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Reconciling digital transformation and sustainability: Towards a tailor-made strategy for manufacturing SMEs

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Abstract: This paper addresses the lack of a comprehensive model for assessing the benefits of Industry 4.0 (I4.0) in small and medium-sized enterprises (SMEs), considering their diverse priorities and objectives. SMEs struggle to balance economic growth and environmental constraints, amid tightening regulations. Existing digital performance models focus on technology integration but rarely align outcomes with SMEs' strategic goals, particularly regarding environmental performance. This study proposes an adaptable model that integrates digital performance dimensions with sustainability indicators, aligning with the Triple Bottom Line (TBL) framework to evaluate the economic, social, and environmental impact of digital transformation in SMEs. Using data from 30 Quebec-based SMEs and hierarchical clustering, we identify groups of companies sharing similar operational realities, resources, and objectives. Clusters inform model customization. The proposed model thus measures I4.0's effects on economic, social, and environmental aspects, providing a structured approach to prioritize digital transformation initiatives.

Keywords: Industry 4.0, SMEs, Environmental Impact, Digital Transformation, Hierarchical Clustering, Indicators, Modeling, Digital Impact, Digital Benefits, Sustainable Development, Industry 5.0

1. INTRODUCTION

With the world's population reaching unprecedented levels (Profiroiu et al., 2020), environmental challenges are increasingly influencing everyday life. Issues such as rising energy consumption (Bpifrance, 2021), escalating greenhouse gas emissions (Ritchie and Roser, 2017), and the growing number of natural disasters (Coronese et al., 2019) are now an undeniable reality. In Canada, Small and Medium-Sized Enterprises (SMEs) are responsible for over half of the nation's greenhouse gas emissions (Canada, 2023). As environmental regulations increasingly impose financial penalties on emissions, SMEs face a challenging trade-off: prioritizing economic growth or reducing their environmental footprint (Dincer and Dincer, 2013). Limited resources force SMEs to prioritize survival over compliance.

Industry 4.0 (I4.0) offers concrete solutions to help SMEs resolve this dilemma. These technologies modernize operations and enhance sustainability (Genest and Gamache, 2020). For example, as noted by Brozzi et al. (2020), implementing I4.0 technologies can optimise load balancing and consequently reduce on-site energy consumption. Aït-Kaddour et al. (2024) highlights the positive impact of I4.0 on waste management practices within the food industry. Similarly, Dennison et al. (2024) demonstrate that I4.0 facilitates the adoption of circular economy practices within manufacturing firms. However, the adoption of I4.0 among SMEs is far from uniform. Indeed, their priorities and capacity to embrace I4.0 technologies vary markedly with factors such as size, industrial sector and resource availability (Ghobakhloo et al., 2022). Moreover, this underscores the need to assess how companies integrate I4.0 technologies into their operational processes. To this end, digital performance is frequently employed in the literature as an indicator of the extent to which I4.0 technologies are integrated into a company's operations. Digital performance captures a firm's ability to incorporate digital technologies to strengthen its competitive position (Gamache et al., 2020). Through this framework, various models have been devised to categorise firms according to distinct levels of digital maturity, thus offering a benchmark to inform the incremental adoption of technologies.

Nevertheless, while digital performance can measure the level of I4.0 integration, existing models are still inadequate for addressing the needs of SMEs. They often focus on assessing the technological baseline rather than evaluating tangible digital transformation benefits aligned with the firm's strategic objectives. Hence, there is a lack of a framework that connects digital integration to the intended benefits, particularly in relation to environmental sustainability and SMEs' long-term resilience (Bélanger and Gamache, 2024). While previous models have primarily assessed digital maturity or financial performance, they fail to explicitly capture how I4.0 adoption influences environmental impact and resource efficiency. This gap gives rise to the following problem:

Currently, no model measures the benefits of digital transformation while explicitly accounting for the environmental impact and sustainability objectives of SMEs.

Beyond this gap, it is important to recognise that SMEs also vary in their objectives, mirroring the diversity of their operational contexts. For instance, certain manufacturing SMEs may focus on lowering energy consumption to reduce costs, whereas others in different sectors may prioritise process automation to mitigate labour shortages. Such diversity further complicates the universal applicability of existing digital

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transformation frameworks. Therefore, this heterogeneity among SMEs, combined with the identified problem, underscores the need for a more flexible and adaptive framework that enables SMEs to prioritise their digital transformation efforts in line with their unique contexts and requirements. Hence, a more flexible and adaptive framework is required. Building on these observations, two research questions emerge: *Is it possible to propose an evaluation model that measures the environmental, economic, and social benefits of a digital transformation in SMEs? And if so, how can such a model be adapted to the specific sustainability objectives of each SME?* In this context, the primary objective of this study is to:

Propose a model that measures the effect of Industry 4.0 on the benefits sought by SMEs and which can be adapted to their realities.

This model must assess economic, social, and environmental indicators, and tailor its outputs according to each firm's priorities. The sub-objectives are: (i) To propose a method for identifying clusters of firms so that the model can be adjusted according to their characteristics, and (ii) To develop a new digital performance model that integrates the specific benefits relevant to SMEs. The following sections outline the conceptual foundations, methodology, clustering approach, model, discussion, and conclusion.

2. CONCEPTUAL AND THEORETICAL FOUNDATIONS

First, this section explores the key concepts associated with SMEs' adoption of I4.0, the technological integration indicators suggested by digital performance, and the dimensions of benefits encompassing environmental impact and sustainability.

2.1 I4.0 in SMEs: A Solution to Contemporary Challenges

SMEs (1-500 employees) are key to Canada's economy. (Labelle and Aka, 2010). They stand out due to their flexibility, responsiveness to market fluctuations and proximity to customers. However, their resources, business models, and strategies vary significantly, underscoring the importance of analyses tailored to their diversity.

I4.0 offers a strategic opportunity to transform these enterprises by strengthening their competitiveness and resilience in a constantly evolving economic environment. This concept includes integrating advanced technologies such as the Internet of Things, artificial intelligence, robotics, Big Data, and cyber-physical systems (Hermann et al., 2015), thereby optimising operational processes with a sustainability focus (Genest and Gamache, 2020). However, this adoption depends on available resources, strategic objectives, and the firm's digital maturity. Unlike large firms, SMEs face high adoption costs and lack specialized expertise, slowing their transition.

2.2 Digital Performance: An Indicator of Technological Integration

Digital performance, arising from I4.0, represents the degree of an enterprise's digital transformation. It captures the ability to integrate technologies and is measured by the evolution of its technological state (Gamache et al., 2020). Models, such as the one by Gamache et al. (2020), define digital performance through six essential dimensions: *leadership, organisational culture, technology management, data management, measurement systems, and customer experience*. These dimensions assess the capacity to innovate, integrate technologies, and meet customer expectations in a constantly evolving context (Vivier and Ducrey, 2017). These dimensions provide a global digital maturity diagnosis. However, this diagnostic has limitations in practical utility. It assesses technology but not SMEs' specific needs. A high level of technological maturity does not necessarily ensure benefits. With limited resources and diverse priorities, SMEs require tools that link the impact of adopted technologies to their strategic objectives, such as profitability or sustainability. The digital performance model remains incomplete without measuring its impact on benefits.

2.3 Dimensions of Benefits: Environmental Impact and Sustainability

While environmental impact is a crucial measure of digital transformation's advantages, it represents only one dimension of sustainability, which also includes economic resilience and social well-being. The Triple Bottom Line (TBL) framework provides a holistic approach to assessing how SMEs can achieve sustainable growth through digital transformation. Measuring these benefits allows SMEs to better understand and manage their ecological footprint in response to growing environmental regulations, such as carbon taxes and financial penalties (Dzomonda and Fatoki, 2020). Analytical frameworks, like that proposed by Fortier et al. (2024), identify relevant indicators for assessing these impacts. They classify environmental benefits into three main sub-categories: *resource use, environmental repercussions, and the durability of products and equipment*. However, while the measurement of environmental impact is detailed by Fortier et al. (2024), it cannot be evaluated in isolation. Although crucial, these environmental benefits must be integrated with other fundamental objectives, such as profitability. Indeed, SMEs primarily aim to ensure profitability and long-term viability by securing financial returns (Kiel et al., 2017). They must also consider the impact on employee well-being, particularly in the context of labour shortages (Deschênes, 2023). Therefore, a comprehensive analysis of SME benefits must include economic, social, and environmental dimensions. The next part of this article will present the methodology employed to integrate these dimensions into a structured analytical framework, enabling a quantitative evaluation adapted to SME realities.

3. METHODOLOGY

To achieve the objectives of this study, a three-step methodology was implemented, aligned with the need to integrate the previously identified economic, social, and environmental dimensions. These steps aim to address the diversity of SME realities while offering a structured approach to measure the benefits of I4.0. First, a structured questionnaire was developed to gather data through interviews. These interviews were conducted with 30 SMEs located in Quebec. Data were collected using a Likert scale and then analysed using a hierarchical clustering method based on Euclidean distance and average linkage. The clustering step helped identify homogeneous groups of enterprises according to their operational reality, resources, and strategic priorities. These clusters provide an essential basis for personalising the analysis and better understanding the differences and similarities within groups. Clusters were validated using the Silhouette Score. Finally, the last step was to develop a model for evaluating I4.0 benefits that integrates the results of the other two steps. These steps develop an adaptable model for I4.0 benefits.

3.1 Directed interviews

To identify the enterprise clusters, it was necessary to gather practical data. This section therefore describes the structure and logic of the questionnaire used in the interviews. It is divided into three main sections, corresponding to the dimensions required for the analysis: independent variables (I4.0), dependent variables (environmental impact), and contextual variables (general characteristics of SMEs). The questions were constructed using a Likert scale to standardise the level obtained in each dimension. The questionnaire comprises qualitative questions scored from 1 to 5, quantitative questions also normalised to the same scale, and a few open-ended questions for grouping or further analyses.

The first section of the questionnaire was developed based on the dimensions presented by Gamache et al. (2020). One hundred questions were designed to measure the dimensions of the digital performance model. The data collected here constitute the independent variables of the model presented in this article. Similarly, the second section of the questionnaire includes thirty questions focusing on SMEs' objectives and priorities concerning environmental impact, as proposed by Fortier et al. (2024). This time, the collected data form the model's dependent variables. Finally, the last section includes 18 questions regarding the structural and strategic characteristics of the participating firms. These questions provide information on company size, industry sector, financial and human resources, as well as each SME's growth strategies. This section also includes questions on the SMEs' objectives with respect to I4.0.

The interviews were conducted with company executives. The sample consists of 30 SMEs located in the same Quebec region. They were selected to represent the diversity of a specific area. They differ in terms of industry sectors, company sizes, and geographic locations. The sample comprises 19 product-focused firms, 9 product-and-service firms, and 2 service-only firms. These businesses operate in various sectors, such as metals, construction, and automotive. In terms of size, they range from 4 to 250 employees, with a median around 40 employees. They also exhibit considerable diversity in organisational structures, including family-owned businesses, shareholder groups, and single-owner enterprises. Annual turnovers range from $225,000 to $350 million, reflecting the range of capabilities and economic maturity within the sample. This diversity ensures better representativeness of different SME realities, while justifying the relevance of the clustering method used in this study. The industrial layouts observed include 16 Flow Shop configurations, 10 Job Shop setups, 2 fixed cell arrangements, and 2 assembly lines. The results of these interviews form the basis for the next two parts: the clustering methodology and the model's design.

3.2 Clustering

One of the greatest challenges to achieving the main objective is that the reality of each SME can differ significantly from one firm to another (Ghobakhloo et al., 2022). This diversity reflects the central problem of adapting I4.0 benefits to each enterprise's specificities, considering their operational contexts, resources, and strategic priorities. Without the financial flexibility of large firms, SMEs take bigger risks in digital adoption. To tackle this challenge, three fundamental concepts were chosen as the most robust sorting criteria for separating enterprises into clusters: each firm's unique reality, available resources, and strategic objectives. First, each SME operates in a unique context. They are influenced by factors such as the production type and the products sold. These factors play a decisive role in how a firm structures its operations and generates value. For example, an SME specialising in custom, high-value-added production will not share the same priorities or constraints as another operating in mass production with low margins. Ignoring these realities in a clustering process would lead to groupings of incomparable enterprises, rendering analyses and strategic actions uninteresting. Therefore, the first criteria integrated into the clustering method are the production type and profit margin per sold product. Next, resources, whether human or financial, form the basis of a firm's capacity to take action. They directly influence strategies, resilience, and growth potential. For instance, an SME with a substantial working capital will not hold the same apprehensions towards technological investment as a start-up with limited resources. This is why annual turnover and the number of employees were also integrated into the company sorting criteria. Finally, while criteria related to enterprise realities are extremely important, it is also necessary to include each company's objectives. This is especially true in the context of the model proposed here, where we seek to measure the benefits of implementing I4.0 dimensions. For example, a firm aiming to reduce its ecological footprint will not undertake the same actions as a firm whose main goal is to increase revenue. Hence, the level of interest in economic, social, and environmental benefits is also included among the sorting criteria. By considering operational realities, available resources, and strategic priorities, the clustering method presented in the following section creates groups of SMEs that exhibit highly similar clusters.

To choose the clustering method, von Linde and Riedel (2024) present algorithms for selecting partitioning methods and cluster validation methods. By comparing the context of this research with the methods proposed by von Linde and Riedel (2024), hierarchical clustering was selected as the most suitable. This clustering method is better adapted to moderate-sized data sets and offers a visual representation in the form of a dendrogram (Hu and he Pan, 2015). Similarly, the Silhouette Score method was chosen as an excellent validation method in this context. The Silhouette Score evaluates intra-cluster cohesion and inter-cluster separation (Rousseeuw, 1987). The following section presents the application of these two methods.

4. RESULTS

4.1 Clustering results

The clustering was carried out in three steps. The first involved cleaning the data related to the selected criteria: layout type, profit margin per sold product in dollars, turnover, number of employees, and the levels of interest assigned to economic, social, and environmental performance. For example, data concerning the type of layout were converted into numbers before the clustering step. The second step involved applying hierarchical clustering based on Euclidean distance and average linkage. Minitab was used for cluster analysis and results generation. Hierarchical clustering involves progressively reducing the number of groups and increasing the distance between merged groups at each step. For instance, initially, 29 groups were created; after several steps, the number of groups decreased to 5 final clusters. Once the groups were merged, the distances between the groups' central points were analysed. Smaller distances, as between Group 1 and Group 2, indicate clusters of SMEs with similar characteristics, while larger distances, as between Group 3 and Group 4, reveal more pronounced differences within the groups. For validating the results, the Silhouette Score showed that the formed clusters were coherent, with good intra-cluster cohesion (SMEs within the same group were similar) and sufficient inter-cluster separation (the clusters were distinctly separated). During the analysis, the Silhouette Score helped determine that 5 clusters were best suited, maximising the quality of groupings while maintaining good separation between clusters. The groups are presented in the dendrogram in Figure 1.

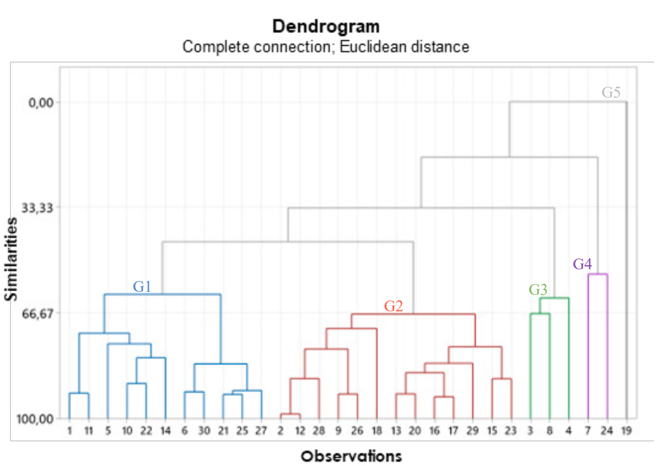

Figure 1. Dendrogram of SME Clusters

The 30 SMEs in the sample were grouped into five distinct clusters, each reflecting operational, strategic, and contextual similarities. These groupings enable the identification of homogeneous business typologies, facilitating the adaptation of digital transformation models to each group's specific needs, thus meeting the second sub-objective of this study.

4.2 New digital performance model

The final step to achieve the objective is the construction of the new model that relies on the dimensions from Gamache et al. (2020) and the indicators from Fortier et al. (2024). This model is based on integrating digital performance dimensions with environmental dimensions. Indeed, the new model proposes measuring the effect of X_i (the digital performance dimensions) on B (the sustainable performance benefits). An adaptive regression approach is used to establish an explicit link between B et X_i. The model is presented as follows:

$$B = \beta_0 + \sum_{i=1}^{6} X_i + \mathcal{E}_0 \quad (1)$$

Where B represents the desired benefits, β_0 the initial benefits, $\mathcal{E}_0$ the model's error, and each X_i represents the level of a digital performance dimension. For example, X_1 represents the level of the company's leadership in the context of I4.0. To deepen our understanding of benefit measurement, B is defined as:

$$B = w_{EP}EP + w_{SP}SP + w_{EnP}EnP \quad (2)$$

Where w_E, w_S, w_{En} represent the weights of the economic, social, and environmental dimensions as proposed in the clustering section, and EP, SP, EnP represent the normalised scores for each dimension. These scores are measured via sub-indicators. For economic dimensions (EP), indicators such as operational cost reduction, turnover increase, or Return on Investment (ROI) could serve as initial leads. For social dimensions (SP), indicators like improved employee satisfaction, reduced turnover, or the number of training sessions completed might be considered. Although still unvalidated, these suggestions provide a practical glimpse of possible measurements. Conversely, no complete method currently allows for fully measuring social and economic dimensions through concrete indicators. Regarding the environmental dimension, Fortier et al. (2024) provide a framework for doing so. Environmental performance measurement is thus divided as follows:

$$EnP = a_1 UR + a_2 ER + a_3 DU \quad (3)$$

Where UR represents resource usage (e.g., energy and raw material consumption), ER represents direct environmental repercussions (e.g., CO_2 emissions and carbon footprint), and DU indicates the sustainability of products and equipment. Coefficients a_i represent the relative importance of these sub-indicators within their respective dimension and are determined for each SME cluster.

The adaptive regression approach used to adjust the coefficients (w_E, w_S, w_{En}) relies on multiple linear regression. Data from the interviews calibrate these coefficients according to the strategic priorities of each cluster. It will be possible to apply this model within each SME cluster to determine which digital performance dimensions are most significant in achieving benefits. Despite the challenges associated with fully measuring economic and social dimensions, the proposed approach remains innovative, as it offers a structured and adaptive method to guide SMEs through their digital transformation.

4.3 Application of Clustering

In addition to the model presented above, the following section uses the collected data to adapt the proposed model to each of the 5 clusters. Data gathered during the directed interviews allowed for building a chart illustrating the level of interest each SME has in the desired benefits. These data are presented in Figure 2.

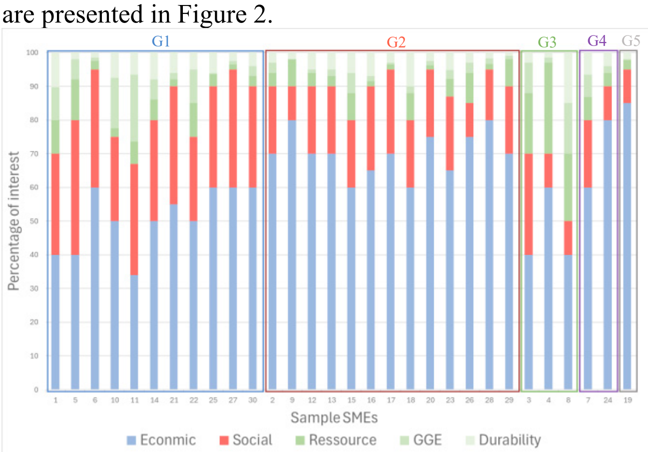

Figure 2. Proportion of interest in the dimensions of sustainable development and environmental impact for each SME

In the figure, one can see the distribution of each SME's interest levels, not only concerning the three dimensions of sustainable performance but also regarding the three environmental sub-dimensions proposed by Fortier et al. (2024). This enables determining the weighting coefficients for the five groups. These weightings are essential for customising benefit evaluation according to the SMEs' priorities. Table 1 shows the average value of each coefficient based on the collected data for each cluster:

Table 1. Average values of the economic, social and environmental interest coefficients for each SME cluster.

	w_E	w_S	w_{En}	a_1	a_2	a_3
Group 1	0,51	0,32	0,18	0,33	0,32	0,36
Group 2	0,70	0,19	0,11	0,43	0,18	0,40
Group 3	0,47	0,17	0,37	0,63	0,22	0,15
Group 4	0,70	0,15	0,15	0,37	0,27	0,37
Group 5	0,85	0,10	0,05	0,55	0,05	0,40

The data presented in Table 1 show a predominant interest among SMEs in economic benefits. This trend is particularly pronounced in Group 5, where the emphasis is overwhelmingly on economic benefits ($w_E = 0{,}85$), and environmental interest is almost negligible ($w_{En} = 0{,}05$). Even groups that exhibit some balance, like Group 1, show low priority for environmental impact. These findings reveal a disconnect between global ecological issues and the strategic priorities of the surveyed SMEs. This reflects not only a structural weakness in adopting sustainable practices but also a concern regarding alignment between emerging environmental regulations and SMEs' strategic goals.

The model highlights gaps between SME priorities and regulations. By offering a structured and adaptable method, it opens avenues for future research aiming to better integrate missing dimensions and deepen our understanding of sustainable benefits in digital transformation. The weighting coefficients calculated for each group allow for prioritising economic, social, and environmental dimensions as well as environmental sub-dimensions according to the strategic objectives of each cluster. For example, Group 1 adopts a balanced approach between dimensions, while Group 5 strongly favours economic benefits. This differentiation ensures the model's customisation according to the SMEs' operational realities, thereby enhancing its relevance in achieving the main objective.

5. DISCUSSION

The results reveal significant variations in the priorities of each SME cluster regarding the benefits sought. Since I4.0 implementation in SMEs cannot be standardised, the new model proposes an adaptive calculation to provide a more appropriate evaluation framework for each reality. The clustering approach also allows SMEs to compare themselves easily with other enterprises that share similar contexts and objectives. Large firms have structured plans and expert support; SMEs rely on trial-and-error, increasing risk. This article makes a significant contribution through the concept of objective weighting. It enhances the understanding of the real impact of I4.0 on SME benefits. The practical application of such a model enables SMEs to align their digital transformation actions with their specific goals. It is the first model to incorporate specific weightings based on the priorities of SME clusters to measure I4.0 benefits. This approach surpasses existing frameworks by linking empirical data to an applicable model. The practical utility of segmenting SMEs into clusters makes it possible to offer tailored recommendations. It provides SMEs with a tool for prioritising their digital initiatives according to their specific objectives, thus optimising the use of their limited resources. This model provides a repeatable methodology for SMEs. It proposes a structured way to explicitly link digital performance dimensions with measurable benefits, while integrating organisational specificities. This contribution helps fill the gap identified by the absence of a digital performance model that measures the benefits of digital transformation. The model provides a basis for developing a generalisable tool to guide SMEs towards I4.0, while enabling comparative analyses across sectors or internationally. Researchers can reuse this approach to develop similar tools in other contexts.

5.1 Limitations and Future Work

This model has important limitations that warrant attention in future research. First, although it integrates weightings for economic, social, and environmental dimensions, it lacks precision in measuring economic (EP) and social (SP) performance. These dimensions have not yet been associated with concrete, quantifiable indicators, limiting the scope of the analyses. A thorough literature review, similar to that conducted by Fortier et al. (2024) for the environmental dimension, is necessary to develop robust sub-indicators for EP and SP. Such efforts would produce a more comprehensive and balanced model, better guiding SMEs in their digital transformation.

Moreover, the proposed model has not yet been applied in practice to validate its relevance. Current results rely solely on theoretical data and calculated weightings. Future work could involve using the questionnaire data to perform ANOVA analyses within the five identified groups, determining which I4.0 dimensions significantly impact the achievement of benefits, thereby strengthening the model's empirical validity.

Finally, the sample size, limited to 30 SMEs, is another major constraint. Although the five identified clusters offer an initial segmentation, they do not capture the full diversity of existing SMEs. The restricted sample size also limits the statistical robustness of the results and the representativeness of the formed groups. In the long term, expanding the sample would be necessary to identify a more comprehensive variety of clusters. With a greater number of groups, an SME outside the sample could easily identify with an existing cluster based on its resources and priorities. This would enable increased customisation of recommendations and broader adoption of the model across different industries and regions.

6. CONCLUSION

This study addressed the absence of a digital performance model capable of measuring I4.0 benefits while accounting for the varied objectives of manufacturing SMEs. In response, the article's findings propose a generic and adaptable model that integrates economic, social, and environmental dimensions, while allowing personalisation based on each SME's specific priorities. The main contribution lies in the model's development, the proposed method for weighting benefits, and the identification of homogeneous SME clusters. From a broader perspective, this work aims to become a universal and accessible tool, enabling any SME, after answering a few simple questions about its reality, to receive specific recommendations to optimise its digital actions. With more data, this tool could guide global SME digital transformation.

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