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Manufacturing Process Selection Integrated in the Design Process: Test and Results.

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Abstract

Research about selection has been focused to the material and current process selection methodologies/tools have problems. Consequently, a methodology for preliminary process selection was created through its integration in a design process. It allows manufacturing influence in early design stages through creating organizational knowledge. This storage of learning, integration and minimum viable product are key aspects. This paper addresses its application in industrial and university environments: manufacturing companies, design professionals, subject and final degree project. The obtained results show that methodology is validated and that the use of existing Manufacturing Process Selection methodologies is not enough for a correct selection.

Keywords: Manufacturing Process Selection; Design for Manufacturing and Assembly; Design Process; Spiral knowledge; vertical integration; horizontal integration; university; industry.

1. Introduction

Manufacturing process selection (MPS) according to their possibilities and limitations in the first design stages has great importance in the product development [1–3]. Due to this, preliminary selection methodologies are necessary to use them in the industrial and university environments. In this last situation, these methods are applied for the improvement of future professionals' capabilities while the insertion of this kind of tools to their future companies is reached. In fact, the origin of the proposed methodology is an Interactive Training Material (ITM). It was the answer

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to the low capacity of students to select manufacturing processes while they were developing their projects (i.e. Industrial Design and Product Development students).

The goals of this work were the validation and adaptation of the methodology called 'Manufacturing Process Selection Integrated in the Design Process' (MPSIDP) for the different application environments. That is to say, the results of this first industrial and educational testing, which are shown in this paper, guide the future of the MPSIDP methodology. The changes adopted from these results are shown in the paper called 'Manufacturing Process Selection Integrated in the Design Process: University and Industry'.

According to the structure of this paper, state of the art and the description of the MPSIDP methodology are addressed in the second section, in the third section the materials and methods used to test MPSIDP are shown, in the fourth section the results because of applying these materials and methods are presented and, finally, in the fifth section the paper is finished with a conclusion of the results and future works.

2. Background

2.1. Manufacturing process selection and Design for Manufacturing and Assembly: MPSIDP methodology basis

On the one hand, three critical aspects must to be select during the Design Process (DP) [4]: shape, material and manufacturing process. These areas can be selected independently in the initial stages of design, but then they begin to interact in a complex way. Consequently, designers can focus on a selection area, e.g. manufacturing process. According to the level of detail, MPS is differentiated into three stages [4]: preliminary selection, functional selection, and task-based selection. Even though the profuse research about the selection since the latter half of the 20th century [5,6], this research has be addressed to get the material selection, instead of preliminary selection of the manufacturing process. Nowadays, some MPS solutions have emerged, but to select the process with high concretion, even to achieve the process planning [7] or to approve or not a specific process [8]. Moreover, many of them follow the tendency to use artificial intelligence. Thusly, the MPSIDP belongs to this preliminary selection which lets evaluate a wide set of manufacturing process and it can be managed by organizations (employees and students) more easily. After that, each possible process is analysed in detail to select the final candidate and, finally, other tools or methodologies can be utilised to find the optimal design and manufacturing process (this is the task-based selection).

Today, several analytical and graphical tools, procedures and methodologies are widely utilised to do the preliminary selection. Some of them [1,2,9,10] were analysed and potential aspects to evaluate or improve them were found: promoting the integration of manufacturing aspects in the design requirements establishment, transforming from a linear approach to an iterative development, reducing the probability of obtaining failed candidate to manufacturing process due to functional an non-functional variables are not differentiated between and the designer do not have recommendation about the value of requirements establishment, and last, integrating the MPS in the DP. To address this last point, first step was the election of most suitable DP according to the objectives. Between the different existing proposals of DP (more or less creative or systematized methods) [11,12] Gero's function-behavior-structure (FBS) framework [13] was chosen due to its classification of variables and the possibility of reformulations [14]. This DP improves the linear ones because it includes the classification of variables in function-behavior-structure and the reformulations, which address to the iterative approach.

On the other hand, several solutions of Design for Manufacturing and Assembly (DFMA) have been developed to apply design considerations related to manufacturing in the DP: general principles and guidelines, rules and design guidelines of each process [12,15], simulations that estimate the part cost or quality [10], design catalogues [16], etc. Besides the design guidelines, a well-defined and quantifiable method for comparing alternative designs is necessary to make decisions [17]. In effort to get that, DFMA guides have been developed inside the MPSIDP. However, majority of existing design guidelines are oriented as restrictions without clarifying their level of demand (essential or recommendable) in order to arrive at compromise solutions. Because of this, in the MPSIDP the functional nature and the requirement level were included in the guides. Moreover, general and specific guidelines are necessary of each manufacturing process, so these have been taken into account in the MPSIDP.

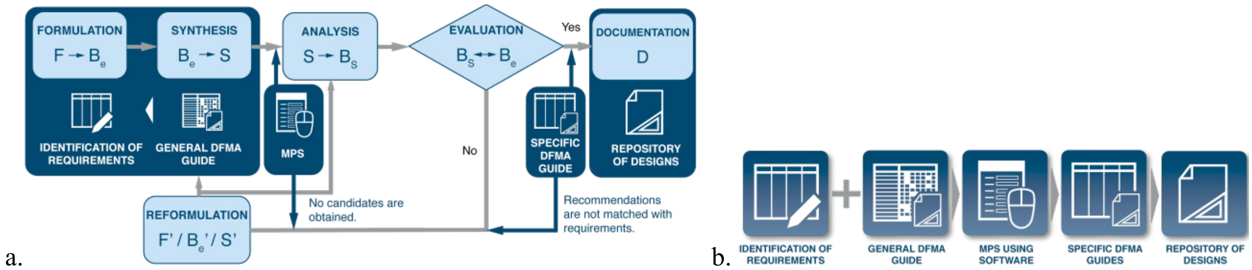


Fig. 1. (a) modification of Gero's FBS Framework; (b) MPSIDP methodology in five stages.

2.2. MPSIDP methodology: brief description

This methodology is based on Gero's DP but it introduces several changes to include the MPS in early design stages and to answer the problems about the current MPS methodologies. Despite the fact that the complete process of the MPSIDP follows more complex fundamentals and flow diagram, which are included in 'Manufacturing Process Selection Integrated in the Design Process: University and Industry' (presented in this conference too) and other papers [14], the MPSIDP can be summarized in (see in Fig. 1): (1) an 'identification of requirement', it means, the FBS variables from the initial design; (2) this first stage is done through the use of general DFMA guide to select the values of these variables; (3) use of a software to select from the identified FBS variables and this stage ends with the *Analysis* and the *Evaluation* of the candidate processes; (4) creation or improvement and use of the specific DFMA guides; (5) and integration of the project documentation in the repository of designs.

In addition, MPSIDP is based in the use of knowledge and resources generated by a group of people from their experience (i.e. it follows the Spiral knowledge methodology [18]). These resources are the specific DFMA guides (4th stage) and the documents in the repository of designs (5th stage), which are created, increased and improved by users of the MPSIDP. In this way, the experiential knowledge (tacit) is transformed in an exteriorised knowledge (explicit), in which data and information can be easily transmitted and shared by a big group of people, in this case, the remainder of the organisation.

3. Materials and methods

3.1. Software and resources

CES EduPack, which is the teaching resource of Cambridge Engineering Selector (CES), has be used to reach 3rd stage (selection of candidates using a software) in the university environment because the ULPGC library has licence. However, other tools can be utilised for the selection because MPS methodologies have in common the features that are taken into account (see it in the related paper that was presented in this conference). CES is a resource for materials in science, engineering, manufacturing and design and it is a result of the Mike Ashby's and Cambridge University publications [19]. Although this software is a material selector and not a specific MPS methodology, it includes a module that can select a preliminary manufacturing process. This selection is done through numeric limits, relation between databases ('tree') or charts.

As information sources to complete the specific DFMA guides (4th stage), many reference texts in manufacturing were utilised by students [1,20–22]. Among them, the PRIMA matrix (PRocess Information MAp) stands out because this methodology provides engineers and designers with process knowledge and the essential technological and cost data to guide the selection of manufacturing processes early in the product development [1]. In a middle stage of this methodology, datasheets of each process, which contents technical and economic features, must be looked up, one by one. Actually, this information from datasheets improved specific DFMA guides because it is about variables FBS (roughness, thickness, dimensions, etc.) and design considerations (draft angles, corners, part complexity, process flexibility, etc.). In the case of the companies (industrial environment), some of them provided their own experience for the creation of the specific DFMA guides (their machines, projects…).

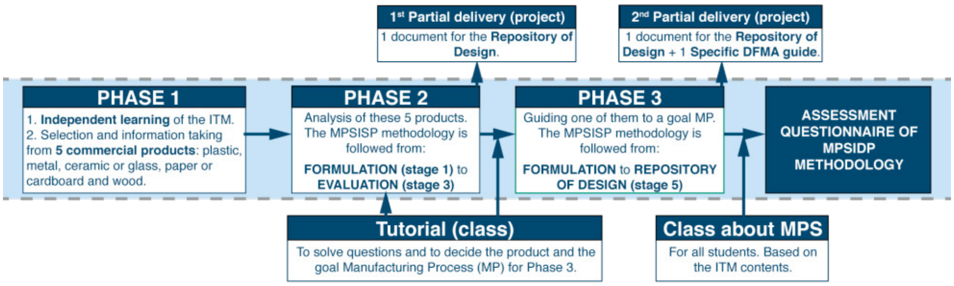


Fig. 2. Process that was followed during the course activity in the subject called *Procesos Industriales*.

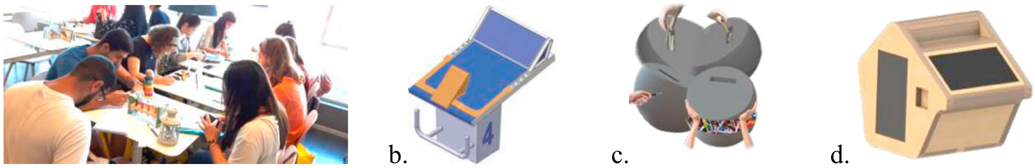
a.  b. c. d.

Fig. 3. (a) students of *Procesos Industriales* taking information in 1st phase. Designs made by students of TFG: (b) swimming device; (c) stationery waste container; (d) and exhibition device. Images courtesy of each TFG student. All rights are reserved.

Related to the format in which the information is collected, eXeLearning was utilized in university environments. In the industrial environments, despite the first test has been done with a text processor, the use of a CMS platform will be evaluated in the future to manage the information. The eXeLearning is an educational content creator that permits to export the result in a compatible format with LCMS platforms (SCORM format) and in HTML.

In both university and industrial environments (the professionals in this last case only), Google Forms has been utilized. However, an interview format was chosen for local companies in order to extract more information.

3.2. Implementation method in the university environment

The methodology implementation in the university environment is being carried out at different levels (master's thesis and PhD programs), although the results of these paper focus on the application in the degree called Engineering in Industrial Design and Product Development (EIDPD) in the ULPGC. To proof the utility and possibility of application of the MPSIDP, a course activity was designed to be tested by a student group from the subject called *Procesos Industriales* (manufacturing process introduction subject) during 2017/18. The project was carried out in three phases, after that, the students answered an assessment questionnaire about the MPSIDP and the ITM. The application process of this course activity is shown in the Fig. 2.

On the other hand, the MPSIDP was applied to EIDPD students' designs final degree project (*trabajo de fin de grado*, TFG, in Spanish) in 2017/2018 too (images-b-c-d Fig. 3). These students used the methodology in a guided way during two sessions. In the first of them, the 3rd stage of methodology was reached with the students. Afterwards, the person in charge of the activity generated the specific DFMA guides for the candidate processes and the document for the repository of designs. It should be noted that these students did not create and complete the specific DFMA guides because they had little time and, if the methodology is applied in subjects, TFG students will use the guides that the students of the subjects have created. In the second session, the students applied the specific DFMA guides in their designs and they carried out the necessary redesigns. Finally, they answered an assessment questionnaire about the MPSIDP methodology.

In addition, several professors were consulted about their assessment of the MPSIDP. This required the access to the ITM, which students of *Procesos Industriales* used in HTML format, the description of course activity, an explanatory presentation with audio and an assessment questionnaire.

a. b. c. d.

Fig. 4. Products of companies: (a) shelf stringer, (b) bin, (c) protective housing for interphone and (d) anchor plate. Images courtesy of each company. All rights are reserved.

3.3. Implementation method in the industrial environment

In the industrial environment, the interest vs. applicability and the validation of the MPSIDP were tackled by two groups: local manufacturing companies and professionals that belong to Industrial Design Engineering and Product Development in multinational companies or located abroad.

With the local companies, the application and validation of the methodology in one of their catalogue products were decided (see Fig. 4). Consequently, the MPSIDP was explained to the company contact, then the results of its application from technical data of the product, which had been provided by the contact firstly, were shown too. Before starting this process, the company contact had done an initial questionnaire about their current DP and it included a MPS test. Finally, a final questionnaire about MPSIDP aspects (e.g. interest, applicability, failures and improvements) was given to get their assessment.

Related to the professionals, they were consulted about their assessment of the MPSIDP. That was achieved through initial and final questionnaires, which were similar to the questionnaires of the local companies. Because they needed to know the methodology, an explanatory document about the MPSIDP in HTML (i.e. the ITM) and an explanatory presentation with audio were provided.

4. Performance and results

Next, the main results of the activities that are described above are shown and analyzed. Both application results of the MPSIDP methodology and the results of the assessment questionnaires are discussed.

4.1. In the university environment

After finishing the course activity about the application of the MPSIDP by students of *Procesos Industriales* subject, the following observations are deduced:

- Because of analyzing commercial products, in many cases only one or two candidates in 2nd phase (around 67% of the cases) were obtained. In addition, the number of necessary redesigns, which resulted from the application of design considerations from guides, was low in the 3rd phase, so can be more interesting to apply the 3rd phase in own designs. However, this is impossible in a manufacturing process introduction subject.
- The way in which the product choice was designed in the 1st phase achieved to take into account a wide variety of processes in the specific DFMA guides created (3rd phase): manufacturing processes for metallic, plastic, glass and wood parts, which belong to casting, moulding, forming, machining and sheet forming processes. In the case of they have enough quality, these guides will be available in following courses and this reduces the number of guides that would be necessary to create and existing ones would be improved.
- Some processes that were obtained in the 2nd phase are wrong (33% student had this problem). These wrong candidates result from both students' mistakes and application problems in the course activity. The following causes stand out: (1) mistakes when defining the shapes of parts and a lack of process data in the selection software, (2) wrong use of the software and the methodology because of doubts that resulted from an independent learning of the ITM and that were solved in classes, (3) and the tendency to copy the only application example that existed at that moment. Eliminating these and other sources of mistakes was the goal of modification for the following

course activity. It should be noted that the third point is solved by the resources generated by the students, because the number of different examples of the MPSIDP application in course activity will increase.

Related to the analysis of the final assessment questionnaire in *Procesos Industriales*, the 75% of the students expressed their agreement with this statement: if only they had had the CES (without the MPSIDP) they would have used discrete values to select instead of ranges (as the general DFMA guide proposed). Moreover, all of them said that they would have accepted the candidate process of the CES if it had been only one, so it means the limitation of the possible candidates and the increment of the probability of obtaining invalid processes. Besides, the 75% of them were unsure about being able to tackle the selection only with the knowledge of the subject (without MPSIDP). This is confirmed by the results that were obtained in the MPSIDP application in TFG. These students recognized that they resorted to tutors or other teachers to carry out the MPS (see it in TFG results in this section). This shows the importance of teaching this type of methodologies before the TFG subject and the access to only MPS software (e.g. CES) is not valid. On the other hand, in the subject, most of answers were “agree” or “strongly agree” (69% on levels 4-5 of a 5-point Likert scale) about the contribution of the MPSIDP in their learning of the manufacturing processes. In fact, as positive aspects, they stood out the practical way of approaching the MPS through the analysis of commercial products and the use of resources from previous courses as an example, being able to apply this methodology in following projects. However, they expressed that understanding the ITM was difficult without a previous explanation and they would have needed more concrete examples about course activity. The rest of questions was about formal and learning features of ITM. They positively appreciated the design, multimedia resources, content quality and efficiency of ITM, specifically, for their future academic background and career. In contrast, their assessment about functionality and ease of use, in which independent learning was included, is lower.

The MPSIDP application in TFG students’ designs and the professors’ experiences with these students show the following aspects: (1) the MPS and redesigns that were carried out before applying the MPSIDP were proposed by their manufacturing professors, so this causes a dependence on them, (2) the final candidate was the same as the manufacturing process that professors had proposed, (3) and the MPSIDP offered new redesigns to facilitate the manufacturing. However, these redesigns could not be carried out because of the deadline. Therefore, TFG students need access to this type of resources from the conceptual design stage.

The assessment answers that were given by TFG students and professors are positive (i.e. they were asked for global assessment, level of interest or utility and applicability of each stage and the influence on the students' ability to select), it means answers of "agree" or "strongly agree" (4-5 of a 5-point Likert scale). In fact, as positive aspects, TFG students said that their designs could be manufactured correctly and the MPSIDP justified the selection and provided design considerations. Professors focused on the potential for the application of MPSIDP in subjects related to Design and Manufacturing. In contrast, TFG students expressed the difficulty of understanding MPSIDP and being able to apply it without support as negative points, which is the same as students’ answers in *Procesos Industriales*. Whereas the professors focused on the complexity and density of the ITM information for a subject and they said that it would be convenient to apply it to students with previous knowledge in manufacturing processes.

4.2. In the industrial environment

Initial questionnaires show a different situation between companies and professionals:

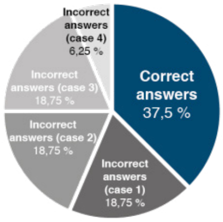
- The local manufacturing companies have a limit access to manufacturing technologies and they focus on advice to their client to manufacture their designs. Only those that work in own original projects carry out MPS at that time. The workers take into account design considerations of the service providers and machinery suppliers but in non-homogeneous formats without structure or controlled location. In addition, the workers’ experience is not extracted and the experience is sometimes communicated to other employees but only verbally.
- In the case of professionals that were consulted, there are two different profiles. Professionals with a profile of EIDPD carry out MPS and collect the experience. Conversely, the professional with a profile in manufacturing engineering do neither selection nor storage of the experience, this is the same as the situation of local companies.

a.

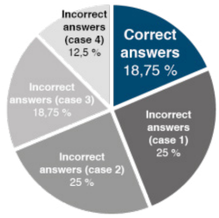
Variable	Values of variable
Annual production	10000-100000 ud.
Mass	50-1000 kg
Shape	Solid 3D, parallel and simple
Tolerance	0,1-0,5 mm
Surface roughness	> 10 μm
Material	Stainless steel
Section thickness	2-10 mm
DFA characteristics	Multi-functional parts

b.

Candidate manufacturing processes	Annual production		Mass		Shape (MP)	Tolerance		Surface roughness		Material (MP)	Section thickness		DFA characteristics (MP)	Impact of values: Independent of MP (x)	Impact of values: Dependent of MP (MP)	Impact of values: Total
Die casting	4	x	4		4	3		5		1	3	x	4	2	9	11
Forge		x		x	4		x		x	5		x	3	5	12	17
Sheet forming		x			1		x			5		x	4	3	10	13
Conventional machining		x		x	4		x			5		x	2	4	11	15



c.



d.

Fig. 5. (a) value ranges of the 1st example case in the initial MPS test, (b) evaluation process of the candidates with the general DFMA guide in the 1st example case, (c) results of the initial test in companies and (d) the professionals' results.

The initial questionnaire included a MPS test from ranges of the design variables (image-a of Fig. 5) without using the MPSIDP. In the results, a low number of correct answers is observed and the number of professionals' correct answers is lower than companies' ones (image-c-d of Fig. 5) when the candidates would be compared easily with the general DFMA guide (image-b of Fig. 5). In conclusion, these methodologies should be applied in EIDPD professionals especially, but also on the companies to carry out their new products and to storage their experience.

The following aspects were observed during the application of the MPSIDP to the companies' selected products: (1) the candidate for manufacturing process was the main process that has been used by these companies, (2) the main process was not obtained in the case of bin (i.e. roll bending) because it was not in the CES software, but it was got as candidate process when its specific DFMA guide was created from other sources and was taken into account (3) and specific DFMA guides have polished up the candidates CES proposed (wrong candidates have been eliminated).

If the companies' assessment and the professionals' ones in the final questionnaire are compared, the first ones have an applicability that is in inverse relation to interest (image-a-b in Fig. 6) but, for professionals, both of them are growing and they value more stages 3 and 4 (image-c-d in Fig. 6). This is probably because of MPS activities and storage learning format (stages 3 & 4) that the EIDPD professionals own in contrast to the companies. Nevertheless, these activities are difficult to carry out for the companies due to day-to-day demands. In fact, they appreciate the more influence of the MPSIDP in their ability to orient the design towards a manufacturing process or to apply recommendations because these are the activities that they carry out most when orienting their client design.

As a consequence of the results, a 'symbiosis' between manufacturing companies and designers (or highly experienced workers and low-experience ones) is proposed. The first ones offer information experiential knowledge about their capacities. This saves on time to do redesigns to the second ones and they can contribute to the creation of custom specific DFMA guides for their manufacturing service providers. This new approach modifies the way to use the MPSIDP because its application is now shorter for the first profile, so they can orient designs toward their processes or can quickly choose between them from the custom specific DFMA guides. On the other hand, the course activity was reconsidered and the most important changes were to complement the independent learning of the current ITM and the future approach of ITM toward the adaptive learning (e.g. new structure and tutorial videos).

Despite these necessary modifications, which are explained more deeply in the other presented paper, the first application results prove that those background opportunities and the objectives of the introduction are achieved: (1) the capacity for select is validated because the candidates are the companies' used processes and professors' suggestions, (2) MPSIDP is a preliminary MPS, which is integrated in a DP, for university and industrial environments, so manufacturing aspects can be applied before the possible increase of the cost or when redesign is impossible (use of DFMA guides in the establishment of design requirement) and (3) the use of existing MPS methodologies or software (e.g. CES) is not enough for a correct selection, since the creation and use of specific DMFA guides let polish up the results and to include the own experience (from university, company and professionals). Related to this last point, Ashby's methodology (CES) and others recommend seeking additional information about candidates, but they do not structure this storage of information nor include it in the future selections.

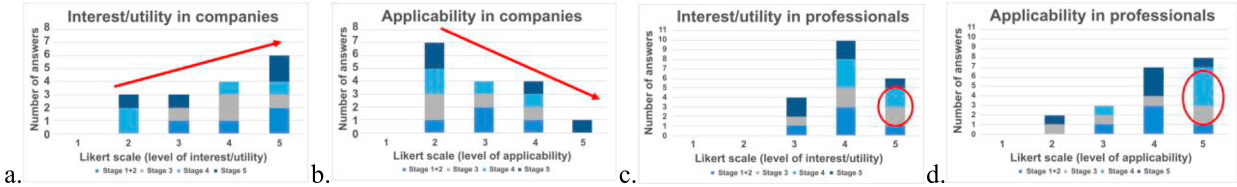


Fig. 6. (a) companies' answers about the interest or utility and applicability of MPSIDP in each stage (1-5) and (b) professionals' answers.

5. Conclusion

Finally, the Manufacturing Process Selection in Design Process (MPSIDP) academic application addresses the Manufacturing Process Selection (MPS) in a practical way and contributes to the vertical integration (use the previous students' experience) and horizontal (between design and manufacturing subjects). In the industrial environment, systematic establishment of requirement, MPS and Design for Manufacturing and Assembly (DFMA) guides are integrated in a Design Process. Moreover, MPSIDP allows the experience storage and its transmission in an explicit way to facilitate the collaboration between industrial designers and manufacturing companies or between industry and university. The integration of these agents in the Product Development is a highly valuable aspect in the current industrial context and the other existing selection tools do not combine all these necessary aspects, in both contexts.

Currently, the MPSIDP necessary changes, which this first proof manifested, are addressing. This year, they are being tested with a whole course of *Procesos Industriales* subject. In the industrial environment, a case of 'symbiosis' between designer and manufacturing company is planned to propose through the MPSIDP application. Other possible future works are the increase of the groups of processes that will be considered in the selection (e.g. tertiary and joining), creation of databases, their analysis and the inclusion of new information in the DFMA guides (environmental aspects, changes in mechanical properties, etc.).

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