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Assessing the impact of high-performance computing on digital transformation: benefits, challenges, and size-dependent differences

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Abstract

High-performance computing (HPC) plays a crucial role in accelerating digital transformation, yet there is a lack of studies that systematically characterize its impact across different company sizes. This study addresses this gap by analyzing a cross-sectoral panel of 294 Portuguese companies, comprising 103 large enterprises and 191 small- and medium-sized enterprises (SMEs). It was applied descriptive analysis and statistical hypothesis testing methods. Two key research questions guide this investigation. The first explores the primary benefits and challenges associated with HPC adoption, while the second examines whether these factors vary between large companies and SMEs. The findings indicate that the benefits and challenges of the HPC are heterogeneously perceived by large companies and SMEs. It identified significant differences in the perceived benefits and challenges of HPC, particularly concerning cost savings, decision-making, cost and skills management, lack of awareness, and workforce skills gap. These findings contribute to a deeper understanding of how HPC supports digitalization processes, highlighting sector-specific and size-dependent differences in its perceived value and implementation barriers. This study provides valuable insights for businesses, policymakers, and researchers seeking to optimize HPC strategies for digital transformation.

Keywords Digital transformation · Supercomputing · Innovation · Resource-based view

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1 Introduction

Over the past few years, significant advances have been made in information, communication, and connectivity technologies that have enabled new functionalities to emerge. Technologies such as sensors, clouds, robotics, automation, and mobile have witnessed a huge increase in the amount of digital information available [8, 73]. A company's digital transformation consists of creating new business models, processes, software, and systems based on technologies [23]. The same author suggests that a digitally transformed process involves changing the way the organization operates by integrating new technologies into various areas of business operation. Despite the focus on new technologies, Kraus et al. [43] point out that digital transformation is not only integrating technologies, but it is also support in a company's ability to achieve better performance using various technologies. Therefore, we define business digital transformation as the technology-driven strategy and process a business undertakes to break down barriers between people and businesses when rebranding or creating new products, services, or procedures. Accelerating this process is crucial to ensure the survival and growth of companies in a highly competitive and dynamic environment. Rapid technological evolution requires an agile response to avoid obsolescence and loss of market relevance. Browder et al. [12] and Codara & Sgobbi [17] reported digital transformation to enhance business resilience, allowing greater flexibility in the face of crises and unexpected changes. In this way, companies that invest early in digitalization become better positioned to capture opportunities, improve productivity, and create sustainable value in the long term.

High-Performance Computing (HPC) refers to the use of supercomputers and parallel processing techniques to solve complex computational problems that require significant processing power. HPC is essential for solving complex problems and processing large volumes of data at high speed. Its impact spans several areas, from scientific research to industrial sectors, enabling advanced simulations, predictive modeling, and process optimization [16, 36, 40]. Furthermore, Chia [15] points out that HPC plays a central role in innovation, as it makes it possible to solve complex problems and drive advances in various areas of knowledge and industry. HPC's massive processing capacity enables simulations and computational modeling that would be unfeasible with conventional computers. In the context of digital transformation, HPC acts as an accelerator by providing the computing power needed to deal with emerging technological challenges, while also facilitating the integration of technologies such as IoT and cloud computing [69]. Data from GVR [32] indicate that in 2022, its market value was estimated at USD 48.51 billion and is projected to grow at a compound annual growth rate (CAGR) of 7.5% between 2023 and 2030. Recognizing its strategic importance, the European Union has made significant investments in HPC infrastructure, particularly through the European High-Performance Computing Joint Undertaking [24]. This initiative may have a critical role in ensuring that HPC benefits not only research but also European industries.

Currently, most studies on HPC focus on its impact on large companies, especially those operating in highly data-intensive sectors such as the aerospace, pharmaceutical, financial, and automotive industries [51, 62, 66]. The role of HPC in large companies is associated with gains in efficiency and competitiveness, making it possible to reduce the time needed for research and development. However, its emerging potential in small- and medium-sized enterprises (SMEs) is becoming increasingly evident. With the increasing availability of HPC in the cloud and models such as HPC-as-a-Service, SMEs can now access advanced computing capabilities without the need for large investments in their infrastructure [9, 50]. Therefore, the democratization of HPC is intended to represent a significant change in the digital transformation of SMEs, allowing them to compete with large companies and drive innovation in their markets. However, there are very few studies linking the impact of HPC adoption on organizations' digitalization processes. Existing studies have sought to explore this phenomenon from the specific perspective of sectors of activity such as the energy transition for the nuclear industry [22] or the development of green digital marketing [58]. There is a lack of studies to characterize the phenomenon, considering the support that HPC can give to digitalization processes from a cross-sectoral perspective, and also to assess its distinctive potential for large companies and SMEs. In this sense, this study aims to respond to this research gap by considering a cross-sectoral panel of 294 Portuguese companies, including 103 large companies and 191 SMEs. To achieve this purpose, two research objectives are explored.

RQ1 Characterize the main benefits and challenges of using HPC by companies in Portugal.

RQ2 Analyze whether these benefits and challenges of HPC during the digitalization process are similar or different between large companies and SMEs.

2 Theoretical framework

Digitalization can be explored from various theoretical perspectives, each offering a specific view of its impacts, dynamics, and challenges. The Resource-Based View (RBV) theory helps to understand how companies develop competitive advantages from the adoption of digital technologies [63]. The Platform-Based View analyzes how digital ecosystems create value and promote innovation [11]. The Diffusion of Innovation (DOI) explains how new technologies are adopted and disseminated in society and organizations [20]. Sociotechnical Systems Theory (SST) investigates the interaction between technology, people, and processes in digitalization [76]. It is recognized that HPC can be explored from different theoretical perspectives, depending on the focus of the study. This study adopted the RBV theory because it triangulates the uses of valuable, rare, imperfectly imitable, and non-substitutable resources such as HPC and digital technologies. These characteristics make the RBV theory the most suitable for exploring the benefits of HPC in companies, and analyzing how advanced computing infrastructure can generate competitive advantage. Unlike the Diffusion of Innovation theory that explains the adoption of new technologies in the organization, the Sociotechnical System theory which illustrates technology, people, and process interaction, and the Platform-Based View narrowly discusses digital ecosystem value creation through innovation, the major advantage of the RBV theory is the emphasizes that tangible resources, such as high-performance hardware, and intangible resources, such as expertise in parallel computing and advanced algorithms, can differentiate a company in the market [33]. The theoretical nuance of RBV lies in its application by organizations during digital transformation projects to enhance an organization's ability to integrate and effectively use new technological resources to transform and directly impact its operational efficiency, innovation, and data-driven decision-making capabilities [30, 34]. RBV allows organizations to gain a competitive advantage through digital transformation [18, 47, 65]. These factors, therefore, help to explain why some organizations can get more value from this investment than others. Figure 1 illustrates the theoretical framework of RBV.

RBV uses the VRIO model to assess whether a resource can generate sustainable competitive advantage, analyzing four essential criteria. The first is "Valuable," which verifies whether the resource allows the company to exploit opportunities or neutralize threats, increasing its efficiency or differentiation in the market. The second criterion is "Rare," which considers whether the resource is scarce and not widely available to competitors, giving the company exclusivity. The third aspect is "Imitability," which assesses the degree of difficulty or cost for competitors to replicate or acquire the same resource, whether due to technological barriers, tacit knowledge, or intellectual property rights. The last criterion is "Organization," which examines whether the company is structured appropriately to capture and maximize the benefits of the resource, ensuring that it is fully used in its strategy.

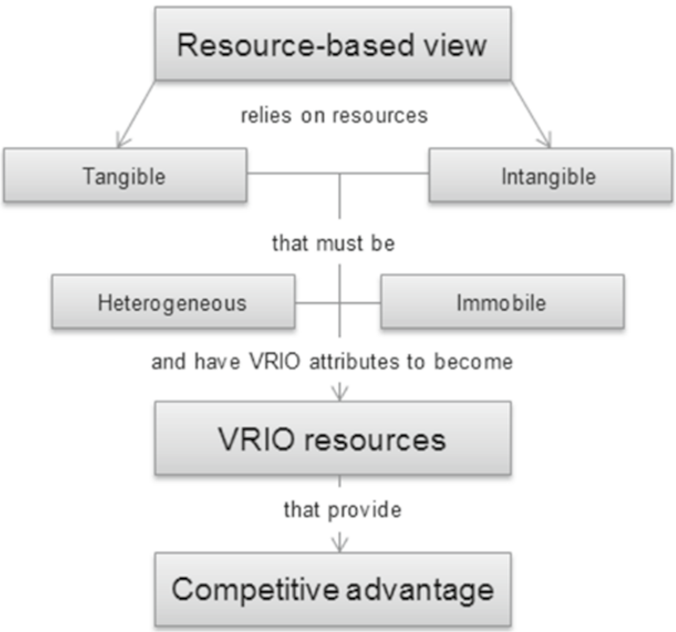

Fig. 1 RBV theoretical framework

The “valuable” component of the VRIO model can be exploited to identify the benefits of High-Performance Computing (HPC) by analyzing how this technology contributes to innovation and the competitiveness of companies. The literature reports several examples of the impact of HPC adoption in different areas such as construction and engineering services in terms of Building Information Modeling, Architectural simulation of buildings [2], Medical systems, and healthcare services during the COVID-19 pandemic, using HPC for machine learning methods on diagnosis and prognosis to create a transparent reporting of multivariable prediction model for individuals—TRIPOD [6], biotechnology [14], and finance [29], with all studies revealing that leveraging HPC in their operations enhanced their project outcomes. Following these outcomes, an analysis of the value of HPC can, therefore, be conducted by assessing its contribution to improving operational performance, creating new business opportunities, and strengthening the company’s strategic position in the market.

The “organization” component can be explored to identify the challenges of HPC adoption by analyzing whether the company is prepared to capture and maximize the benefits of this technology. One of the main challenges is the organizational capacity for integration since adopting HPC requires structural changes, such as adapting the IT infrastructure, adapting internal processes, and reconfiguring workflows to take advantage of the computing power available [60]. Moreover, the lack of specialized skills in working with high technology represents a significant barrier, since the efficient use of HPC requires qualified professionals [26]. Another obstacle lies in change management and organizational acceptance as recognized by Hubbart [35], considering that the introduction of HPC may face resistance from employees.

This study considers that the “rare” and “imitable” components of the VRIO model are not as relevant to exploring the benefits and challenges of HPC adoption because this technology is neither inherently scarce nor difficult to imitate. HPC is widely available to companies in different sectors and can be accessed through cloud services, which reduces its rarity as a competitive resource [68]. Furthermore, even if an organization implements an advanced HPC system, its competitors can adopt similar solutions, making imitation relatively accessible, especially with the democratization of cloud computing. In this way, the benefits of HPC for companies stem more from its capacity for efficient use and its strategic integration, rather than its exclusivity or difficulty of reproduction. Therefore, to explore the benefits and challenges of HPC adoption, it makes more sense to focus on the dimensions of value (how HPC generates advantages) and organization (how the company can structure itself to maximize its impact).

Finally, Table 1 summarizes the benefits and challenges of using HPC by giving a brief explanation of their relevance and presenting the main authors who support each of them. The benefits include enhanced competitiveness through faster production processes and cost reduction, improved computing performance that enables high-speed data processing, and cost savings by optimizing resource utilization. HPC also supports data-driven decision-making and fosters technological innovation by enabling advanced research and testing. On the other hand, the challenges of adopting HPC include the complexity of system management, which requires specialized expertise, and limited accessibility due to barriers in resource availability.

Table 1 Benefits and challenges associated with HPC

Variable	Authors	Description
Benefits		
Competitiveness (CMP)	Lee & Lee [45] Tomašević et al. [72]	Obtaining competitive advantages by speeding up production processes and reducing operating costs
Computing Performance (CP)	Dakić et al. [19] Flanagan et al. [27] Li et al. [46]	Processing large volumes of data at high speed, significantly reducing the time needed to run simulations
Cost Saving (CS)	Mauch et al. [56]	Reduces operational costs by optimizing resources and improving productivity
Decision-Making (DM)	Sharma et al. [67] Tomašević et al. [72]	It promotes data-driven decision-making
Technological Innovation (TI)	Flanagan et al. [27] Thottempudi et al. [71]	Drives innovation by enabling advanced research and testing of complex solutions before practical implementation
Challenges		
Complex System Management (CSM)	Lynn [52] Massari et al. [55]	Needs specialized knowledge for operating
Limited Accessibility (LA)	Lynn [52] Michels et al. [57]	There are significant barriers to accessing HPC resources
Security Risks (SR)	Bulusu et al. [13] Debnath & Xie [21] Lynn et al. [51]	Large-scale data processing increases exposure to cyber threats and vulnerabilities
Software Compatibility (SC)	Gamblin & Katz [28] Navaux et al. [60]	Applications may require modifications to run efficiently on HPC systems
Workforce Skills Gap (WSG)	Alexandrov [4] Filinger et al. [26]	Requires trained professionals with specialized expertise

Security risks are also a concern, as large-scale data processing increases exposure to cyber threats. Additionally, software compatibility issues may require modifications to applications, and there is a workforce skill gap due to the need for trained professionals with specialized knowledge.

3 Methodology

This study aims to identify the benefits and challenges of adopting HPC in the context of digital transformation projects. To this end, a quantitative approach has been adopted, which aims to identify the relevance of each of the variables and is complemented by a comparative analysis of their impact considering the context of SMEs and large organizations. The use of quantitative methods makes it possible to statistically evaluate the benefits and challenges of adopting High-Performance Computing (HPC) in digital transformation projects [44]. This makes it easier to identify the most relevant variables and their relationship with the success or difficulties in implementing HPC. The distinction between SMEs and large organizations is essential, as these types of companies face different challenges in terms of resources, infrastructure, and technological adoption. The quantitative approach enables a robust comparative analysis, allowing us to check whether the differences are statistically significant [3, 53]. Finally, the collection and analysis of quantitative data allows for broader inferences, increasing the applicability of the results to different sectors and types of companies [48]. This contributes to the formulation of guidelines and best practices in the adoption of HPC.

A survey instrument was developed to create a customized questionnaire that meets the study's needs. The survey instrument adopts a Likert scale of five values from not important (1) to very important (5). As a result, three preliminary questions were formulated based on this review to evaluate the current status of implementing the HPC. These questions include:

Q1 Have you ever used HPC in your business?
Q2 Do you have any ongoing projects that require HPC?
Q3 Do you have any future plans to use HPC?

Figure 2 presents a line diagram of the phases of the methodological process. The survey was administered between September and December 2024 and was distributed to companies operating in Portugal and registered on Informa DB. It is a widely used business database in Portugal, which provides detailed information on companies and economic activities. It is developed by Informa D&B, a company specializing in business intelligence and risk management solutions. The recipients of the survey were the companies' Chief Technology Officers (CTOs). A total of 1258 companies were contacted by email, of which 76 emails were rejected due to company closure or relocation to other countries. Therefore, 1182 contacts were considered valid. A reminder email to respond to the survey was sent 15 days before the deadline. A total of 294 companies took part in this study after removing missing responses, which corresponds to a response rate of 23.37%. The distribution of responses was homogeneous throughout the period during which the questionnaire

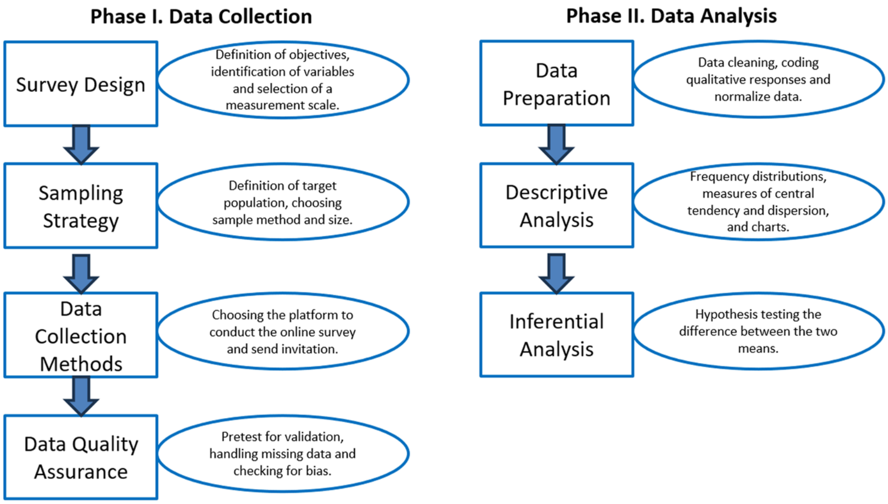

Fig. 2 Phases of the methodological process

was open, and there was no bias due to a greater number of responses at the beginning or end of the deadline. Furthermore, a pretest was performed considering 12 companies (six large companies and six SMEs) to get feedback regarding the reliability of the survey.

Table 2 characterizes the profile of the companies that took part in the study in terms of their size, industry, and company age. Data regarding the identification of the companies (i.e., name and location) were removed to ensure anonymization to comply with GDPR. The characterizations were done and presented using absolute frequency (AF), relative frequency (RF), cumulative absolute frequency

Table 2 Profile of the companies

Variable	AF	RF	CAF	CRF
Size				
Large Companies	103	0.3503	103	0.3503
SMEs	191	0.6497	294	1
Industry				
Energy	33	0.1122	33	0.1122
Financials	27	0.0918	60	0.2040
Healthcare	55	0.1871	115	0.3911
Information Technology	84	0.2857	199	0.6768
Others	95	0.3231	294	1
Company Age				
Less than 5	61	0.2075	61	0.2075
Between 5 and 10	70	0.2381	131	0.4456
Between 10 and 20	78	0.2653	209	0.7109
More than 20	85	0.2891	294	1

(CAF), and cumulative relative frequency (CRF) offering a robust analysis and interpretation of respondent profiles, leading to a deeper strategic insight for effective planning. Significantly, most companies participating in the study are Small and Medium Enterprises (SMEs), indicating that SMEs are the dominant companies in Portugal according to the Informa DB. The sector with the largest number of companies is information technology (28.57%), healthcare (18.71%), energy (11.22%), and finance (9.18%), while the manufacturing, construction, agriculture, and other industries were captured under others returning a relative frequency of (32.31%). Examining the company's age of operation, we discovered a unique case of a fairly age-homogeneous, with none of the individual classes representing more than 30% of the sample. This suggests that the companies had a balanced mix but diversified experience level which affected how they perceived, adopted, and used HPC to drive transformation, workplace dynamics to digital transformation, benefits yield, and overall company performance.

The survey data were then loaded into IBM SPSS software v.27 for statistical analysis. Two methods were applied: descriptive analysis and hypothesis testing the difference between the two means. Descriptive analysis helps to gain an initial overview of the profile of the companies and enables trends to be identified and any anomalies to be identified [1, 75]. Furthermore, the hypothesis test of the difference between the two averages allows us to confirm whether the differences observed between large companies and SMEs are significant. A significant level of 5% was adopted.

4 Results and discussion

We started by examining preliminary questions 1, 2, and 3 using data on the historical, current, and future states of HPC implementation within the participating organizations. We measured if a company has ever used HPC in business, if they have any ongoing projects that require HPC, and if they have future plans to use HPC. The outcome presented in Table 3 reveals more than 62% of respondents, indicating that 183 companies had not used or developed any initiative to implement HPC in their organizations, which confirms the findings of Kljajic Borstnar and Ilijas [41] who reported HPC adoption by SMEs to be scarce and less visible due to the difficulties of SMEs in adopting this technology. Further analysis of the data reveals that more than 65% of respondents, representing 192 companies, indicated that they do not currently have any projects that require HPC. This finding is supported by the empirical findings of Grandi et al. [31], which indicate that most European SMEs do not participate in projects requiring HPC. Consequently, this lack of engagement hinders the development of HPC initiatives for SMEs by the European Union. However, when it comes to future initiatives, the scenario is different, 50% of the respondents representing 147 companies indicated their future intention to use HPC in their business digitalization process. This indicator is higher than the number of negative responses of 131 companies making up 44% of the sample size. This significant flip indicates that both SMEs and large companies currently were developing plans to use HPC to support their digitalization process. This finding reflects that

Table 3 State of the HPC implementation

Variable	AF	RF	CAF	CRF
Have you ever used HPC in your business?				
Yes	78	0.2653	78	0.2653
No	183	0.6224	261	0.8877
Not answered	33	0.1122	294	1
Do you have any ongoing projects that require HPC?				
Yes	91	0.3095	91	0.3095
No	192	0.6531	283	0.9626
Not answered	11	0.0374	294	1
Do you have any future plans to use HPC?				
Yes	147	0.5000	147	0.5000
No	131	0.4456	278	0.9456
Not answered	16	0.0544	294	1

of Botelho and O'Gorman [10] whose study reported most European SMEs specifically those in the Southeast region of Ireland to be incipient in usage and knowledge of HPC to support the digitalization process. Furthermore, Atanassov et al. [5] reported that Bulgarian SMEs have recently increased their interest in building interest in the adoption and usage of HPC to support the digital transformation process of their operations. According to this result, we can infer that Portuguese SMEs are currently building competencies to adopt HPC to support the digitalization process supporting the findings of Narasimhamurthy et al. [59] whose study reported the growth in European SMEs' increased willingness to adopt HPC to increase business competitiveness.

4.1 RQ1. Characterize the main benefits and challenges of using HPC by companies in Portugal

Figures 3 and 4 visualize data from respondents answering RQ1 by identifying and characterizing the benefits and challenges of implementing HPC in organizations. Results indicate that CP and TI are the two main benefits associated with HPC by the respondents, with an average of over 4.5. On the other hand, CS only has an average value of 3.38, which indicates that this benefit is less important. The results confirm the data obtained by Kagita et al. [38] and Limet et al. [49] who recognize the role of HPC in dealing with large volumes of data and solving computationally intensive problems. Investment in HPC is also perceived by organizations as a strategic investment that makes it possible to sustain innovation in the long term, exploring areas highlighted by Resch [64] such as artificial intelligence and machine learning. The results also suggest that HPC is not seen primarily as a cost-saving tool, but as an investment that generates indirect returns. A unique explanation for this might be that HPC infrastructure involves high acquisition, implementation, and maintenance costs, but this situation is strongly mitigated by national and European-scale HPC access projects [7, 59, 74]. These collaborative access networks can be

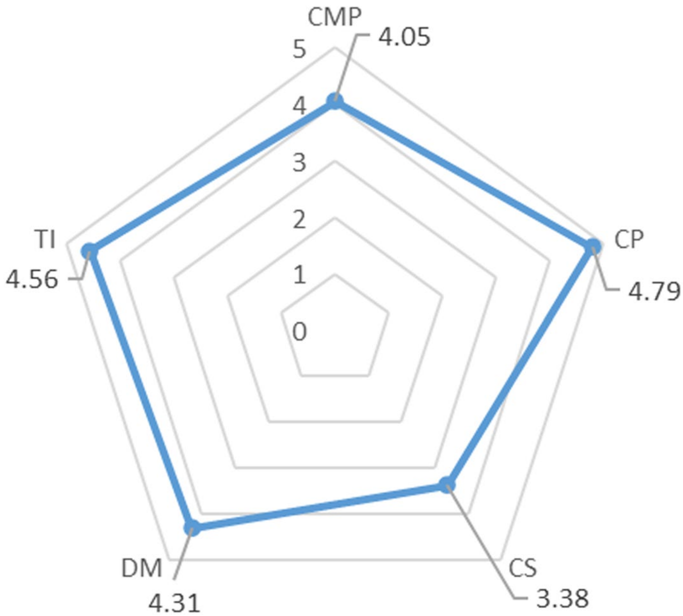

Fig. 3 Benefits of HPC

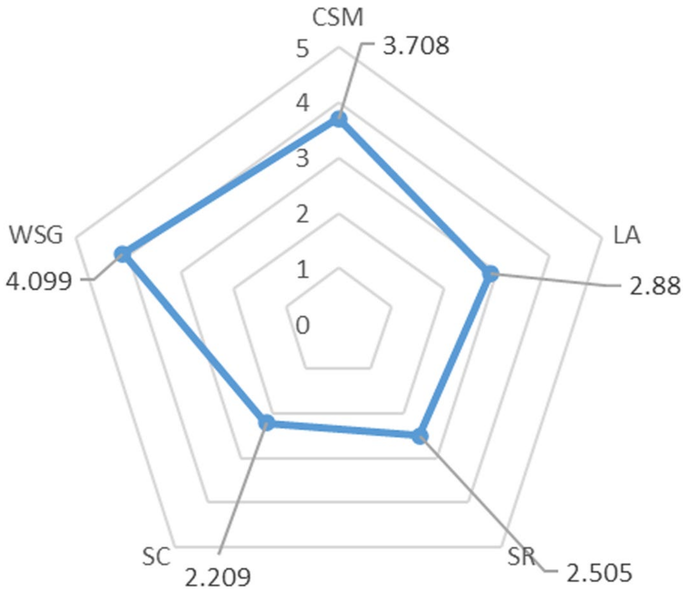

Fig. 4 Challenges of HPC

important for organizations, particularly SMEs, to use shared resources instead of investing in their own infrastructure. Regarding the challenges, WSG (mean equal to 4.099) and CSM (mean equal to 3.708) are the two main challenges highlighted by respondents, while the other three challenges measured have a mean of less than 3. WSG is a significant challenge due to the complexity inherent in this technology and the lack of professionals with the necessary skills to take full advantage of it. As Karozis et al. [39] report, the training of professionals with these skills has not yet kept pace with technological advances and the growing demand for HPC-based solutions.

Table 4 deepens the statistical analysis by presenting the mean, mode, standard deviation, and quartiles of the variables associated with each benefit and challenge. The benefits indicate that CP has the highest mean (4.788) and mode (5), indicating strong agreement among respondents regarding its benefit. The small standard deviation (0.244) suggests little variability in responses. TI follows closely with a mean of 4.561 and a mode of 5, showing high perceived importance, with most responses concentrated around 5. CS has the lowest mean among benefits (3.380) and the highest standard deviation (1.209), indicating greater variability in perceptions. The mode (4) and median (3) suggest that responses are split between moderate and high agreement. Looking to the challenges, WSG has the highest mean (4.099) among challenges, with a mode of 4, showing that it is widely perceived as a major issue. SC has the lowest mean (2.209) and mode (2), with a narrow spread (Std. Dev. = 0.520), indicating consensus that it is a lesser challenge. SR and LA have means below 3 but modes of 3, suggesting a mix of moderate and low concern. There are relevant consequences for this study analyzing the mean, mode, and percentiles. The mean provides an overall indication of central tendency, showing that CP and TI are the most valued benefits, while WSG is the most pressing challenge. The mode reflects the most common response, aligning with the mean in most cases but showing variation where responses are more polarized (e.g., CS).

Table 4 Descriptive statistics of the benefits and challenges of HPC

	Mean	Mode	Std. Dev	25th Percentile	Median	75th Percentile
Benefits						
CMP	4.053	4	0.602	3	4	4
CP	4.788	5	0.244	4	5	5
CS	3.380	4	1.209	3	3	4
DM	4.306	4	0.910	3	4	5
TI	4.561	5	0.588	4	5	5
Challenges						
CSM	3.708	4	0.921	3	4	4
LA	2.880	3	0.803	2	3	3
SR	2.505	3	0.713	2	3	3
SC	2.209	2	0.520	2	2	3
WSG	4.099	4	0.655	3	4	4

The percentiles (25th, median, 75th) provide a deeper look at response distribution: A small gap between the 25th and 75th percentiles (e.g., CP and TI) indicates strong agreement among respondents. A wider gap (e.g., CS) suggests more variability, meaning some respondents perceive significant benefits while others do not. In challenges, a high 75th percentile (e.g., WSG and CSM) indicates that a substantial portion of respondents perceive these as major issues. It can be concluded that HPC is seen as highly beneficial, particularly in computational power and innovation, but challenges such as workforce skills gaps and cost concerns are significant. The percentile distribution highlights variations in perceptions, suggesting that while some aspects of HPC are widely agreed upon, others (like cost savings) elicit more diverse opinions.

4.2 RQ2. Analyze whether these benefits and challenges of HPC during the digitalization process are similar or different between large companies and SMEs

Finally, we sought to identify whether the benefits and challenges identified are different for large companies and SMEs, as established in RQ2. To effectively accomplish this, we adopted a hypothesis test method and set a significance level of 5% to compare the mean scores of all the variables under the benefits and challenges of implementing HPC to support the digitalization process. The result of the hypothesis testing in Table 5 indicates two benefits (CS and DM) with significant differences in their means and a *p*-value of 0.012 and 0.005, respectively. Despite the importance of these two benefits, SMEs find more difficulties in allocating financial resources, which makes it essential to maximize the efficiency of any investment in them. It could conceivably be hypothesized that HPC can be seen as a way of reducing operating costs and optimizing processes, especially in tasks that would be more expensive or time-consuming if carried out without this type of technology. In addition, studies carried out by Faiz et al.

Table 5 Differences in the perception of the benefits and challenges of HPC

Variable	Large Companies		SMEs		*p*-value
	Mean	Std. Dev	Mean	Std. Dev	
Benefits					
CMP	4.125	0.455	3.988	0.709	0.421
CP	4.832	0.210	4.765	0.288	0.691
CS	3.117	1.098	3.670	1.355	0.012
DM	4.066	0.703	4.569	1.086	0.005
TI	4.590	0.338	4.710	0.781	0.452
Challenges					
CSM	3.205	0.809	4.061	0.992	$<1*10^{-3}$
LA	2.231	0.650	3.339	0.950	$<1*10^{-3}$
SR	2.407	0.533	2.598	0.812	0.480
SC	2.132	0.406	2.246	0.583	0.595
WSG	3.680	0.510	4.359	0.790	0.002

[25], Justy et al. [37], and Peters [61] indicate that SMEs often face restrictions in creating and maintaining teams specialized in data analysis or computer simulation. The use of HPC allows these companies to access advanced computing resources on a shared basis. The statistical data collected also indicates that the decision-making benefit provided by the use of HPC is particularly more relevant for SMEs than for large companies due to the unique characteristics of their operations and the need for agility in their strategic decisions. [42] and Marín-Idárraga & Hurtado González [54] argue that SMEs generally have leaner organizational structures, which can limit the number of specialists available to carry out in-depth analysis or predictive modeling. Thus, HPC can be an important element in enabling complex simulations and predictive analysis, which allows SMEs to make decisions based on hard data, reducing the risks associated with intuition or lack of detailed information. However, access to HPC remains limited for SMEs, despite public efforts to address this issue. Therefore, as stated by Thakkar et al. [70], increased efforts are still needed. Finally, large companies are better able to attract and retain specialized talent and invest in training their teams. The existence of departments dedicated to data analysis reduces direct dependence on HPC as a solution to the shortage of skills. Thus, HPC in large companies can be seen as an extension of existing capabilities rather than as a means of overcoming critical skills gaps. On the other hand, skilled human resources in this area have an even more significant impact on SMEs as it allows them not only to perform previously inaccessible tasks but also to compete on an equal footing with larger organizations in areas such as innovation and operational efficiency. Moreover, HPC can stimulate internal learning and empower existing teams to deal with advanced technologies, which can have a multiplier effect by helping these organizations become more adaptable and resilient over time.

5 Conclusions

5.1 Final remarks

This study contributes to highlighting both the benefits and challenges of implementing HPC in organizations. The results show that respondents consider CP and TI to be the most significant benefits of HPC. In contrast, CS receives a significantly lower rating, suggesting that organizations do not prioritize HPC primarily for reducing expenses. The findings reinforce the critical role of HPC in handling large datasets and solving computationally intensive problems, making it a key enabler of advanced data processing. Additionally, organizations view HPC as a strategic investment rather than a cost-cutting measure. Instead of offering immediate financial returns, HPC is seen as a driver of indirect value, contributing to technological advancement and competitive advantage. Regarding the challenges, this study identified WSG and CSM as the main factors. This suggests that organizations perceive these two factors as the primary obstacles. WSG stands out as a major issue due to the inherent complexity of HPC technology and the shortage of skilled professionals capable of maximizing its potential. Moreover, this study reveals significant differences in the perceived benefits and challenges of HPC for large organizations and SMEs, particularly in terms of CS, DM, CSM, LA, and WSG. It can be concluded that large organizations may benefit more from cost efficiency and improved decision-making due to greater financial and human resources, while SMEs often struggle with the high cost of skilled professionals, limited awareness of HPC capabilities, and a shortage of qualified personnel. These disparities underscore the need for tailored HPC adoption strategies to maximize its impact across different business scales.

5.2 Theoretical and practical contributions

This study offers both theoretical and practical contributions. Theoretically, it enhances the understanding of how HPC serves as a foundational technology in the digital transformation of organizations, considering the specific context of large organizations and SMEs. It contributes to discussions on the challenges of HPC adoption, particularly the skills gap and financial constraints, providing insights into the barriers that organizations face. From a practical perspective, the study provides organizations with a clearer understanding of how HPC investments can lead to long-term innovation and competitive advantage. It highlights the importance of strategic decision-making in resource allocation, emphasizing that HPC should not be viewed merely as a cost-saving tool but as a means of enhancing efficiency and optimizing processes. Additionally, it offers valuable insights for policymakers and industry leaders by identifying workforce development as a critical area, underscoring the need for more training initiatives to bridge the gap between technological advancements and available expertise.

5.3 Limitations and future research directions

This study is limited in geographic scope as it focuses on Portugal alone and does not allow a Europe-wide generalization. Therefore, it is imperative for a comparative study that will consider other European economies. Essentially, another avenue of future research involves examining the evolving relationship between HPC and emerging technologies such as quantum computing, edge computing, and federated learning, and assessing how these advancements will shape digital transformation. Another important focus is the role of HPC in specific industries, including healthcare, finance, and manufacturing, to understand how sector-specific challenges and opportunities influence adoption. Research could also investigate the socioeconomic impact of HPC-driven transformation, particularly in SMEs and developing economies, where resource constraints may limit access to high-performance computing solutions. Additionally, addressing the skills gap remains a crucial area, with future studies exploring effective training models, workforce development strategies, and the integration of HPC education into academic and professional curricula. Finally, longitudinal studies could assess the long-term benefits and challenges of HPC investments, providing a deeper understanding of their impact on business resilience and innovation over time.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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