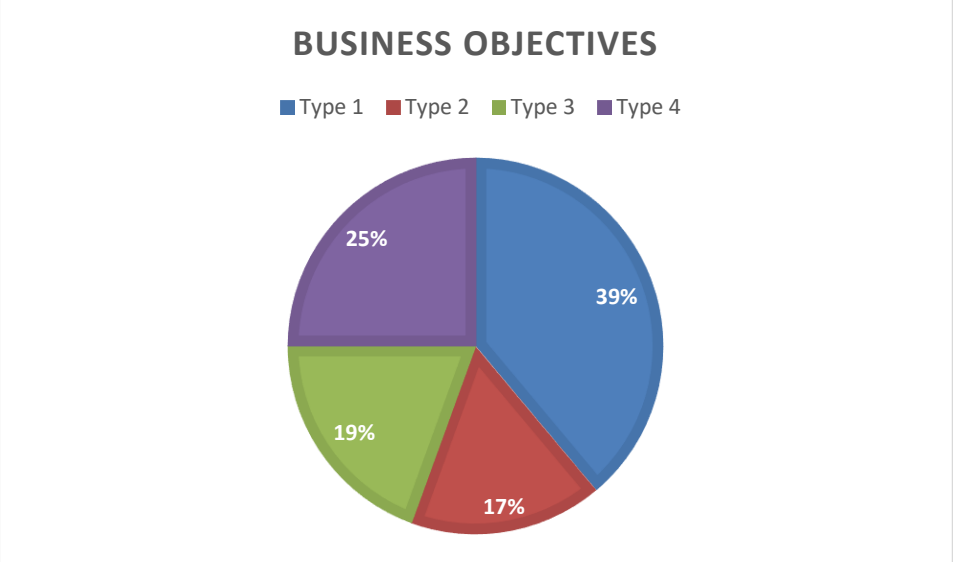

Figure 5: Classification by objectives of the companies. Stratification by objectives (see Table 1)

Applying a stratification by country and business objectives, it can be seen that the number of companies found in Spain (20) has been slightly higher than those located in Portugal (16) (Figure 6). However, a significant asymmetry has been detected in Type 4 companies. These companies were located to a greater extent in Portugal.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

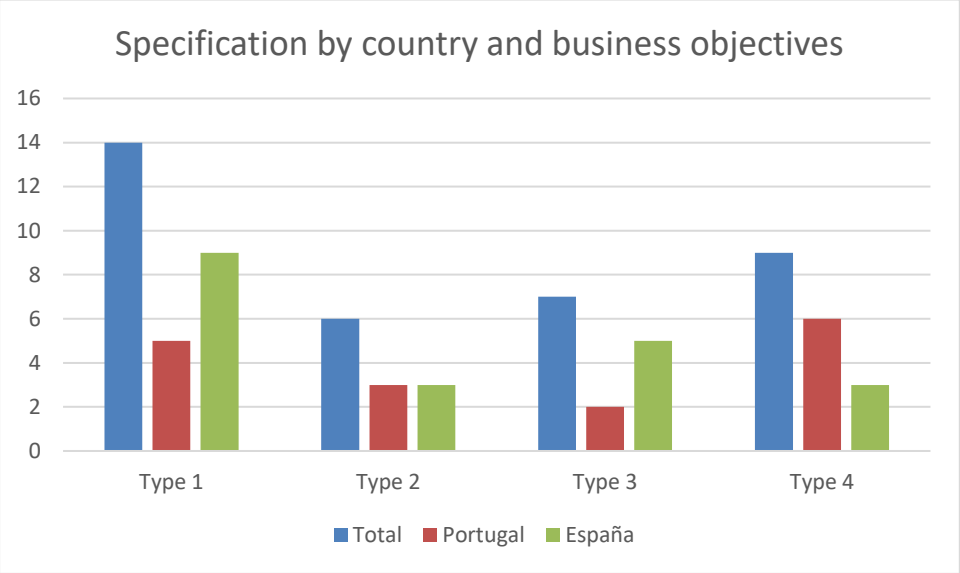

Figure 6: Classification by objectives of the companies. Stratification by objectives (see Table 1)

Regarding the analysis of the operating income results (Table 2), it can be seen that the highest sales figures correspond to the two large companies, both located on the Portuguese side. This generates a significant bias in the distribution of data and requires the use of robust statistics such as the median and interquartile range (IQR) to assess the central trend of the data and its variability. In general, if the effect of these two companies is discriminated, the operating income of the companies is slightly higher in Spain than on the Portuguese side, with a greater variability in the latter, even with the use of robust statistics. As for the statistics on the number of employees, the analysis proposed for operating income can be extended. In fact, both variables maintain a significative correlation (Figure 7).

Table 2: Statistics of operating income data (sales figure in thousand. USD) and the number of employees in the last year available.

	Statistic	Operating income one thousand (USD Last. year available).	No. employees
Total	Median	1001,31	6
	IQR	2298,23	23
España	Median	1001,31	5
	IQR	1220,09	11
Portugal	Median	834,35	7
	IQR	3546,66	35
Total	Mean	7649,35	36
	SD	19746,11	86
España	Mean	2493,61	20
	SD	4818,62	38
Portugal	Mean	12408,48	50
	SD	26597,28	114

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

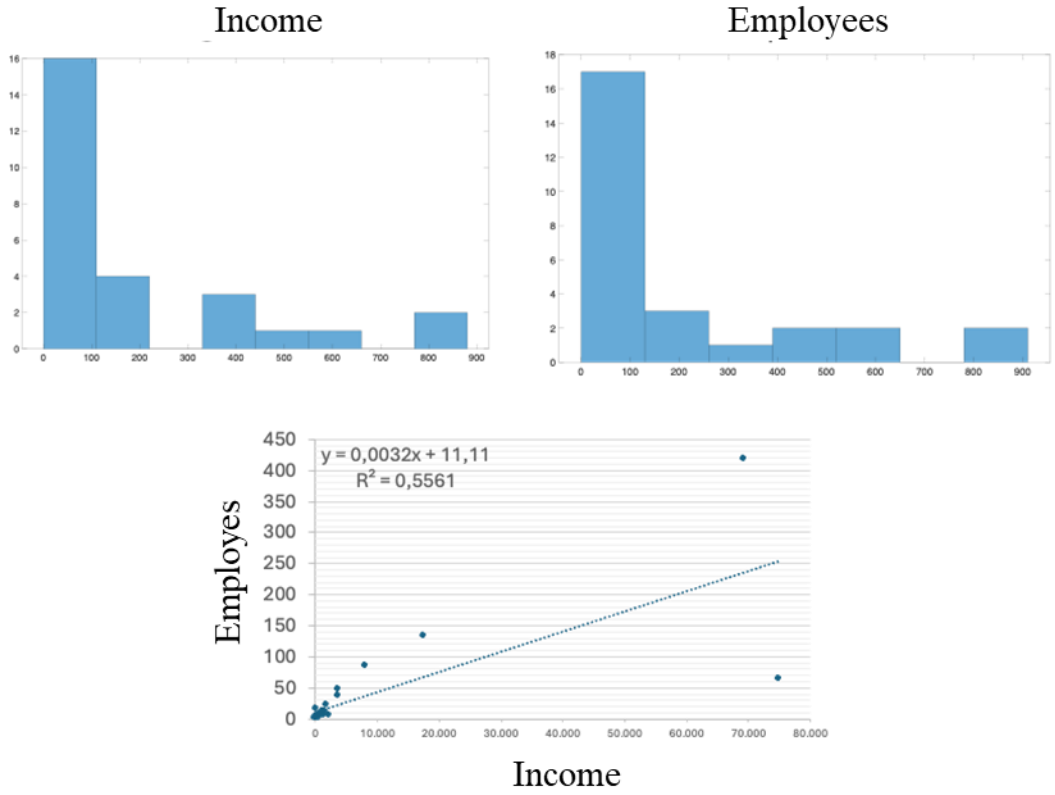

Figure 7: Distribution of the variables operating income and number of employees (top). Correlation diagram between both variables (bottom).

Once the variable "operating income" and the variable "employees" have been analysed individually, a breakdown is made by country and by type of company. As can be seen in Figure 9, a higher volume of SME revenues was located on the Portuguese side, while the situation was the opposite for technology centres. The same situation was maintained with respect to the variable "employees".

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

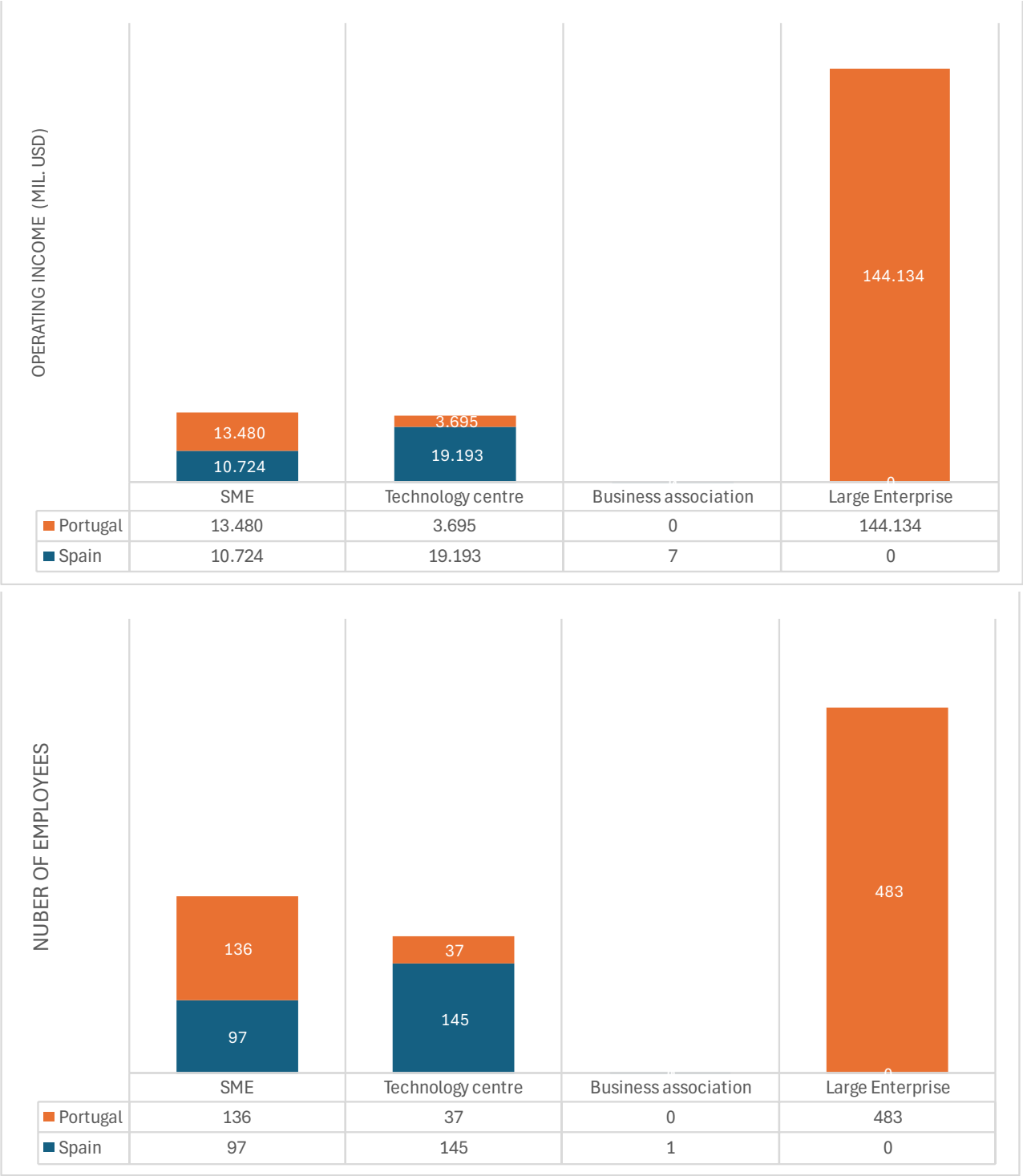

Figure 8: Disaggregation of data by country and type of company for the variable "operating income" (top) and for the variable "employees" (bottom).

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

4.2. Qualitative analysis

Two large companies have been located. One of them, Augusto Guimaraes & Irmao [22], located in Vila Nova de Gaia (Portugal), is a company that distributes industrial equipment and materials, mainly polymers and construction materials, such as facades and cladding. They also distribute 3D printing supplies and machines, mainly with Fused Deposition Modeling (FDM) technology, although they also offer solutions based on other technologies, some of them with high added value. Given its experience in the sector, this company could have expectations of scalability in the field of additive manufacturing towards advanced materials, such as biopolymers or recycled polymers. It could also expand into the distribution of equipment for more complex and differentiating additive technologies that could cover advanced materials, such as high-performance alloys compatible with biomedical uses.

On the other hand, Critical Manufacturing [23], based in Maia (Portugal), offers consulting and equipment in special industries such as the semiconductor industry, medical services, and other high-tech industrial equipment. In addition, it offers Industry 4.0-based systems to optimize manufacturing processes. It is worth noting the fact that the largest companies offering 3D printing services have been located on the Portuguese side. Critical Manufacturing, aligned with the paradigms of Industry 4.0 and 5.0, is well positioned to play a fundamental role in the optimization of all types of industrial processes. In this context, it is foreseeable that consulting companies such as this one will become increasingly important, facilitating the integration of additive manufacturing into the workflows of various industries.

From the perspective of SMEs, a prominent example is Nagami Design [24], a company based in Ávila, Spain, whose uniqueness lies in the innovative use of large-format additive manufacturing for the creation of sustainable furniture and ornaments. Beyond design, its focus on recyclable materials and its participation in R+D+i projects reinforce its model of success. The technology developed and used by this type of company, as well as the know-how necessary to work outside conventional standards, is high, representing a competitive advantage and a barrier to entry into the sector, which means that very few companies in the world can offer these services. A company of this type has very high scalability potential for its technology, given that large-format additive manufacturing allows high flexibility and diversification in terms of the possible products to be manufactured, and can even move from the most ornamental and design field to the development of functional structures based on engineering materials.

In Portugal, X3D [25], located in Leiria, specializes in reverse engineering and additive manufacturing for key sectors such as automotive, aeronautics, and medicine. Its 3D digitization, CAD design, and metrology capabilities optimize industrial processes, benefiting from the strong local automotive industry. These types of companies that provide highly specialized and widely differentiated equipment, both for additive manufacturing (e.g. SLS printers, multijet, etc.) and for metrology and reverse engineering (3D scanners by structured light, photogrammetry, etc.), have significant growth potential. As Industry 4.0 integration progresses, technologies such as additive manufacturing and reverse engineering will play a key role in the digital transformation of the industrial sector [5-6].

On the other hand, AENIUM Engineering [26], based in Valladolid (Spain), stands out for its high specialization in additive manufacturing with metals by selective laser fusion, combining advanced technology with advice and quality tests. This additive technology requires a high investment in capital goods, which makes it possible to differentiate and create barriers to entry. Its location in Castilla y León, a region affected by deindustrialisation, shows how innovation can revitalise the productive fabric. In addition, metal 3D printing is one of the fastest-growing areas of research, so it is expected that the technologies associated with the additive manufacturing of high-performance metals (mainly in the additive manufacturing technology called Selective Laser Fusion, SLM) will tend to be progressively democratized and cheapened. At the same time, the performance of the final products is increasingly advanced, improving in terms of resistance, biocompatibility, etc.

In the aerospace sector, CiTD Engineering [27], based in Seville (Spain), is highly specialized in manufacturing consulting at the aerospace level and collaborates with high-level clients such as Airbus. Its focus on additive manufacturing of flying parts, both in high-performance polymers and in metals for defense and aeronautics, demonstrates the enormous potential of additive manufacturing in highly specialized niches, where a significant evolution is expected. This sector is strategic at the European level, not only because of its relevance in commercial aviation, but also in defense and space engineering. However, this type of sector has very high barriers to entry, both in terms of specialized know-how, the technology to be used, and the strict regulation of the sector.

In contrast, 3DLAC [28] based in Benavente (Spain) presents an opposite case to the previous one, insofar as its product is aimed at a general public and has emerged in a poorly industrialized and depopulated environment. The company has found a very specific niche with the manufacture of lacquers for adhesion in 3D printing, showing how innovation can thrive outside the large industrial centers and in small urban centers without the category of provincial capital. It is also an example of the development of a basic but necessary product in additive manufacturing processes, despite its crucial added value in FDM additive manufacturing technology, which is the most widely used at the user and enterprise level for parts that do not require high performance.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

Finally, in the field of materials, Filament2Print (Pontevedra-Spain) [29] and León 3D (León) [30] have consolidated their position in the distribution of advanced filaments, while AGI in Portugal complements the sector with specialized supplies and equipment. For this type of company, the development of new polymer and composite materials (mainly for FDM), both on the functionality and sustainability side, will be able to boost their growth and competitiveness.

Together, these companies demonstrate that success in additive manufacturing depends not only on technological disruption but on continuous improvement and strategic adaptation. The geographical decentralization of the sector highlights a key message: talent and specialization are more determining factors than location.

4. - CONCLUSIONS

Based on the qualitative analysis carried out, the relevance of additive manufacturing transcends the merely manufacturing field, as it allows the design and production of customized components that respond to the specific needs of various sectors, even those less technical. In this context, the potential of additive manufacturing is not only limited to technical improvements but also responds to a growing demand for sustainability, aligning with the principles of Industry 4.0 and 5.0. In addition, the integration of this technology within the production process improves both digitalisation and sustainability and the transition to the circular economy [31].

However, the adoption of additive manufacturing presents significant inequalities from a geographical point of view. There is a significant regional imbalance in terms of its implementation, with a greater concentration of companies and resources in highly industrialized areas, while less developed regions, such as the areas bordering the border area between Spain and Portugal, its implementation faces limitations and suffers significant barriers to entry, both due to the improvable dynamization of the industrial fabric, and by the distance to potential customers to whom added value can be given.

Despite these limitations, this regional inequality reflects a structural challenge, but also an opportunity, since the potential of this technology to revitalize less industrialized areas through the decentralization of manufacturing processes is undeniable and can be a strategic factor for growth because, on the one hand, it allows autonomy and self-sufficiency in terms of manufacturing without depending on connections or transport with more industrialized areas within the supply chain and, on the other hand, a large part of the materials could be generated from endogenous resources of these regions promoting sustainability and local development, as is currently being researched [15].

The business fabric that adopts this technology in Spain and Portugal is mainly composed of SMEs, followed by technology centers: SMEs on the Portuguese side and technology centers on the Spanish side achieved higher operating income. However, the provided data are only indicative as it is not possible to access all the data of all companies

SMEs represent the bulk of the additive manufacturing sector, and their predominance indicates that this technology has been especially attractive for medium- and small-sized companies, which tend to have greater flexibility to adapt to new processes, although they also suffer significant limitations in economic terms, and access to high-value-added technology.

In contrast, large companies have limited representation in the sector, although higher than the Spanish average. In terms of diversification, there are differences in the type of companies involved in the additive manufacturing sector between the two countries. In the area of Portugal, companies supplying printing materials predominate, which responds to a specific demand and reinforces the importance of the supply of materials in the development of this technology. In the western part of Spain, consultancies and service providers related to additive manufacturing make up the majority group. This diversity between countries highlights the heterogeneity of the sector and highlights the opportunity for cross-border collaboration to capitalize on the strengths of each region and take advantage of synergies and complementarities between companies on both sides of the border to promote Industry 4.0 and 5.0, which would also benefit greatly from incentive policies and improvements in technological infrastructure. The integration of sustainability into additive manufacturing processes is another important element. Companies, such as Nagami Design, have incorporated recyclable materials and large-format printing technologies, making it possible to respond to the growing demand for sustainable solutions in industrial production. AENIUM Engineering stands out for its innovation in advanced processes such as selective laser sintering and selective laser fusion, techniques that open up new possibilities in the design of functional components. These companies demonstrate that success in the field of additive manufacturing is not limited to disruptive innovation but also depends on continuous improvement and the gradual adoption of new technologies that allow the sector to grow exponentially. Despite the aforementioned advantages, additive manufacturing faces significant challenges, such as limitations in production size.

Additive manufacturing continues to evolve [5-6], adapting to changes in market demand and positioning itself as a technology with great potential for expansion in the industrial sector. In conclusion, additive manufacturing in western Spain and northern Portugal is in a growth phase, with possibilities for synergy between companies and, in certain sectors, also for consolidation, characterized by constant growth and a series of challenges and opportunities that will shape its future. Its uneven development at the European level

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

between more and less industrialised regions represents a challenge, but it also opens the door to collaborative initiatives that encourage more equitable adoption and facilitate the creation of collaboration frameworks.

However, in order to reach its full potential, it will be necessary to overcome the current technical barriers and promote greater integration of this technology into the industrial fabric through close collaboration between companies, research centres and public administrations. This will include incentives through subsidies and aid for R+D+i.

The results obtained in the study suggest that additive manufacturing is emerging as a strategic sector in the cross-border region of Spain and Portugal, aligning with the dynamics of smart specialization [11]. In this context, it not only represents a technological advance, but also a strategic tool to promote the development of deindustrialised, depopulated regions with communication barriers with respect to large industrial centres, such as the north of Portugal and the region of Castilla y León.

Finally, even though rigorous search criteria have been established that are coherent and in line with the objectives of the work, the use of open sources implies that some relevant organizations that take value from 3D printing in the cross-border area may not have been included, suggesting the need for broader and more detailed studies in the future.

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ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX