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# Innovation in the product development process and performance of firm: An experience of value co-creation based on incorporation of technological innovations by the 3D modeling and additive manufacturing

Selma Regina Martins Oliveira[a,*], Jorge Lino Alves[b], Harry Boer[c]

[a]*Federal University Fluminense, Rua Nestor Rodrigues Perlingeiro - Aterrado, Volta Redonda – RJ,* 27213-14, *Brasil*
[b]*University of Porto,* Rua *Dr. Roberto Frias, 4200-465 Porto, Portugal*
[c]*Fibigerstræde 10, Building: 2-02, 9220 Aalborg Ø, Denmark*

* Corresponding author. Tel.: +55 24 3076 8700; fax: +55 24 3076 8700. *E-mail address:* selmaregina@webmail.uft.edu.br

**Abstract**

This article aims to show the influence of the incorporation of technological innovations based on 3D modeling and additive manufacturing on the performance of firm and value co-creation for client , in the perspective of product development process (PDP), systematized in two phases: elaboration and verification of a conceptual model. To confirm the conceptual model, a case study of multiple products was elaborated in a traditional segment of pewter in Portugal. The research involved the intervention of experts. Several support tools will be used to formulate the modeling to reduce subjectivity in the results: psychometric scaling – Thurstone's Law of Categorical Judgments (LCJ), Multicriteria Analysis-Compromise Programming, Electre III and Promethee II, Artificial Neural Networks (ANN) and Neurofuzzy Technology. The results were satisfactory, validating the submitted proposal, allowing to show that it is possible to combine additive manufacturing techniques and traditional processes of production of components in pewter and the incorporation of other components in composite materials and other metallic alloys, allowing to develop innovative products in very short time frames, with market acceptance and creating business value.

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*Keywords:* Incorporation of technological innovations, 3D modeling and additive manufacturing, Performance of companies, Front end fuzzy of the PDP

## 1. Introduction

Recently, relevant changes have made organizational boundaries more fluid and dynamic in response to the rapid pace of knowledge diffusion, and innovation and international competition [1]. This helps to reconsider how to succeed with innovation [2, 3]. One of the main challenges is to develop products in high complexity environments. In any case, product development is a complex chain of events and decisions, which can break at any of the weakest link: some projects lost due to unrealistic predictions or the absence of its real role in the agenda, or other motivations that somehow followed ideas that had many missteps or a detail error. The integration and the speed between the various stages of product development are essential elements in the competitiveness of companies. The quick transition from the concept of the product to its production is in fact an instrument of competitiveness in which the additive manufacturing is an innovative mechanism for the PDP, which enables time reduction between the conception and the placement of this product on the market, translating into reduction in investment costs and improvement in the quality of the final product. In this sense, the incorporation of 3D modeling and additive manufacturing technologies, when used in an appropriate way and based on


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projective methodology, enables innovation, regardless of the complexity of the object intended to be designed. Thus, this article aims to show the effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of companies, in the product development process (PDP). The article is divided according to the following sections: Framework of conceptual model and hiphotesis; Verification of the conceptual model and subjacent analyzes subjacent; conclusions and implications.

## 2. Methodology

### *2.1. Framework of Conceptual Model: Constructs and hypotheses*

This section examines the conceptual model (Figure.1) and presents the hypotheses to be tested throughout this work. The following variables and hypotheses of this study were raised:

*Independent Variables:* from the findings in the literature the following Characteristics of product development projects fuzzy front-end PDP were identified: Production capacity (PC); Congruence with the strategy (CS) ; Strength of the Client (SC); Market research (MR); Impact on Strategy (IS) ; Technical Complexity (TC) ; Costs (C) ; C*lient needs analysis* (CNA) ; Durability technical and market (DTM) ; Financial Risk (FR); Platform for growth (PG) ; Channels to Market (CM); Skills (SK); Access to external technologies (AET); Risks of environmental security (RES); Proprietary position (PP); Synergy with other business operations (SOBO); and Raw material (RM).

*Moderating variables*: from the findings in the literature were identified: Advanced systems modeling 3D CAD and rapid prototyping and additive technology.

*Dependent Variables:* the following dependent variables were selected for this research: *Performance of the Firm:* P1: Impact on Customer; P2: Business results; and P3: Percentage of Sales Innovative Products.

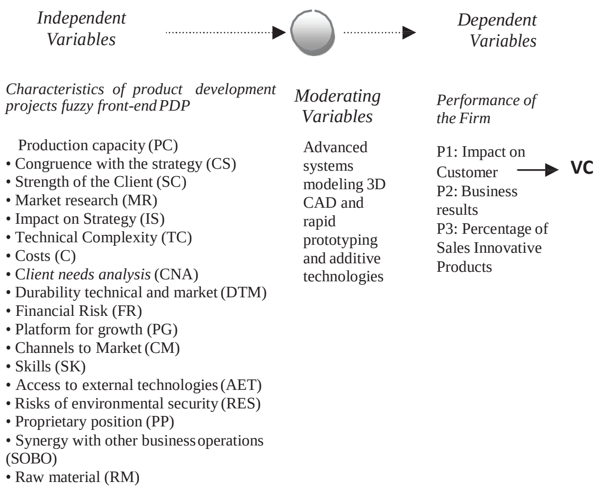


Fig. 1: Framework of Conceptual Model

*Hypothesis:*

*H1:* The modeling 3D CAD and rapid prototyping and additive technology influence to a greater or lesser degree the performance of firm in the front end fuzzy of PDP.

*H2:* Optimal Efficiency Rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company, in the front end fuzzy of the product development process depends on the combination and interaction of the projects characteristics of the companies.

## 3. Conceptual Model Verification and Underlying Analyses

This section presents the verification procedures for the conceptual model. This article aims to show the effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of companies, in the front end fuzzy of the product development process (PDP). This section is structured in three phases: Phase 1: Determination of Critical Success Factors (CSF) of firm. Phase 2: Identification and evaluation of characteristics of product development projects fuzzy front-end PDP in Relation to CSFs. Phase 3: Evaluation of characteristics of product development projects fuzzy front-end PDP in relation to performance of firm, under modeling and additive manufacturing, using Spearman. And Phase 4: Determination of effects of additive technologies and 3D on performance of firm in light of characteristics of projects. Next, these procedures were detailed.

*Phase 1: Determination of Critical Success Factors (CSF) of firm*

This phase is focused on determining the CSF, and is itself structured in two stages: (A) identification of CSF and (B) evaluation of CSF. As a result, a hierarchical structure of CSFs is obtained.

*Phase 2: Identification and evaluation of characteristics of product development in Relation to CSFs*

In this phase are evaluated the characteristics of product development projects fuzzy front-end PDP in relation to CSFs, in light of literature and the Method of Categorical Judgments of Thurstone (1927). Thus, the research is based on the literature and confirmed by the assessment of experts. In other words, prioritize the "characteristics of product development projects" according to their classification using the method Categorical Judgments. After this procedure, the following characteristics are evaluated using the multicriteria methods in the light of the data obtained by the experts. The methods used were *Compromise Programming, Electre III and Promethee II.*

*Phase 3: Evaluation of characteristics of product development projects - PDP in relation to performance of firm, under modeling 3D CAD and additive technology using Spearman*

In this section the evaluation of characteristics of product development projects fuzzy and performance of firm are determined using Spearman's correlation. The method is often used to describe the relationship between two ordinal characteristics. The data are extracted by the experts from a judgment matrix.

*Phase 4: Determination of the effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company using Neurofuzzy Technology*

This phase focuses on determining the optimal efficiency rate (OERP) of the effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company using Neurofuzzy Technology. It is a process whose attributes usually possess high subjectivity characteristics, in which the experience of the decision maker is very significant. Thus within this spectrum there is the need for a tool that allows adding quantitative and qualitative variables that converge towards a single evaluation parameter [4, 5]. Here this model supports the planning of technological innovation in companies, as it allows to evaluate the desirable rate toward the acceptable of the effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company. The model shown here uses the model of [4]. Based on the Neurofuzzy technology, the qualitative input data are grouped to determine the comparison parameters between the alternatives. The technique is structured by combining all attributes (qualitative and quantitative variables) in inference blocks (IB) that use fuzzy-based rules and linguistic expressions, so that the preference for each alternative priority decision of the optimal rate of the effects of the additives technologies and modeling 3D on the performance determinants, in terms of benefits to the company, can be expressed by a range varying from 0 to 10. The model consists of qualitative and quantitative variables, based on information from the experts. The neurofuzzy model is described below.

*Determination of Input Variables (IV):* This section focuses on determining the qualitative and quantitative input variables (IV). These variables are extracted from the independent variables (dimensions of Characteristics of product development projects fuzzy front-end. The linguistic terms assigned to each IV are: High, Medium and Low.

*Determination of Intermediate Variables and Linguistic Terms:* The qualitative input variables go through the inference fuzzy process, resulting in linguistic terms of intermediate variables (IVar). In summary, the fuzzy inference occurs from the base-rules, generating the linguistic vector of the OV, obtained through the aggregation and composition steps. For example, when the experts' opinion was requested on the optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company, the response was 8.0. Then the fuzzification (simulation) process was carried out, assigning LOW, MEDIUM and HIGH linguistic terms to the assessment degrees at a 1 to 10 scale. Degree 8, considered LOW by 15% of the experts, MEDIUM by 45% and HIGH by 40% of the experts. In summary, the expert's response enabled to determine the degree of certainty of the linguistic terms of each of the input variables using the fuzzy sets. The results confirm the H2: optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company, in the front end fuzzy of the product development process depends on the combination and interaction of the projects characteristics of the companies. The generic fuzzy sets were defined for all qualitative IVars, which always exhibit three levels of linguistic terms: a lower, a medium and a higher one. After converting all IVars into its corresponding linguistic variables with their respective DoC, the fuzzy inference blocks (IB), composed of IF-THEN rules, are operated based on the MAX-MIN operators, obtaining a linguistic value for each intermediate variable and output variable of the model, with the linguistic terms previously defined by the judges. With the input variables (features extracted from product development projects), the rules are generated. Every rule has an individual weighting factor, called Certainty Factor (CF), between 0 and 1, which indicates the degree of importance of each rule in the fuzzy rule-base. And the fuzzy inference occurs from the rule-base, generating the linguistic vector of OV, obtained through the aggregation and composition steps.

*Determination of Output Variable* – Optimal efficiency rate of effects of the Incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company

The output variable (OV) of the neurofuzzy model proposed was called Optimal Efficiency Rate of optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company. The fuzzification process determines the pertinence functions for each input variable.

*Fuzzy Inference:* The fuzzy inference rule-base consists of IF-THEN rules, which are responsible for aggregating the input variables and generating the output variables in linguistic terms, with their respective pertinence functions.

*Defuzzification:* For the applications involving qualitative variables, as is the case in question, a numerical value is required as a result of the system, called defuzzification. Thus, after the fuzzy inference, fuzzification is necessary, i.e., transform linguistic values into numerical values, from their pertinence functions [5].

## 4. Sample and Data Collection

The case study of multiple products was elaborated in a traditional segment of pewter in Portugal. The objective of this study is to present the effects of the advanced systems of additive technologies in the performance of company. The study was designed, based on the literature and confirmed by the assessment of experts. The data collection was performed using a scale/matrix assessment questionnaire. The technique used was the stated preference, taking into account that these methods work with the preferences of the decision makers, revealed by the choice made among the alternatives selected from a set of real alternatives, or not. In this classification framework, the research interviews and consultations with the experts are highlighted. The experts issued their judgments through a scale questionnaire for the first external validation. Before applying the final collection instrument, a pretest was conducted with experts to clarify whether the instructions were clear and objective; to verify that the questions were objective and without interpretation ambiguity; and to investigate possible comprehension problems by the experts on the expected responses. There were few adjustment suggestions. Next, a survey was conducted with experts, selected according to their technical-scientific criteria. The researcher regarded the new product project managers, experienced product planning personnel, innovation managers, engineers, designers, organizational managers, R&D managers, technology manegers, planning, technological innovation and modeling managers. The phases and steps of the model were based on the following methods: (i) Thurstone's Law of Categorical Judgment psychometric scaling; (ii) multivariate analysis; and (iii) multicriteria: Compromise Programming, Promethee II, and Electre III, and neurofuzzy technology. Next, these procedures were detailed.

*The Case Study of Multiple Products: Implementation and Results*

In this section, a case study is developed in the light of an innovative experience in product and process, It was performed by a multidisciplinary team consisting of designers, engineers and production technicians who have worked together to develop new products that were intended to be introduced into the national and international market through a partnership between two institutions of higher education and a pewter product company in, Portugal, whose traditional products developed by this company were in discontinuity of the innovation process. This project allowed to combine additive manufacturing techniques and traditional processes of production of pewter components and the incorporation of other components in composite materials and other metallic alloys, allowing to develop innovative products in very short time frames and contributing to an increase in the creation of business value. The multiple products investigated (Parts "Synesthesia", Effect in Candlestick - wax, M. Packaging, Identification L. Products, Cover Catalog, Candlesticks "Cube", Candlesticks "Lágrimas", Fruit Bowl Symbiosis and Gutta, Parts "Unda", Fruit Bowl "Nirvana", Solitary Spiral and Bellevalia, Parts Cube and Bateau, and Parts Spiral and Synesthesia, others) in this research are innovative for the company and for the market. From the first initial sketches to the introduction of products in the market, it took little more than five months. The company introduced a whole new line of products on the market, more innovative, within a short period of time, through the adoption of new methods and new product development technologies, such as 3D CAD modeling, use of virtual "prototypes", additive manufacturing technologies to obtain prototypes for viewing, conversion technologies and rapid manufacturing of tools for production of functional prototypes and final pieces. The innovation and introduction of design and new projective methodologies in this type of enterprise of traditional nature allow a more efficient return of funds, definition of more innovative, more aggressive and of higher quality strategies of product and market in order to increase business value and gain sustainable competitive advantage in the global market. The study presents the PDP, the manufacture and placement on the market of pewter products aimed at innovating developed products and, simultaneously, it introduces new methods and product development technologies in the referred company. Thus, it was possible to know the details of the PDP of this company.

*Product Development*

*Centrifugal Casting:* This is one of the most used processes in the company, as it allows large production output.

*The 3D CAD Modeling:* All of the objects made were modeled in SolidWorks 2007 software. The use of this tool allowed to build virtual simulations of the objects, their adjustment and correction whenever necessary. Once the phase 3D CAD modeling was completed, the files were converted in the format *.vrml to make its reading in Cinema 4D software possible. From the 3D modeling it was possible to create the technical drawings of all the parts to create a technical file to be consulted by the employees of the company during the manufacturing process. The files of some of the pieces developed were converted to the format *.stl to make prototyping in the stereolithography possible (additive manufacturing).

*Prototypes in Stereolithography:* Stereolithography is a process that provides for the production of three-dimensional prototypes by photopolymerization, layer by layer, of a liquid resin (epoxy, polyester or vinylester) through the incidence of a laser beam of ultraviolet rays. The Cube, Bateau and Stroke pieces were selected to be manufactured by this process.

*Developed products*

The Figure 2 shows a piece obtained by plastic deformation where the spiral shape functions as an extension of a flower (Solitary).

Fig. 2: Solitary Spiral and Bellevalia

The other single one involved casting/foundry and welding process. In both cases, glass test tubes are used to count the flower and the water.

*Fruit Bowls:* In this product segment, the piece is made of pewter with two elements in epoxy resin or polyurethane, which can be varied from object to object to the formal and the material level, with the possibility of mixing it with pewter powder, sand, mica, coconut fiber or other materials.

*Candlesticks:* This project was conceived with the intention to use a base in carbon fiber, where the pieces of pewter supporting the candles are glued. The parts of pewter were obtained by spinning pewter plates, using a mold obtained from the additive manufacture model. In summary, the process of product development was backed by the theoretical clippings: development of the concept of product, development of project scope, production preparation, launch and post-launch of product.

*Underlying Analises*

This section is structured in three phases: Phase 1: Determination of Critical Success Factors (CSF) of firm. Phase 2: Identification and evaluation of characteristics of product development projects in Relation to CSFs. Phase 3: Evaluation of characteristics of product development projects fuzzy front-end PDP in relation to performance of firm, under modeling and additive manufacturing, using Spearman. And

*Phase 4: Determination of effects of additive Technologies and 3D on performance of firm in light of characteristics of projects.* Next, these procedures were detailed using the "Synesthesia" product.

*Phase 1: Determination of Critical Success Factors (CSF) of firm :* The section present the results of c*ritical success factors (CSF) of firm (Table ).*

Table 1: Classification of CSF

| **Stimulation** | **C1** | **C2** | **C3** | **C4** | Classification |
|---|---|---|---|---|---|
| Market | -1,2 | -1,2 | -0,8 | -0,1 | **1º** |
| Economical and Financial | -0,8 | -0,1 | 0,13 | 0,76 | **3º** |
| Environmental | -0,1 | 0,43 | 0,76 | 3,86 | **5º** |
| Political | -1,2 | -0,8 | -0,4 | 1,22 | **2º** |
| Technical | -0,8 | 0,13 | 0,76 | 1,22 | **4º** |

*Phase 2: Identification and evaluation of characteristics of product development projects fuzzy front-end PDP in Relation to CSFs*

This section evaluates the characteristics of product development projects fuzzy front-end PDP in Relation to CSFs. This procedure was developed using the multi-criteria analysis, with the methods Compromise Programinng, Electre III e Promethee II. The results produced by this prioritization enable managers to better focus their efforts and resources on managing the capacities that perform best, which results in achieving the goals sought by the companies The structure of this prioritization (classification by hierarchical analysis) is proposed at three planning levels in a judgment matrix, in which at the first hierarchical structure level it defines the goal, which is to achieve the value creation for companies that will feed the system; the criteria are in the second level, which are the performances of the companies: Performance of the Firm: P1: Impact on Customer; P2: Business results ; and P3: Percentage of Sales Innovative Products. The characteristics of product development projects fuzzy front-end PDP are: Production capacity (PC) ; Congruence with the strategy (CS); Strength of the Client (SC); Costs (C); Market research (MR); Impact on Strategy (IS); Others. The prioritization process obeys the judgment of the evaluators (experts). With the results of the judgment matrix, the methods were applied: Promethee II, Electre III and Compromise Programming to evaluate the innovation capacities in relation to the performance of the companies. Next, the degree of correlation between the dimensions of projects characteristics and performance of the firm, under modeling 3D CAD and additive technologies was determined. For this Spearman's multivariate statistical technique was used. The technique adapts to the case in question.

*Phase3: Determination of the effect of additive technologies in the Company performance in the light of the characteristics of the projects*

The variables produced by ROI – Business results and Additive Technologies and Modeling 3D are strongly correlated. It is believed that this partnership is not a recent event in company. From a business perspective, this can be explained by the need to conduct new technologies for development of new products and processes; in addition to product quality improvement. Innovation. The Congruence with the strategy (CS), Market, Strength of the Client (SC), Production capacity (PC) / Access to external technologies (AET) and Additive Technologies and Modeling 3D are strongly correlated and together have a strong influence on the business return dimension. From a global industry perspective, a country's competitive position is dependent on the relative strength and weakness of other companies. In fact, the modeling 3D CAD and rapid prototyping and additive technology influence to a greater or lesser degree the performance of firm in the front end fuzzy of PDP. In this perspective, value create for the business.

*Phase 4: Determination of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of companies, in light of characteristics of projects using Neurofuzzy Technology*

This phase focuses on determining the optimal efficiency rate of the effects of the incorporation (OEREI) of technological innovations based on 3D modeling and additive manufacturing in the performance of companies, in light of characteristics of projects using Neurofuzzy Technology [4, 5]. The results is described below.

*Determination of Input Variables (IV):* This section focuses on determining the qualitative and quantitative input variables (IV). These variables were extracted (15 variables) from the independent variables (dimensions of *characteristics of projects* of the company). The linguistic terms assigned to each IV are: High, Medium and Low. In summary, based on data collected, to achieve this step, the top 15 projects characteristics (Production capacity (PC); Congruence with the strategy (CS); Strength of the Client (SC); Market research (MR); and Others. For example (hypothetical), when the expert's opinion was solicited about which desired degree of projects characteristics the product development manager should have, the answer was 7.0. Next, the fuzzification process (simulation) took place, assigning the linguistic terms: LOW, MEDIUM and HIGH levels of evaluation on a 1 to 10 scale. For score 7, considered LOW by 0% of the specialists, MEDIUM by 55% and HIGH by 45%. The fuzzy inference takes place from the base of rules, generating the VS linguistic vector obtained through the steps of aggregation and composition.

*Determination of Intermediate Variables and Linguistic Terms:* The qualitative input variables go through the inference fuzzy process, resulting in linguistic terms of intermediate variables (IVar). Thus, the linguistic terms assigned to IVar are: Low, Medium and High. The intermediate variables were obtained from: A - Market Performance: Channels to Market (CM), Strength of the Client (SC), Market research (MR), C*lient needs analysis* (CNA), Access to external technologies (AET); and Others. The architecture proposed is composed of nine expert fuzzy system configurations, qualitative input variables that go through the *fuzzy* process and through the inference block, thus producing an output variable (OV), called intermediate variable (IVar). Then, the IVars, which join the other IVar variables form a set of new IVars, thereby configuring a sequence until the last layer in the network. In the last layer of the network the output variable (OV) of the *neurofuzzy* Network is defined. This OV is then subjected to a defuzzification process to achieve the final result: Optimal Efficiency Rate. The results confirm the *H2: Optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company, in the front end fuzzy of the product development process depends on the combination and interaction of the projects characteristics of the company.*

*Determination of Output Variable* – Optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company. The output variable (OV) of the neurofuzzy model proposed was called optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company (by type of product). By way of demonstration, using assigned IT (average) hypothetical Parts “Synesthesia”, Effect in Candlestick - wax, M. Packaging, Identification L. Products, Cover Catalog, Candlesticks "Cube", Candlesticks "Lágrimas", Fruit Bowl Symbiosis and Gutta, Parts “Unda”, Fruit Bowl "Nirvana", Solitary Spiral and Bellevalia, Parts Cube and Bateau, and Parts Spiral and Synesthesia. The numerical value scale corresponds to value for optimal efficiency rate (0,8936 – corresponds all the products). With this result (optimal efficiency rate) produced for a better combination and interaction of strategic innovation projects of products multiples of the Company that converged toward a single parameter, To illustrate this, assuming that the study-object company demonstrate the following optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company by type of product (Figure 3).

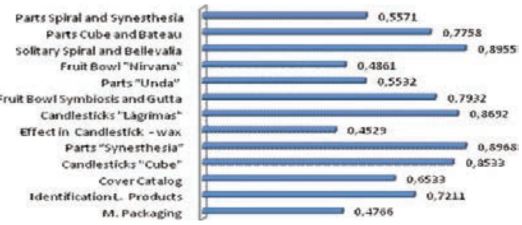


Fig. 3: Optimal efficiency rate of effects of the incorporation of technological innovations based on 3D modeling and additive manufacturing in the performance of company for each product

The expected reference performance for all products is 0.7756 (hypothetical). It is concluded that: Candlesticks "Cube", Parts “Synesthesia”, Candlesticks "Lágrimas", Fruit Bowl Symbiosis and Gutta, and Solitary Spiral and Bellevalia products, show efficiency in the combination of their innovation activity strategies and value creation, based on the performance expectations (P1: Impact on the Customer; P2: Business results, P3. Percentage Sales of Innovative Products).

## 5. Conclusions and Implications for Practice Management

In fact, the company object of this research introduced a whole new and more contemporary line of products on the market in a short period of time. This was due to the adoption of new methods and new product development technologies, such as 3D CAD modeling, the use of virtual "prototypes" in the perspective of meeting customer expectations, the use of additive manufacturing technologies to obtain prototypes for visualization and conversion technologies and rapid manufacturing of tools for producing functional prototypes and final pieces. From different dimensions, the results refer to the additive technologies as a mechanism that leads to increasing business value from the perspective of the project, consistency with the strategy, production capacity, strength of the client/market need, technical competence and cost. In the research, a survey was developed for company in Portugal in a static context, which may represent a limiting factor. Therefore, it is recommended to reproduce and replicate the model in companies from other countries in order to confirm the results. Nevertheless, the capacity to innovate companies will have to be anchored in efficient planning policies.

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