Product/Process Strategy, Manufacturing Technology and Workforce Qualifications: Impact on Labour Productivity and Flexibility

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This paper analyses the impact of manufacturing technologies (MTs) and workers' qualifications on labour productivity and flexibility, taking into account the product-process (P-P) strategy adopted by the company. This allows for a discussion about the well-known P-P matrix initially proposed by Hayes and Wheelwright (1994) in order to evaluate options of production systems. The empirical analysis is performed by means of a panel of data of 13 years for the Spanish manufacturing industry, which includes a total of 7,741 observations. The results indicate a complementary effect between technology and skills to overcome the trade-offs of production systems.

Keywords: product-process strategy; manufacturing technologies; worker qualifications; complementary effects; labour productivity; flexibility

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1. Introduction

For years, companies have faced global competition in contexts characterized by uncertain and changing demand conditions, with customers becoming increasingly demanding. Consequently, the key challenge for manufacturers and service providers has been the design of production processes and products that fulfil both market requirements and the strategic goals of organizations (Hill 2005), stressing the need for consistency between manufacturing strategy and the competitive strategy of the company (Slack 2015). Fortunately, technological progress has brought a wide variety of new approaches—such as just-in-time, flexible process, total quality management, or combinations of these—as a means to improve productivity, flexibility and quality (Sousa and Voss 2008). As a result, investments in manufacturing competitive resources, mainly in technology and knowledge, have been on the agenda of every competitive plant (Borges and Tan 2017; Nair, Ataseven, and Swamidass 2013; Swink and Nair 2007).

Although the impact of manufacturing technologies (MTs) on manufacturing performance has received a great deal of attention in the literature of operations management (OM), under what circumstances the adoption of technology and knowledge contributes to improving performance in the manufacturing industry has received little analysis until now. The potential competitive advantage associated with MTs gathered by the literature is not related only to their presence in production centres but depends largely on the configuration of different MTs and their fit with the product-process (P-P) strategy adopted by the company.

The product-process (P-P) matrix proposed by Hayes and Wheelwright (1984) delineates operations decisions in terms of process structure and product structure in order to define a set of P-P strategies. Process structure is defined as including everything from production batches or projects to systems of mass production and continuous production systems (process changing, vertical axis). The range covering the structure of products extends from customized to standardized products (horizontal axis). For years, it has been a guiding principle for practitioners to match product variety and production process in order to achieve the best operational performance (Das and Jayaram 2003; Marsillac and Roh 2014). If companies move along, or close to, the diagonal of the matrix from the top left to bottom right, production flexibility and costs will gradually reduce and competitive strategy will change from differentiation-dominant to cost-leading dominant. In doing so, companies face an inevitable trade-off between cost and flexibility (Chryssolouris et al. 2013). However, the adoption of MTs and management systems may overcome trade-offs, allowing firms to remove themselves from the diagonal of the P-P matrix (Ahmad and Schroeder 2002; Ariss and Zhang 2002; Kotha and Orne 1989).

Related empirical evidence about the performance implications of normative propositions of the P-P matrix demonstrates that other P-P strategies can overcome the model's trade-off between flexibility and productivity (Ahmad and Schroeder 2002; Guisado-Gonza, Guisado-Tato, and Del Mar Rodriguez-Dominguez 2014; Helkiö and Tenhiälä 2013). However, it has been signalled that the P-P matrix has not been deeply discussed in relation to technology adoption and human resource management (Helkiö and Tenhiälä 2013). This paper tries to fill this gap, analysing how the existence of complementarities among several MTs and workforce qualifications is contingent on the product-process manufacturing strategy adopted in explaining labour productivity and flexibility.

As for the effect of complementarities among and between MTs and workforce qualification, there is a valuable contribution embodied in the vast literature related to resource-based view theory (RBV). This theory describes how organizations achieve a sustainable competitive advantage by means of resources that are not easily transferable; thus costly-to-copy attributes of the firm that require a broad learning process will be harder for competitors to imitate, allowing the achievement of superior performance (Barney 1991; Hamel and Prahalad 1996; Wernesfelt 1984). In this context, as some authors point out, combinations of advanced technologies can increase the firm's technology advantage over its competitors (Milgrom and Roberts 1993; Stoneman and Kwon 1994), since the existence of complementarities among technologies can make them inimitable and build a sustainable competitive advantage (Sihna and Noble 2008). Close to this view, sociotechnical system (STS) theory (Emery and Trist 1960) views the organization as a work system with two interrelated subsystems, the technical system and the social system (Pasmore 1988). While the technical system concerns the processes and technologies applied to transform inputs, the social system focuses on the relationships among people and the attributes of these people, such as abilities and skills. The outputs of a work system are a result of the joint interaction between these two systems. In other words, from this perspective, the production system is made up of two jointly independent, but correlative interacting systems, the social (attributes of people) and the technical (technology) (Sethi and Sethi 1990). According to these ideas, the inclusion of MTs to increase the level of automation in a factory should be complemented with workers who have reasonable maths, language skill and knowledge to act in complex information environments (Doms et al. 1997) to get the most out of those automations.

In line with this trend, the present study addresses the effects that MTs and skilled worker complementarities may contribute to improve the performance in the manufacturing industry, measured as labour productivity and flexibility, while taking into consideration the product-process strategy adopted by the plant. Our starting hypothesis is that MTs, employees' qualifications and potential synergies can be conditioned for the product-process strategy in order to explain performance. Complementarities between technical and organizational aspects could explain the existence of systems with an off-diagonal P-P matrix position with high levels of both productivity and flexibility (Zhang et al. 2015). These systems, defined as mass customization, have been analysed extensively in literature (Da Silveira, Borenstein, and Fogliatto 2001; Sandrin, Trentin, and Forza 2018).

Empirically, the database used to test the hypotheses is strongly representative of the overall Spanish manufacturing industry, covering the period from 2002 to 2014. This allows us to evaluate for time-persistent effects through panel data with 7,741 observations, which is key to the evaluation of performance implications of long- and medium-term strategies, such as production systems, technology adoption and human capital of firms. In addition, the adoption of a large sample of manufacturing firms, covering a large period of time, and a whole industrialized country gives our estimations great value not only in terms of robustness but also because it makes generalization of the findings to similar manufacturing environments more feasible.

The remainder of the paper is organized as follows. Section 2 presents a literature review and includes a set of hypotheses. Section 3 describes the sample, the descriptive statistics, the variables used and the proposed models. Section 4 presents the results and discussion. A conclusions section closes the study.

2. Theoretical background and hypotheses

2.1 Manufacturing technologies, product-process strategy and performance

The adoption of technologies has been widely discussed in the OM literature (Khanchanapong et al. 2014; Kotha and Swamidass 2000; Swink and Nair 2007). In manufacturing, technology is understood to be the set of tools aimed at automating and integrating the different stages of design, manufacturing, planning and control of the product (Ettlie and Reifeis 1987). However, there is no consensus on how to refer to or categorize these. Some authors refer to advanced manufacturing technologies (e.g. Boyer et al. 1997; Fulton and Hon 2010; Khanchanapong et al. 2014), while others refer only to MTs (e.g. Nair et al. 2013). Empirical studies evaluating the adoption of these technologies usually are unable to measure whether or not technologies are advanced. For instance, we know if the company has automatic robots, but not if they are second, third or fourth generation. The same applies to versions of enterprise resource planning (ERPs) or computer aided design (CAD) systems. In this paper, we consider that MTs more appropriately refer to technology adoption in manufacturing plants.

On the other hand, Boyer et al. (1996) divided MTs into three groups of components: technologies of production design, including CAD, computer aided engineering, and computer aided process planning; technologies of manufacturing processes (robots); and administrative production technologies, including material requirement planning and ERP. Other authors distinguish between soft (ERP and material requirement planning) and hard (robots, CAD) MTs (Nair et al. 2013). Many empirical studies consider MTs as an additive index measuring the level of adoption of MTs by the company. Regardless of the type of classification used, it is important to highlight that all these authors capture the idea of adopting a set of manufacturing technologies rather than the extent to which a specific technology is adopted. In the background, the adoption of a set of complementary MTs may be the element behind the enhancement of performance and competitiveness of manufacturing firms.

In this sense, there is abundant literature backing up the idea of the positive effect on manufacturing performance. Since resource-based theory describes how organizations achieve sustainable competitive advantage with resources that are not easily transferable (Barney 1991; Hamel and Prahalad 1996), some authors point out that combinations of advanced technologies can make them inimitable and able to build a sustainable competitive advantage (among others, Milgrom and Roberts 1993; Sihna and Noble 2008; Stoneman and Kwon 1994). These complementarities among technologies permit the building of complex manufacturing systems (Gómez and Vargas 2012) that improve the flow of technology and information among departments, unlike individual technology.

Empirically, most of the evidence shows that investments in new technologies drive firms to enhance results (see, for instance, Cozzarin 2016; Dean and Snell 1996; Gordon and Sohal 2001); however, contrary to what is expected, some evidence shows mixed outcomes (Boyer et al. 1997; Koc and Bozdag 2009). Different failures in the introduction phase of MTs have been identified; these might include, for example, an unsuitable technological choice for given production processes, inappropriate implementation procedures, or misalignment between the selected technology and the business strategies of the company (Fulton and Hon 2010; Iakymenko, Alfnes, and Thomassen 2016). In spite of these contradictory results, what is also seen is that manufacturing companies continually invest in technology. Therefore, the mixed results observed could hide problems of model specification because they are generally measured without considering potential interactions with other factors (Percival 2009).[1] In this vein, some researchers have suggested that different contingencies may govern the effect of MTs on manufacturing outcomes—for instance, on human resource practices (Bello et al. 2011;

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[1] For instance, some researchers have found positive relationships (Dean and Snell 1996; Gordon and Sohal 2001) while others have found no relationship or even negative relationships between AMTs and performance (Boyer et al. 1997; Koc and Bozdag 2009).

Cagliano and Spina 2002; Swink and Nair 2007) or lean practices (Khanchanapong et al. 2014).

Following this perspective, and in line with Kotha and Swamidass (2000), we consider that the enhancement of performance related to MTs is not only the consequence of its adoption, but is also related to how these technologies fit with the P-P strategy. The adoption of different MTs is a response to the trade-off between flexibility and efficiency, which is determined by the P-P strategy adopted by the firm (Williams and Novak 1990) and collected in the P-P matrix. Batch shop systems, characterized by low volume and low standardization of products, are highly dynamic in the adoption of MTs in order to face the complexity of process characterized by several discontinuities (Kotha and Orne 1989). Several dimensions of MTs are needed to quickly adapt the production process for small-sized production (Hill 2005; Kotha and Swamidass 2000). Schroder and Sohal (1999) demonstrate that these systems benefit from the improved flexibility provided by MTs. On the other hand, continuous-flow line production systems (high volume and high standardization) are usually less dynamic in the implementation of a high number of MTs but are intense in the use of capital (Sohal et al. 2001). This systems typically focus on process-related technologies such as numerical control machines and programmable controllers (Kotha and Swamidass 2000). Thus, the adoption of MTs will vary with the P-P strategy adopted by the company.

Finally, in order to respond to customers' demands, companies look to increase the volume of product options for a relatively large market that demands customization without substantial trade-offs in cost, delivery and quality (McCarthy 2004; Pine 1993). The existing complementarities among MTs may help firms to reduce the trade-off between flexibility and efficiency (Kotha and Swamidass 2000; Williams and Novak

1990), allowing the achievement of superior performance and even moving off the P-P matrix diagonal (Ahmad and Schroeder 2002; Helkiö and Tenhiälä 2013). In addition, Kotha and Swamidass (2000) find that dual strategies, involving cost, high volume and differentiation (quality and variety), are more likely to be achieved in that more MTs are implemented. In this vein, Zhang et al. (2015) associate mass customization with the constant reconfiguration of different MTs to give customers exactly what they want when they want it, and at competitive prices.

According to these arguments, we propose the following hypotheses:

H1: The positive effects of MTs on labour productivity are expected to be higher in high volume-high standardization systems.

H2: The effects of MTs on flexibility are expected to be higher in high volume-low standardization systems.

H3: The adoption of MTs is positively associated with the likelihood of adopting an off-diagonal strategy (high volume-low standardization systems).

2.2 Manufacturing technologies, product-process strategy and performance: the moderating role of workers' qualifications

Following RBV theory, MTs are valuable resources; however, from a strategic point of view, their ability to generate competitive advantage is questionable. Generally, these technologies are generally not rare or scarce, and they are the subject of continuous replacement as a result of technological progress. Therefore, the potential competitive advantage associated with MTs is not related only to their presence in production centres, but depends largely on the configuration of different MTs and their fit with the production systems adopted by the company. Hence, the inimitability that RBV theory predicts to achieve a sustainable competitive advantage can be achieved by the combination of MTs and organizational elements (Zhang et al. 2015).

Close to this line of thought, STS theory predicts that the technological system requires the presence of a body of knowledge and skills to face the higher complexity of process (Pasmore 1998), which indicates the existence of complementarity between new technologies and skilled workers. This idea of complementarity refers to the nature of the resources required to capture the benefits associated with a particular strategy or technology (Teece 1986). Assets or practices are mutually complementary ‘if doing (more of) any one of them increases the returns to doing (more of) the others’(Milgrom and Roberts 1995). Complementary assets are essential for technology exploitation (Shane 2001).

Evidences suggest a growing demand for skilled workers in developed and industrialized countries over time, especially in OECD (Organisation for Economic Co-operation and Development) countries. It seems to be that companies have undertaken more highly qualified and demand-driven work, used more advanced technologies (Bayo-Moriones, Billón, and Lera-López 2008), and replaced low-skilled workers (Machin and Van Reenen 1998). In general, tasks associated with the adoption of MTs are more sophisticated and require more knowledge-related skills (Mital and Pennathur 2004). Close to this view, Doms et al. (1997) argued that skilled workers are the only ones able to fully implement MTs for several reasons. Firstly, MTs increase the level of automation in factories and workers using these machines must have basis capabilities in language, reading and maths, and higher levels of abstraction to solve complex information problems. For instance, using the information handled by ERP systems or local data networks requires advanced knowledge and a capacity for teamwork (Bayo-Moriones, Billón, and Lera-López 2008). In addition, more advanced technologies will require qualified support staff to install and maintain them. Thus, the adoption of MTs and the use of highly skilled workers are complementary resources and the effects associated with the presence of one will be associated with the presence of the other.

With regard to the production systems adopted by companies, it is expected that the complementarity between resources allows systems to overcome their trade-offs. For instance, in batch systems, typically highly flexible but less productive, the presence of highly skilled workers may help MTs to enhance productivity by reducing the switching times and reconfiguring machines faster, or even through the ability to operate on multiple cells at the same time. In these systems, productivity gains can be achieved through the adoption of technologies that allow quick reconfigurations and changes (financial restraints may limit investments in robots, automatization systems, etc). This in turn requires skilled labour to control the handling of data, information systems, programming and control. For instance, an ERP system improves planning and control by translating customer choices into manufacturing instructions quickly and efficiently, which speeds up decision making. Not only the implementation but also the day-to-day adoption of an ERP requires specific knowledge and skills (Falk and Biagi 2017).

At the other extreme, manufacturing technologies such as CAM, computer-integrated manufacturing and flexible manufacturing systems enhance manufacturing precision and process flexibility and remove barriers to increasing product variety, mainly in mass process (Zhang et al. 2015). Continuous process usually produces a discrete number of products and adopts specific and capital intensive MTs aimed at improving the manufacturing side of process (less than the product side). Thus, specific MTs that assist in the storage, retrieval and manipulation of large quantities of process-related information are determinants of productivity and may help to improve the variety of products (Kotha and Swamidass 2000). The presence of highly skilled workers is a determinant for this purpose, enabling manufacturers to benefit from both economies of scale and economies of scope (Da Silveira, Borenstein, and Fogliatto 2001). Following this idea, adopting an efficient off-diagonal strategy characterized by a high volume-low standardization production system is more likely to be achieved using bundles of MTs including a wide number of technologies and techniques that reduce trade-off between systems (Clark 1996). Brown and Bessant (2003) stated that qualified workers and specific skills and capabilities are, in addition to any investment in technology, mandatory to facilitate this optimal strategy.

According to these arguments, we propose the following hypotheses:

H4: Workers' qualifications positively moderate the relationship between MTs and labour productivity in low volume-low standardization systems (small batch).

H5: Workers' qualifications positively moderate the relationship between MTs and flexibility in high volume-high standardization systems (mass and continuous).

H6: Workers' qualifications and MT adoption are complementary in explaining the likelihood of adopting an off-diagonal strategy (high volume-low standardization systems).

3. Hypothesis testing

3.1 Data collection

The data for quantitative analysis have been drawn from the Survey of Business Strategy, which is an unbalanced panel of Spanish manufacturing firms covering the period from 1990 to 2014. The survey was compiled by the Spanish Ministry of Science and

Technology and the Public Enterprise Foundation; it is random and stratified according to industry sector and firm size (Fariñas and Jaumandreu 2002). It provides information on markets, customers, products, employment, outcome results, corporate strategy, human resources and technological activities. The aim of the Survey of Business Strategy is to document the evolution of the characteristics and strategies used by Spanish firms. This survey is highly valuable because relatively few data sets contain information at the firm level about production systems and MTs over a period of several years. Although the survey has queried firms annually since 1990, information regarding firms' technology and manufacturing activities and employment characteristics was included only for the years 2002, 2006, 2010 and 2014. This does not permit us to assign a causality relationship, because the date of the MTs is unknown for other years (Gómez and Vargas 2012).

3.2 Measurements

To test hypotheses 1, 2, 4 and 5, two dependent variables were used that include two dimensions of manufacturing performance measures, mostly drawn from previous research studies: productivity per worker and new product flexibility.

The first dependent variable refers to the firm's productivity per worker. This is a commonly used productivity metric that measures the labour efficiency of a firm by transforming inputs into outputs (Bertrand and Capron 2015). The firm-level labour productivity is measured as the total value added divided by the total number of employees.

The second dependent variable corresponds to the number of different products manufactured by the firm; this variable captures the range of attributes of flexibility. It includes the unit's ability to anticipate the needs of markets and customers by providing a varied product mix and an increased range of tasks, obtaining timely supplies and rescheduling the order of production (Ling-yee and Ogunmokun 2008).

The database classifies organizations into three distinct production systems: small batch, mass production and continuous process. Specifically, the questionnaire asks if the manufacturing system is in small batches (fewer than 200 units), big batches or mass production (assembly line), manufacturing in continuous process, or other quantities. This classification permits us to test hypotheses 1, 2, 4 and 5.

To test hypotheses 3 and 6, we considered another denominated high volume-low standardization system variable*,* measuring the firm's ability to achieve customized products in large volume and in a cost-efficient way (Huang, Kristal, and Schroeder 2008). This variable is near to the 'mass customization' concept considered as a new paradigm in terms of product-process strategy. High volume-low standardization system is a dummy variable that takes the value 1 when the firm implements a continuous or mass production system but manufactures products with low standardization, and 0 otherwise.

Our independent variable 'breadth of manufacturing technology' (Breadth_MT) is a count variable that captures the five MTs usually adopted in the production process adopted by a firm. Specifically, we focus on computer numerical controlled machines, CAD, robotics, flexible manufacturing systems and local area networks. Therefore, this variable varies between the value of 0 if firms did not implement any of these technologies and 5 if all technologies are implemented. These MTs have been used in previous studies (Gómez and Vargas 2012).

The moderating variable ‘human capital’ (HC) was measured as the percentage of engineers and graduates among the total workforce; although this is not a perfect proxy to measure employee skill, it has been adopted from prior studies because it reasonably captures employee qualifications (Arvanitis and Loukis 2009; Gómez and Vargas 2012).

Furthermore, we included several control variables in our analysis. We controlled for firm size, measured by three categories of variable regarding the number of personnel. In this way, we differentiated between small firms that have up to 49 workers, medium-sized firms that have between 50 and 249 workers, and large firms with more than 250 workers. The small firms were used as the baseline category. Research suggests that firm size can potentially influence labour productivity (Bertrand and Capron 2015; Roca-Puig, Beltrán-Martín, and Segarra-Ciprés 2012) because large firms are associated with larger scale operations (Lannelongue, Gonzalez-Benito, and Quiroz 2017). To control for corporate status, we included a dummy variable indicating whether or not the firm is part of a larger business group. We account for the firm’s propensity to export via the export intensity variable, which represents the volume of export sales as a proportion of total sales. Research has shown that international trade is conducive to the bilateral exchange of information on new technologies (Gómez and Vargas 2012) and is positively related to firm productivity (Bertrand and Capron 2015). Consistent with other researchers, the percentage of share capital held by another firm was included as a control variable (e.g. Roca-Puig et al. 2012). Because the productivity of firms is closely linked to their respective industry sector (Bertrand and Capron 2015), we also controlled for the firm’s industry affiliation based on the classification proposed by the OECD in terms of technology intensity and knowledge intensity (OECD 2005). We created four dummy variables that identified high-tech, medium-high, medium-low and low-tech industries (see Annex 1). The baseline is low-tech industry. Finally, four years of dummy variables are included to control for unobservable factors that could affect productivity.

3.3 Model and estimation

This study estimates empirical models with panel data covering the period from 2002 to 2014 and a representative sample of the overall Spanish manufacturing industry. A total number of 7,741 observations allows us to control for unobserved heterogeneity of firms within the sample and for time-persistent effects (Benito-Osorio, Colino, and Angel 2016). To this end, two models—fixed effects or random effects models—were possible. The simple way to check for the best model is to compare the fit of standardized regression coefficients of the fixed effects model with those of the random effects model using a Hausman test (Hausman 1978). A Hausman specification test was implemented to compare the two models, which ascertained the validity for using a random effects specification. The p-value[2] of the test was insignificant, suggesting that the random effects model is more appropriate for this study.

Three regression models are used depending on the character of our dependent variables (Stata 14 software). The first model corresponds to a generalized least squares (GLS) regression, where the dependent variable is the productivity per worker. More specifically, we adopted a random effects generalized least squares design according to the Hausman test, which supported the use of the random effects model as the appropriate model rather than the fixed effects model for our GLS test. The GLS estimators are more efficient than the ordinary least squares for our specific model because they address the

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[2] The results of the Hausman specification test supported the use of random effects in the different models used in this study because there was not a systematic variation between the fixed and random effects estimations (p=0.10 for GLS regression; p=0.24 for the Poisson specification and p=0.11 for the logit model).

problems of autocorrelation and heteroscedasticity (Rothaermel, Hitt, and Jobe 2006) and thus ensure a robust analysis.

Our second dependent variable measures the flexibility of production process. The quantification of flexibility has been the object of study in academic literature. In this study, we consider one type of flexibility (Sethi and Sethi 1990), product flexibility, which measures the ease with which the manufacture of a product can be changed inexpensively and rapidly. Since our second dependent variable (product flexibility) is a count of the number of products and takes zero values, we used a random effects Poisson regression model. This model has been commonly used in previous studies because the Poisson specification incorporates zero values for the dependent variables rather than a negative binomial regression (Caner and Tyler 2015). A random effects logit model was used to determine the probability of a firm achieving high volume-low standardization of its products, which is our third dependent variable. This variable can take only two values: 1 if the firm achieved this production system and 0 if not.

Finally, to avoid multicollinearity problems associated with interaction terms, we followed Aiken and West's (1991) procedures. This involved centring the independent variables between the interaction terms and the variables that constitute them. In addition to reporting the significance and the signs of the estimated coefficients for the interaction terms, we calculated marginal effects and standard errors across a substantively meaningful range of the moderating variable, while the other variables were constrained at their means to bring meaningful and informative marginal effects (Brambor, Clark, and Golder 2005). Previous studies have shown that interpreting the coefficients on constitutive terms, as if they are unconditional marginal effects, could be misleading, especially when the statistical model is nonlinear (Seth and Lee 2017).

4. The results of hypothesis testing

4.1. Descriptive analysis

Descriptive statistics for all the variables used in our analysis are reported in Table 1. We split the sample into three main groups according to the product-process strategy: small batch, mass production and continuous process. In addition, we identified separately plants implementing an efficient off-diagonal strategy characterized by a high volume-low standardization production system. Of the total number of firms, 46.1 per cent utilise small batch production, followed by mass production (27.1 per cent), a high volume-low standardization system (19.2 per cent), and firms with continuous process (7.6 per cent). This distribution of companies corresponds to the structural characteristics of the Spanish manufacturing industry, where, as in the countries of southern Europe, small- and medium-sized enterprises predominate.

Relatedly, descriptive statistics show that both technology and workers' qualifications have low levels in the Spanish manufacturing industry. On average, the level of use of MTs is low; in no productive system was the value of 2 exceeded (the scale is 0 to 5). As expected, the lowest levels of MTs are observed in batch systems and the highest in mass production, mainly due to reasons of scale. On the other hand, the percentage of graduates and engineers does not exceed an average of ten per cent of the total workforce, which is lower than the average for other OECD countries but similar to other European countries such as Belgium, the United Kingdom and Norway. Firms with small batch production tend to have lower productivity and poorer employee skills than those with continuous and mass production systems. As was also expected, flexibility is higher in batch systems than in mass production and continuous process.

As far as firm size is concerned, all sizes (small, medium and large) are represented and reflect the overall character of Spanish industrial demographics. Small batch production firms are smaller in size—around 68.3 per cent of the firms are considered small, with the number of employees below 50—while 11.2 per cent of the firms have a size greater than 250 employees. However, mass production and continuous process firms present larger proportions of firms with more than 200 employees. The distribution of the number of employees for high volume-low standardization systems is equally distributed between small (35.9 per cent), medium (31.5 per cent) and large firms (32.6 per cent). Regarding the technological intensity of firms, small batch and mass production firms operate in sectors characterized by lower levels of technology (43.9 per cent and 57.7 per cent, respectively), whereas many of the firms with continuous process operate mainly in medium-low technology sectors (50.2 per cent). The share of high- and medium-low technology firms are similar in high volume and low standardization systems. The main sales market varies, as expected, by system of production; compared with mass production and continuous process productions, small batch companies are engaged in export activities to a lesser extent and are characterized by a lower percentage of share capital.

Table 2 displays the means, standard deviations and correlations of the variables in our analyses. Correlations among variables range from low to moderate. Furthermore, we also tested for multicollinearity problems, calculating the variance inflation factors (VIF) for all our variables. As a rule of thumb, VIF values higher than 10 show problems of multicollinearity, which adversely affect the regression estimates. Testing showed that mean VIF values were below 1.35; thus multicollinearity is not an issue in this study (Souto and Rodriguez 2015).

Tables 3–5 show the results of the different econometric models applied for each subsample (i.e. small batch, mass production, continuous process). We present the regression results in a hierarchical manner to illustrate the incremental predictive power associated with the addition of the main effects and the interaction effects in the analysis. Specifically, Model 1 represents the baseline model with all control variables; Model 2 introduces the predictor variables, MT and HC; and Model 3 introduces the two-way interaction. A Wald chi^2 statistic was carried out to evaluate the improvement in the model fit between the different hierarchical steps. The results show that all steps (from one model to the next) provide a significant improvement over their previous model.

[Insert Tables 1 and 2 here]

4.1. Direct effects

Hypothesis 1 suggested that the adoption of MTs is positively associated with high labour productivity, asserting that this effect is expected to be higher in high volume-high standardization systems (mass production and continuous process systems). The results obtained in Model 2 (Table 3) indicate that the coefficient of MTs is positive and significant only for mass production (β = 2.37, *p-value <0.01*) and not found to be significant for small batch (β = 0.26, *ns*) and continuous process (β = -0.11, *ns*) production. These findings partially support H1, which suggests that MTs are beneficial for mass production (but not continuous process) rather than for the other systems of production. In the case of continuous process systems, typically highly productive, the estimation results can be understood by the fact that in this system the relationship with productivity is mainly justified by the adoption of a small number of technologies, capital-intensive and centred on process improvement, which leads to high levels of productivity and efficiency.

Hypothesis 2 predicted that the adoption of MTs is positively associated with high flexibility, asserting that these effects are expected to be higher in low volume-low standardization systems (small batch). Results in Model 2 (Table 4) indicate that MT usage is positively associated with product flexibility in both small batch ($\beta = 1.03$, p-value <0.05) and mass production systems ($\beta = 1.05$, p-value <0.01), whereas for continuous process, the adoption of MTs was nonsignificant. Therefore, these results partially support H2.

Hypothesis 3 predicted that the adoption of MTs is positively associated with the achievement of high volume and low standardization. Results in Model 2 (Table 5) contribute positively to these types of process system. Hence H3 is fully supported.

Regarding the control variables, the results show that being part of a business group has a positive effect on labour productivity for all three production systems (Table 3) and on high volume standardization production systems (Table 5). However, business group seems not to have any effect on firm flexibility, given its nonsignificant coefficients, as Table 4 shows. Export activity is positively and significantly related to labour productivity only in the case of mass production (($\beta = 0.11$, p-value < 0.05; Table 3), and it is found to be negative and significant for firms with continuous process production ($\beta = -0.22$, p-value < 0.05; Table 3). Export intensity presents highly significant and positive coefficients for high volume-low standardization production systems. This indicates that international trade is an important diffusion channel for productive firms, especially those with mass production and high volume-low standardization production systems. Share capital is positively related to labour productivity for all three production systems (Table 3), and it also increases the probability of achieving a high volume-low standardization production system (Table 5). Concerning firm size, the results show that large firms are more positively related to firm profitability, production flexibility and high volume-low standardization products than smaller ones (Tables 3–5). Finally, firms in industries with higher technological intensity are positively associated with labour productivity in batch and mass production systems, and this is not significant in the continuous process (Table 3). Curiously, high-tech sectors do not favour the achievement of high volume-low standardization products, being not significant or negative in effect (Table 5).

4.2 Moderator effects

Hypothesis 4 predicted that workers' qualifications positively moderate the relationship between MTs and labour productivity in batch production systems. Model 3 (Table 3) tests this hypothesis by adding the interaction term between MTs and HC: the results show that HC positively moderates the relationship between MTs and performance in small batch systems ($\beta = 0.11$, $p < 0.05$). In order to gain more insights into precisely how human capital moderates this relationship, we plotted the marginal effect of MTs on firm productivity for different levels of the human capital variable (Figure 1). This type of graph, which is regularly used when examining interaction effects, allows us to correctly interpret the interaction effect in more detail. The marginal effects are illustrated by the solid lines and are calculated following work by Corten, Steijvers, and Lybaert (2017). The dots surrounding the two lines indicate 95 per cent confidence intervals. As can be observed, Figure 1 suggests a positive moderating impact of human capital on the relationship between MTs and labour productivity in small batch systems. The confidence interval bands do not cross zero for values of human capital greater than or equal to 20 per cent; therefore, when human capital rates are above those values, MT has a statistically significant impact on firm productivity. When the proportion of human capital is under 20 per cent for small batch systems and under ten per cent for mass production systems, the marginal effect of MT on firm productivity becomes insignificant (the lower 95 per cent confidence interval line crosses the zero line). These results support H4, which indicates that a high level of human capital helps firms to improve their productivity in small batch systems.

Hypothesis 5 postulated that workers' qualifications positively moderate the relationship between MTs and flexibility in mass systems. Model 2 (Table 4) provides individual support for H5, since the interactive effect of MTs and HC is positive and statistically significant ($p < 0.01$) for mass production systems ($\beta = 1.01$, $p < 0.05$). Figure 2 suggests a positive moderating impact of human capital on the relationship between MTs and product flexibility in mass production system. Both upper and lower 95 per cent confidence interval lines (dashed lines) are above the zero line when human capital is above zero per cent, corresponding to the fact that 79 per cent of the observations in the sample have HC values greater than zero per cent. These results suggest that HC is more helpful in creating product flexibility when industries adopt a higher level of HC in a mass production system. Human capital acts as a facilitator for exploring new technologies by firm, and for exploiting them to achieve high performance.

Finally, we do not find support for H6, since the interaction term between MTs and HC resulted in being not significant in high volume-low standardization production systems (Table 5).

[Insert Tables 3, 4 and 5 here]

[Insert Figures 1 and 2 here]

4.3 Robustness checks

Several additional checks were carried out to assess the sensitivity of the results to changes in our model specification. Firstly, we addressed endogeneity issues in our analysis by applying an instrumental variable approach. Specifically, we analysed whether our moderating variable is exogenous. The Durbin-Wu-Hausman endogeneity test is one of the most commonly used methods for ensuring the robustness of estimates potentially threatened by endogeneity. According to this approach, our regression results do not suffer from serious problems of endogeneity (Durbin-Wu-Hausman chi-squared test: 2.759; p-value = 0.10). Secondly, we used another alternative measure for firm productivity, and the results were highly robust to these changes in specification. Thirdly, we estimated our model using ordinary least squares and the results were consistent.

5. Discussion and conclusions

This paper deals with the trade-off between productivity and flexibility associated with the product-process strategy of manufacturing companies and on how the adoption of MTs and high qualifications for workers allows companies to overcome this trade-off. To this end, using a panel of data over a period of 13 years that included 7,741 observations of Spanish manufacturing companies, we analysed the impact of MTs and the qualifications of workers, individually and in interaction, to explain productivity results and flexibility in different productivity systems.

Results of our study empirically verify, firstly, that the effect of MT adoption on performance, measured as labour productivity and flexibility, is conditioned by the system of production adopted by the firm. For instance, when the organization operates in an environment where product variety is larger batch production, this requires organizations to implement MTs to achieve high flexibility. In the case of mass production, where the strategy is characterized by the production of large numbers of standardized products, the adoption of MTs can provide the firm with both high productivity and flexibility. However, our results show that a great variety of MTs have no effect on productivity when the production system is continuous. This outcome could indicate a key characteristic in these systems: the adoption of a small number of technologies, capital-intensive, centred on process improvement, which leads to high levels of productivity and efficiency.

Secondly, we can conclude that the relationship between MTs and manufacturing performance measures should not be analysed individually but in terms of how they interact with other factors, as suggested by Swink and Nair (2007) and Khanchanapong et al. (2014). Drawing on the resource-based view and complementarity theory, our study finds support that firms that acquired higher-level human capital are able to assimilate and exploit new and complex technologies to enhance performance. In this sense, it can be observed that for production systems characterized by low volume and low standardization (batch systems), the main effect of MTs on productivity is not significant. However, when considering a two-way interaction effect between MTs and workers' qualifications, the impact is positive and significant for labour productivity. These results highlight that workers' qualifications serve as infrastructure practices for the effectiveness of in this system. In addition, the trade-off of flexibility-productivity can be overcome.

In the same way, we observed that interaction between MTs and worker qualifications is synergetic in mass production systems, characterized by greater volume and greater standardization. Qualified workers generally possessed a great deal of knowledge about the machines, which allowed them to solve complex production problems and to achieve the expected work goals (Genaidy et al. 2010). Cross-functional teams avoid the waste of equipment downtime and speed losses. By investing in the acquisition of new skills, employees could more effectively absorb and deploy new process technologies relevant to firm performance. In addition, a high level of human capital enhances the firm's absorptive capacity and mitigates the high risk and uncertainty involved in adopting manufacturing technology. Our findings suggest that top-skilled staff act as a facilitating mechanism to understand, implement and manage such technologies.

Finally, the probability of a company designing a good off-diagonal P-P strategy is positively associated with the adoption of MTs rather than the qualifications of workers. This result would indicate that overcoming the efficiency and flexibility trade-off depends largely on the availability of MTs. Mass customization production is frequently led by developing sophisticated software systems to manipulate and control several manufacturing process requirements (Dean, Xue, and Tu 2009). MTs benefit the firm in creating customization volume effectiveness and cost efficiency to better meet heterogeneous consumer preferences.

5.1. Implications

This study also provides several managerial implications for manufacturers to understand the effect of MTs on their manufacturing performance. The study offers insights into how to enhance performance by exploiting the full potential of MT adoption. Firstly, our results indicate that investment in technology is not currently under discussion, regardless of the product-process adopted by the firm, and therefore manufacturers need to invest continuously in MTs. Organizations whose production systems are characterized by low volume and low standardization should leverage their manufacturing flexibility to produce a variety of products in significant quantities. However, despite this overwhelming evidence, this is a major challenge for the industry as a whole. As we indicated previously, small scale can limit companies in making the necessary investment to be competitive. A lesser challenge seems to be for companies engaging in mass production to invest in technology, because they could raise performance in terms of both productivity and flexibility.

On the other hand, we observed that the successful implementation of MTs depends on firms' ability to assimilate these technologies and exploit them to enhance performance. Organizations seeking MTs must develop internal capabilities that enable them to achieve high flexibility that meets specific needs, which is highly associated with the presence of qualified workers, because complementarity effects exist between the two factors. Accordingly, firms should invest in both MT and human capital assets simultaneously in order to achieve higher performance and overcome trade-offs of production systems. Again, the challenge seems to be large for those firms that produce in small batches, which typically are less attractive for qualified workers.

For academia, the results validate the continued adoption of the PPM matrix in operations management courses. The matrix is still relevant and can continue to help in designing strategies for production processes. In this sense, and in line with what some studies have pointed out, we have observed how the trade-off between flexibility and productivity can be overcome by means of technology, giving rise to the possibility of designing processes that allow competitive solutions for companies outside the diagonal (Ahmad and Schroeder 2002; Helkiö and Tenhiälä 2013). Also, this paper provides a rigorous empirical approximation to evaluate the medium-term strategy, using data over a long period of time and the econometric techniques suitable for its treatment. These techniques, not usually used in the field of operations, permit a major comprehension of phenomena, especially those involving resources and medium- to long-term decisions.

In sum, this study demonstrates how a long-term decision such as the design of a productive process can overcome natural barriers of efficiency and flexibility through technology adoption and human capital. Decisions remain strategic, but are, thanks to technology and human capital, less irreversible. They also demonstrate how technology can become a competitive strategic resource with appropriate qualifications of personnel, especially in mass production systems and small batch systems, to achieve improvements in flexibility and productivity respectively. Investing in human resources will permit a higher level of effectiveness with the implementation of MTs, which in turn will lead to significant improvements in firm performance. In this sense, the operations and human resource managers need to cooperate to produce flexible organizations and ultimately achieve success with manufacturing technology.

5.2. Limitations and future research

This study nevertheless has some limitations that should be overcome in future research. Firstly, our emphasis on human capital focused mainly on the workforce qualifications of engineers and graduates. Future researchers should investigate other kinds of dimension related to human capital, such as knowledge, talent, experience and training. Secondly, given the limitations of the database, this study only collected data from a Spanish survey. Future research should collect data from other countries on the differential impact of technology adoption and workforce qualifications on performance in order to develop more general empirical evidence that can be compared with the Spanish case. Finally, manufacturing technology is an umbrella term to describe a broad variety of technologies that include, in addition to those considered in this paper, others such as manufacturing resource planning or automated material handling systems. However, the emergence of new technologies like additive manufacturing that are capable of building complex 3D objects could considerably increase the flexible production of customized products. In addition, industry 4.0 is receiving a great deal of attention from researchers and practitioners (Lasi et al. 2014). Future research should analyse the fit of these new paradigms in manufacturing with the trade-offs of production systems analysed in this paper.

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Figure 1: The moderating effect of Human Capital on the link between AMT and firm productivity for small batch system

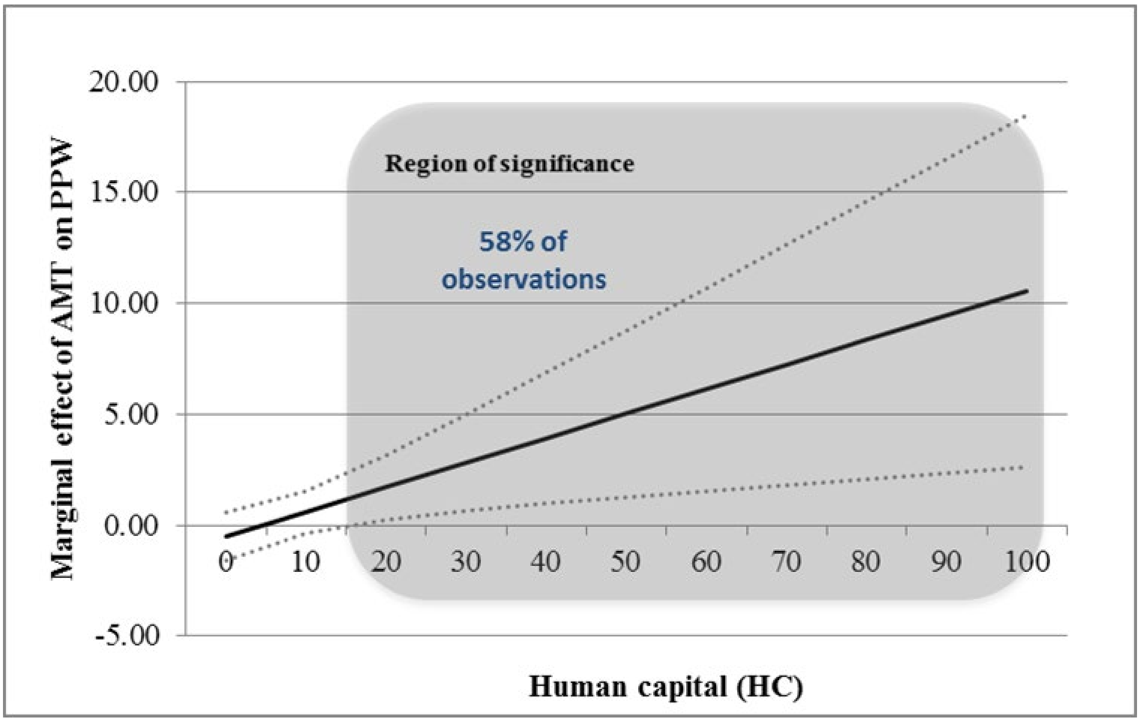

Figure 2: The moderating effect of human capital on the link between AMT and product flexibility productivity for mass production system

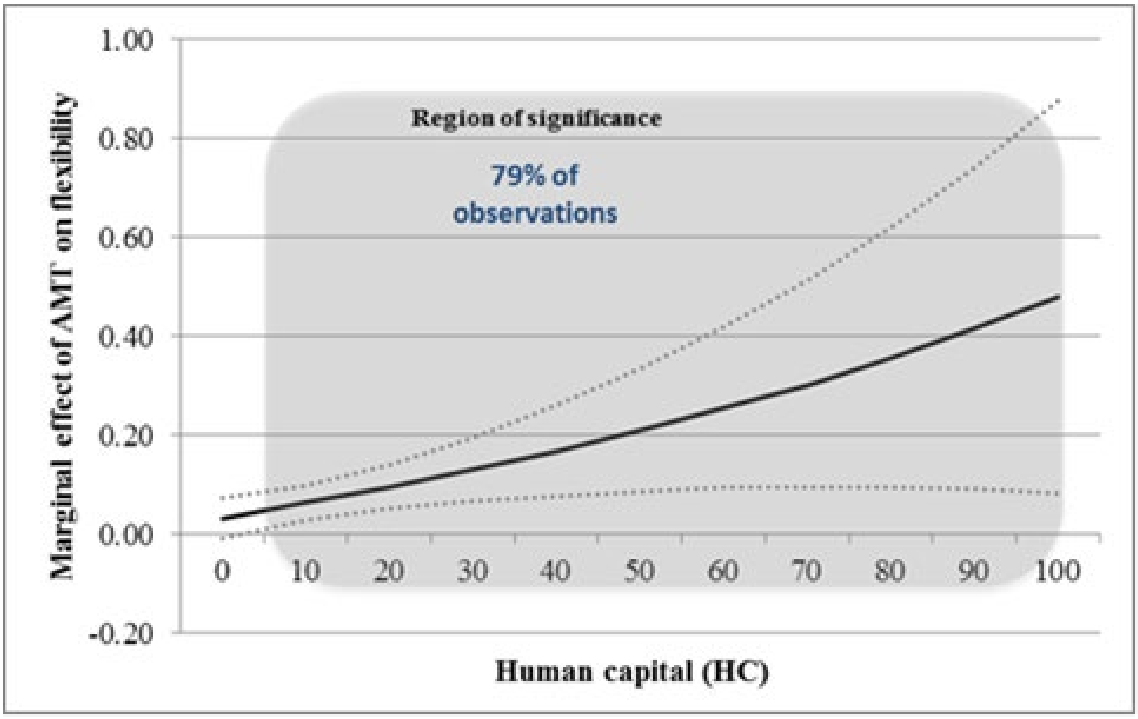

Table 1. Samples descriptive statistics

	Small Batch ***(N=3,568)***		**Mass production** ***(N=2,097)***		**Continuous process** ***(N=590)***		***High volume-low standardization*** ***(N=1,486)***	
	Mean	Std dev.	Mean	Std dev.	Mean	Std dev.	Mean	Std dev.
PPW	40.37	72.48	55.54	45.48	76.14	58.51	52.80	51.89
New product flexibility	1.19	0.50	1.16	0.44	1.18	0.48	1.18	0.47
MT	1.55	1.50	1.81	1.62	1.82	1.59	2.31	1.63
Human capital	5.54	8.63	7.41	10.13	8.02	8.37	6.32	7.11
Number of employees (size)								
Less than 50 (%)	68.33	-	35.93	-	31.20	-	35.88	-
Between 50 and 249 (%)	20.43	-	27.41	-	25.00	-	31.45	-
More than 250 (%)	11.24	-	36.65	-	43.80	-	32.68	-
Technological intensity								
Low-tech	43.89	-	57.72	-	33.39	-	37.25	-
Medium low-tech	28.53	-	19.15	-	50.18	-	32.53	-
Medium high-tech	21.41	-	11.31	-	1.28	-	23.17	-
High-tech	6.17	-	11.82	-	15.15	-	7.04	-
Export intensity	16.36	25.93	23.37	27.98	24.55	28.46	29.23	31.23
Share capital	7.51	25.65	20.47	39.36	25.32	41.93	23.06	41.29
Business group	0.14	0.35	0.33	0.47	0.41	0.49	0.35	0.48

Table 2. Correlation matrix

Variables	**Mean**	**S.D.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. PPW	50.35	62.97	1								
2. High volume-low st.	0.18	0.38	0.03*	1							
3.Product flexibility	1.16	0.49	0.01	-0.03	1						
4. MT	1.79	1.59	0.14*	0.16*	0.07*	1					
5.Human capital	6.37	8.81	0.25*	-0.04	0.02	0.14*	1				
6. Business group	0.25	0.43	0.21*	0.10*	0.02*	0.28*	0.23*	1			
7.Export intensity	22.94	29.22	0.18*	0.13*	0.03*	0.28*	0.17*	0.28*	1		
8. Share capital	14.74	34.62	0.19*	0.11*	0.02*	0.24*	0.19*	0.32*	0.30*	1	
9. Firm size	2.89	1.64	0.22*	0.12*	0.09*	0.46*	0.22*	0.46*	0.42*	0.44*	1
Vif			1.35	1.28	1.28	1.30	1.35	1.29	1.31	1.30	1.18

*$P < 0.05$

S.D, standard deviation; Vif, Variance Inflation Factor

Table 3. Hierarchical GLS model for Productivity per worker (PPW)

	Productivity per worker (PPW)								
	Small Batch			**Mass production**			**Continuous process**		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Controls									
Business group	0.17 ***	0.15***	0.15***	0.10***	0.08**	0.08**	0.17***	0.15**	0.15**
	(0.04)	(0.04)	(0.04)	(0.03)	(0.03)	(0.03)	(0.06)	(0.06)	(0.06)
Export intensity	0.03	0.03	0.03	0.11***	0.10**	0.10**	-0.22**	-0.21**	-0.21**
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.08)	(0.08)	(0.08)
Share capital	4.26**	4.16**	4.23**	15.43***	12.49***	12.49***	28.70***	28.03***	28.05***
	(2.07)	(2.08)	(2.08)	(2.40)	(2.39)	(2.39)	(5.67)	(5.68)	(5.86)
Large size	6.66**	6.23*	6.23*	9.99***	5.77*	5.77*	32.47***	29.22***	29.19***
	(3.31)	(3.32)	(3.31)	(3.00)	(3.10)	(3.11)	(6.81)	(7.04)	(7.04)
Medium size	2.04	2.03	2.17	5.35*	3.04	3.04	12.56*	13.04**	12.78**
	(2.16)	(2.17)	(2.17)	(2.73)	(2.72)	(2.72)	(6.50)	(6.46)	(6.46)
High-tech	17.35***	16.80	17.05***	14.83***	7.22**	7.22*	4.43	-3.93	-3.77
	(4.68)	(4.73)	(4.73)	(3.53)	(3.57)	(3.57)	(7.31)	(7.53)	(7.52)
Medium high-tech	10.20***	10.16***	10.20***	-6.56	-6.94*	-6.94	-17.06	-15.13	-15.48
	(3.72)	(3.72)	(3.72)	(3.73)	(3.70)	(3.70)	(20.13)	(19.87)	(19.88)
Medium low-tech	2.31	1.91	2.16	-4.21	-4.02	-4.02	1.47	3.08	3.22
	(3.46)	(3.46)	(3.46)	(2.84)	(2.79)	(2.79)	(5.00)	(5.01)	(5.01)
Main effects									
MT		0.26	0.19		2.37***	2.37***		-0.11	0.26
		(0.47)	(0.47)		(0.68)	(0.69)		(1.48)	(1.52)
Moderating Variable									
HC		0.21***	0.22***		0.99***	0.99***		1.14***	1.11***
		(0.07)	(0.07)		(0.10)	(0.10)		(0.30)	(0.30)
Two-way interaction									
MT*HC			0.11**			0.01			-0.16
			(0.04)			(0.05)			(0.17)
Wald χ^2	78.36***	85.16***	92.05***	247.2***	371.2***	371.1***	158.3***	181.1***	182.1***

*$p < 0.1$, **$p < 0.05$, ***$p < 0.001$; Standard errors between brackets; Note: Year dummy variables were included in the analysis but results are omitted here

Table 4. Poisson Regression Analysis for Product Development

	Number of Products Development								
	Small Batch			**Mass production**			**Continuous process**		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Controls									
Business group	0.94	0.92	0.97	1.07	1.05	1.06	0.98	0.98	1.00
	(0.05)	(0.05)	(0.04)	(0.06)	(0.06)	(0.06)	(0.09)	(0.09)	(0.09)
Export intensity	1.00**	1.00*	1.00	0.99	0.99	0.99	1.00	1.00	1.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Share capital	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Large size	1.24***	1.18**	1.14**	1.21**	1.12*	1.13*	1.30**	1.30**	1.23*
	(0.08)	(0.08)	(0.06)	(0.07)	(0.07)	(0.08)	(0.17)	(0.17)	(0.14)
Medium size	1.05	1.03	0.97	1.03	0.99	0.99	1.07	1.07	1.01
	(0.05)	(0.05)	(0.04)	(0.06)	(0.06)	(0.06)	(0.13)	(0.13)	(0.10)
High-tech	1.17	1.13	1.11*	1.14*	1.12	1.12	0.98	0.98	0.97
	(0.08)	(0.08)	(0.07)	(0.08)	(0.08)	(0.08)	(0.13)	(0.13)	(0.12)
Medium high-tech	1.08	1.06	1.05	1.15	1.09	1.11	2.04**	2.04**	1.03
	(0.05)	(0.05)	(0.06)	(0.08)	(0.08)	(0.08)	(0.63)	(0.63)	(0.22)
Medium low-tech	1.06	1.05	1.02	1.11	1.10	1.10	0.95	0.95	0.92
	(0.04)	(0.04)	(0.04)	(0.06)	(0.06)	(0.06)	(0.09)	(0.09)	(0.08)
Main effects									
MT		1.03**	1.03*		1.05***	1.03*		0.99	1.02
		(0.01)	(0.01)		(0.02)	(0.01)		(0.03)	(0.03)
Moderating Variable									
HC		1.00	1.00		1.00*	1.00		1.01	1.01
		(0.00)	(0.00)		(0.00)	(0.00)		(0.00)	(0.01)
Two-way interaction									
MT*HC			1.00			1.01**			0.99
			(0.00)			(0.00)			(0.0)
Wald χ^2	200.82***	207.95***	212.16***	141.87***	160.07***	168.8***	50.75	51.67***	51.72***

*$p < 0.1$, **$p < 0.05$, ***$p < 0.001$; Standard errors between brackets; Note: Year dummy variables were included in the analysis but results are omitted here

Table 5. Random-effects logit for high volume-low standardization achievement

	(1)	**(2)**	**(3)**
Controls			
Business group	0.29**	0.24**	0.24**
	(0.16)	(0.16)	(0.16)
Export intensity	0.01***	0.01***	0.01***
	(0.00)	(0.00)	(0.00)
Share capital	0.01***	0.01***	0.01***
	(0.00)	(0.00)	(0.00)
Large size	0.77***	0.45**	0.45**
	(0.21)	(0.22)	(0.22)
Medium size	1.04***	0.87***	0.86***
	(0.17)	(0.18)	(0.18)
High-tech	-0.50*	-0.42	-0.42
	(0.28)	(0.29)	(0.29)
Medium high-tech	0.37*	0.25	0.25
	(0.20)	(0.20)	(0.21)
Medium low-tech	0.61***	0.54***	0.54***
	(0.17)	(0.17)	(0.17)
Main effects			
MT		0.26***	0.28***
		(0.04)	(0.05)
Moderating variable			
HC		-0.02**	-0.01*
		(0.00)	(0.00)
Two- way interaction			
MT*HC			-0.02
			(0.04)
Wald χ^2	150.3***	182.02***	182.6***

*$p < 0.1$, **$p < 0.05$, ***$p < 0.001$; Standard errors between brackets; Note: Year dummy variables were included in the analysis but results are omitted her