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Manufacturing Process Selection Integrated in the Design Process: University and Industry.

Pedro Hernández-Castellano[a*], María Dolores Martínez-Rivero[a], María Dolores Marrero-Alemán[a], Luis Suárez-García[a]

[a]Mechanical Engineering Department, University of Las Palmas de Gran Canaria, Campus Tafira, Las Palmas de Gran Canaria 35017, Spain

Abstract

Currently, methodologies of manufacturing processes selection are not clearly oriented for the early phases of the design process. Industry 4.0 has offered new opportunities to improve the integration of design and manufacturing processes. As a result, a methodology based on Design for Manufacturing and Assembly and organisational knowledge was created through its integration into an existing design process: Gero's function-behaviour-structure variables framework. This methodology, called Manufacturing Process Selection Integrated in the Design Process, has been included in Interactive Didactic Material, and its application is expected to contribute to the use of these kinds of tools which will be instrumental in training future Engineers.

Keywords: Manufacturing Process Selection; Design for Manufacturing and Assembly; Design Process; Industry 4.0.; Spiral knowledge.

1. Introduction

Of all the activities which are carried out in Product Development, the Manufacturing Process Selection (MPS) is a critical activity and it should be tackled in the early stages of the Design Process (DP) because it reduces the cost that results from late redesigns. Although, some people might think the consideration of the manufacturing process in the design requirements establishment means a limitation of designer creativity, the intention is to take advantage of selected process capacities from the early stages in order to avoid the need for late redesigns. Traditionally, MPS has

* Corresponding author. Tel.: +34-928-451-896; fax: +34-928-451-484.
E-mail address: pedro.hernandez@ulpgc.es

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been carried out in two ways: by drawing on the company's own knowledge and experience using people with a high level of their own personal experience (but it is knowledge-dependent) or using the experience of other companies in the same sector. Although, considering internal and external information are both important, companies often make incorrect decisions because they do not have an analytic, systematic and structured method to verify their decisions, and their database is not updated (e.g. to include new processes or the learning as a result of developed projects).

The specific methodology called Manufacturing Process Selection Integrated in the Design Process (MPSIDP) was developed in response to this situation. Unlike other existing methodologies for Manufacturing Process Selection (MPS), that can support our methodology, the MPSIDP integrates the MPS and DFMA guidelines in the Design Process. It allows for maximisation and adaptation of the manufacturing contribution in the early design stages in order to avoid incorrect usage and to establish what parameters and values should be considered. Another important difference is that the MPSIDP includes features of the product in Industry 4.0: agility (minimum viable product and iterative design), sustainability (application of design guidelines to reduce unnecessary waste of resources in late redesigns) and smart (the possibility of obtaining information and how to manage it). In addition, it generates and controls the creation of new organisational knowledge (university or industrial knowledge) that is included in the selection procedure.

2. Background

In the Manufacturing Industry, two fractures have occurred. The first one took place in the 1990's: industry in traditional industrialised countries grew 17% in stark contrast to emerging countries where it grew 179%, representing 40% of the total increase in manufacturing worldwide in 2014. The second fracture has appeared recently between the traditional industrialised countries: there are countries (Germany, Italy and Switzerland) which have kept their high industrial added value despite the reduction of industrial employment but other countries (France, Spain and United Kingdom) have suffered a decrease in both employment and added value [1]. Despite the fall in employment, there are engineering jobs in the field of Design and Product Development which have a high demand due to their creative nature, so these professional profiles are at lower risk of disappearing. However, these profiles need their competencies to be renewed and their tools adapted to the new context in order to create added value within the Industry 4.0 context.

The 'Design for X' (DFX) strategies aim to consider the entire lifecycle of a product during the design stage, and they are essential in the Industry 4.0 [2]. These strategies increase the effectiveness of Product Development and they avoid wasting unnecessary resources. One of the first DFX strategies was Design for Manufacturing and Assembly (DFMA) which aims to simplify the construction of the product itself and its assembly [3]. In Product Development, both general guidelines and specific guidelines for each manufacturing process are necessary because they incorporate the whole manufacturing experience. Moreover, taking into account the requirement level (essential or recommendable) is necessary in order to arrive at compromise solutions. Besides the design guidelines, a well-defined and quantifiable method for comparing alternative design is necessary to make decisions [4].

2.1. Industry 4.0

Industry 4.0 or the 4th Industrial Revolution can be defined as a new trend in the manufacturing industry and other sectors, based on the integration of a set of technologies that enable a connection between factories, people, machines and products [5]. Although this new context causes several fast transformations in the design, manufacturing, operation and service, currently, Industry 4.0 is focused on Production. If specific solutions and design guidelines for Industry 4.0 were implemented, the positive effect generated could be even greater [2].

To define the approach and opportunities for the development of these design guidelines, it is necessary to define the products and their development in Industry 4.0. Firstly, there are four Product Development challenges in Industry 4.0 [2]: orientation, data, interaction and resources. In addition to these challenges, there are some key aspects to achieving efficiency and they are [6]: the iteration that allows for introducing new process, products, technologies and satisfying the market needs; the technical and organisational integration along the whole value chain; and the innovation resulting from learning processes and the inclusion of new material, functions and technologies. After taking into consideration this information and the papers that have been cited about Industry 4.0, it appears that the product in Industry 4.0 has three principal characteristics. It is:

- Agile. The product passes from the traditional approach of a "perfect product" to that of a "minimum viable product" which consists of a fast product development and the improvement of the product through multiple iterations [2]. In this agile methodology, specifications are detailed only when it is necessary and the learning that takes place between each iteration upgrades the product [7]. Other strategies have also been developed in response to consumer needs [6,8].
- Sustainable. Products have short lifecycles, so design guidelines are necessary to optimise the product along the whole value chain (DfX) and therefore, they should include additional specific aspects for this context.
- Smart and hybrid. Smart products collect and communicate information during their whole lifecycle: about themselves, their environment and their users [6,9]. Consequently, there are new opportunities such as cyber-physical systems (CPS), internet of things and services (IoT, IoS) and cloud computing. They contribute to combining the virtual and physical world, analysing and evaluating a large amount of collected data (big data) [8]. However, this data is collected in diverse IT systems [2] and this causes difficulties in its access and use in Product Development.

Product Development in Industry 4.0 aims to integrate engineering and industrial design requirements through a structured process to achieve lower cost, shorter development time and higher quality, so the choice of product engineering and design methods are very influential [6]. There have been attempts to join Engineering Design Processes and Creative Design Processes [10] but they were not adapted to Industry 4.0. Due to this, the proposed methodology has considered the following objectives for Industry 4.0: it considers the use of iterative processes and collecting the learning generated in each iteration; it pursues the "minimum viable product", determining the minimum design parameters necessary; it establishes how product development information should be collected in order to manage the information; it gives a data structure, which can enable its future inclusion in a database; it considers DFX but is focused on DFMA; the information can be integrated into a network tool; and smart and hybrid products will be able to be used as sources in the establishment of requirements.

2.2. Manufacturing Process Selection

Three critical aspects must be selected during the DP [11]: shape, material and manufacturing process. If the designer focus is on MPS, it is differentiated into three stages related to level of detail [11]: preliminary selection, functional selection, and task-based selection. Preliminary selection is an integrated approach that consists of the elimination of technically or economically non-viable processes when there is a high level of uncertainty, then candidates are analysed in more detail. Thus, the proposed methodology is a preliminary selection. Today, there is a tendency to use artificial and complex systems in MPS, but the processes are selected with a higher level of concretion both for process planning [12] and to approve or not a specific process [13].

Nowadays, there are several analytical and graphical tools, procedures and methodologies to do the preliminary MPS such as the analytic methodology with graphic support called PRIMA (PRocess Information MAp) and the graphical software for material selection with an MPS module called Cambridge Engineering Selector (CES). From the analysis and consultation of these methodologies and others [14–17], the following conclusions were drawn: (1) despite using two methodologies to select a candidate for a commercial product, the candidate was the same, so the proposed methodology can be supported by diverse MPS methodologies; (2) current methodologies do not provide recommendations about the value to be established before the MPS; (3) they are not integrated in a design process that considers the growth of concretion in the definition of the design requirements; (4) they have a linear approach, which is not adapted to the "minimum viable product" that has an iterative development and (5) there is a high likelihood that the MPS might have an invalid result (no candidates) or the designer might select a manufacturing process with high capacities when it is not necessary. So, a change of perspective is necessary in the MPS which leads to its integration in a DP, that considers the relevant design parameters, and integrates a method and DFMA guidelines in order to evaluate the different options and to avoid an invalid selection.

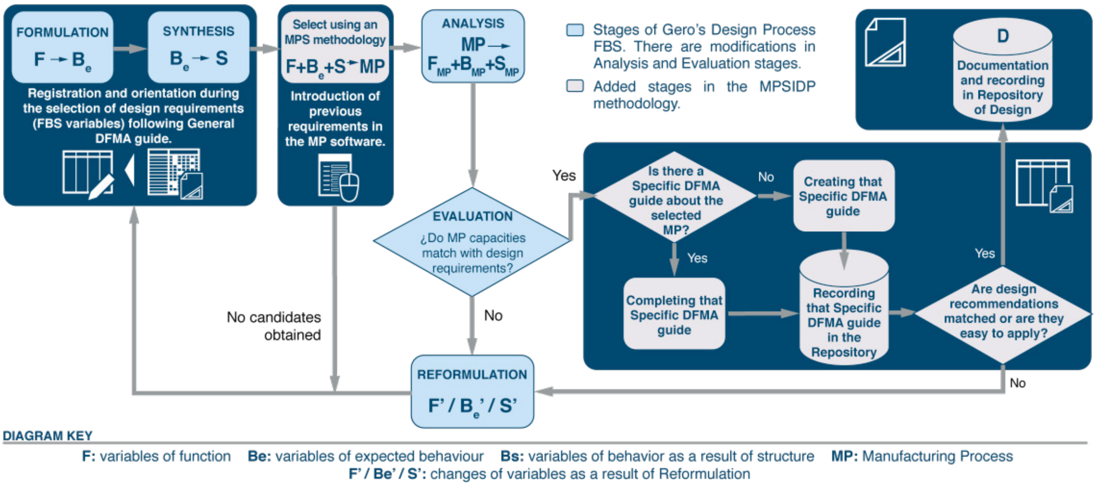


Fig. 1. Flow diagram of MPSIDP methodology.

3. *Manufacturing Process Selection Integrated in the Design Process methodology*

The Manufacturing Process Selection Integrated in the Design Process (MPSIDP) methodology is based on Design Process (DP) Gero's Function-Behaviour-Structure framework [18]. It was the selected DP because it achieves the improvement of traditional linear models, which are effective for teaching novice designers and managing the design process, because it considers the design variables classified and the reformulations (iterative process). There are other, more creative design processes but they do not have systematisation (e.g. divergent-convergent and knowledge space models) [10]. This can be summarised in the following stages: from *Formulation* to *Analysis*, the design requirements are transformed, firstly, function (F) into expected behaviour (B_e), then, into a structure (S), which will generate the real behaviour of the product (B_S); after that, the *Evaluation* stage compares the real behaviour with the expected one to decide if the solution is accepted; finally, if the answer is positive, the *Documentation* will be generated but, if it is negative, FBS variables must be reconsidered (*Reformulations*). However, MPSIDP introduces several changes to include the MPS in early design stages and to address the problems about the current MPS methodologies (Fig. 1):

- Firstly, an 'identification of requirement', which refers to the FBS variables from the initial design.
- This first stage is done through the use of the general DFMA guide to select the values of these variables. This guide, which has been developed for the proposed methodology, is a first orientation for the designer in the established design requirement and it facilitates Manufacturing support in the early stages of Design. The possibilities to establish the design parameters ranges and consider their influence (impact) on Manufacturing, are shown to avoid restriction of the options by non-functional requirements.
- The third stage is the use of software to select from the identified FBS variables. This stage ends with the *Analysis* and the *Evaluation*, which check whether the candidate processes meet all product requirements. If no candidates for the manufacturing process are obtained, we must modify the value of the variable that is out of range, and either consider that this value can be met with a subsequent process or go back with a Reformulation
- The fourth stage is the creation or improvement and use of the specific DFMA guides. These guides contain information about FBS variables and design recommendations for each manufacturing process. If the design recommendations for this/these process/es, which are contained in these guides, cannot be applied, a modification in the design aspect or a Reformulation must be made.
- Finally, the integration of the project documentation in the repository of designs. This repository and the database of the specific DFMA guidelines allow for collection, improvement and use of the knowledge and resources generated by a group from their experience and they contribute to the inclusion of the new information about processes or new techniques. It is called organisational knowledge (i.e. Spiral knowledge) and is useful for agile methods.

The minimum design parameters we need to consider, according to the 'minimun viable product' philosophy, were determined and classified in FBS variables: function (application and annual production), behaviour (properties as a result of shape, material and process such as mass, characteristics of the process and cost unit) and structure (tolerance, surface roughness, section thickness, material, shape, assembly, number of parts and dimensions). In the identification of requirements (1st stage), the values of variables expressed as ranges (quantitative variables) or as a unique value (qualitative variables) are collected and their impact follows the general DFMA guide. Moreover its table includes information about the classification of the variable (functional or not, requirement level, characteristic or property, etc.). The numeral impact establishment from 1-5 has been done to ease the comparison between the different candidates and the design variations. Depending on the kind of variable, the impact has a different meaning: (1) independent of manufacturing process, if the impact is greater, the value range is greater too; or (2) dependent on the manufacturing process, if the impact is greater, the adaptation of this process to achieve these variable values is greater.

In this first version (or generic use) of MPSIDP, two possible profiles and how they should act depending on whether requirements are functional or not and essential or recommendable were considered. On the one hand, the profile of a designer who does not know what manufacturing process should be used, so that this designer establishes the functional requirements according to the product function. To avoid restricting the candidates in the selection, the designer must express both the functional and non-functional requirements as the predominant values in the piece (critical values will not be considered until the *Evaluation* stage) and establish an intermediate impact (a value range which can be obtained by most processes) in the non-functional requirement. On the other hand, the designer profile who designs a product to be manufactured by a specific manufacturing process orients the design from the beginning toward a specific manufacturing process.

In this paper we explain the essential aspects about MPSIDP and its background. Other works address its more in-depth use with images about the general DFMA guide and the example tables of each stage [19]. However, that work does not show the Interactive Training Material (ITM) and the consequences of the first application.

3.1. Interactive Training Material

The MPSIDP has emerged from the development of Interactive Training Material (ITM) about Manufacturing Process Selection. After consulting many methodologies in the educational innovation, both Project Based Learning (PBL), which makes the student responsible for their learning, and the use of repositories, which facilitates the Spiral of knowledge in subsequent years, were chosen to support the ITM and its course activity. In fact, the course activity of the first proposal established the independent learning of the ITM before and during the application of the MPSIDP. The chosen format for ITM was SCORM package because it stores reusable educational resources that can be used on Learning Content Management Systems (LCMS), e.g. Moodle, which have tools for adaptive learning. SCORM was created by eXeLearning, it is an open source interactive content editor that can be used without the need to understand programming and allows the content that is created by other tools to be embedded.

Related to the ITM content and its structure, before addressing the MPSIDP, a brief introduction about the industrial and selection context is made. The main sections are: (1) preface with an introduction, the explanation of interactivity and abbreviations; (2) industrial and professional context and DFMA; (3) the problem of the selection; (4) existing MPS methodologies; (5) explanation of the MPSIDP; (6) PBL activity; (7) an evaluation test; (8) and references.

In terms of interactive elements to facilitate the explanation of the content, the following elements stand out: (1) pop-up windows with additional textual information or videos (image-a Fig. 2); (2) to zoom pictures; (3) several examples of graphics in image galleries (image-b Fig. 2); (4) virtual magnifying glass to increase certain parts of images; (5) download of templates for PBL activity; (6) and test questions. The graphic examples of shapes in the image galleries were taken from lab classes, which seek to join together the lessons and MPSIDP. The configuration of the pages was done by modifying the base style of eXeLearning to create an individual style. This is shown on the template download page (image-c Fig. 2). These issues about ITM are extracted from another paper [20]. In that work, the additional reasons to choose these educational tools and its background are shown.

The results of the MPSIDP first application suggest that several modifications will be needed to adapt to each environment in future applications. The specific activities that were carried out and their results can be consulted in the other article presented at this conference called 'Manufacturing Process Selection Integrated in the Design Process: Test and Results'.

Fig. 2. Interactive elements: (a) video in pop-up window, (b) image gallery and (c) template download page.

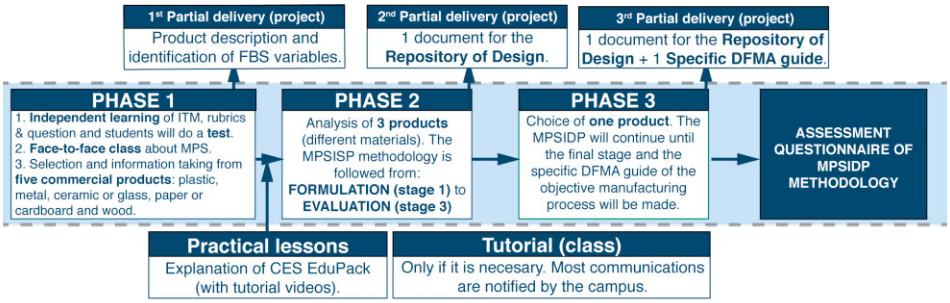


Fig. 3. Course activity in 2018/19.

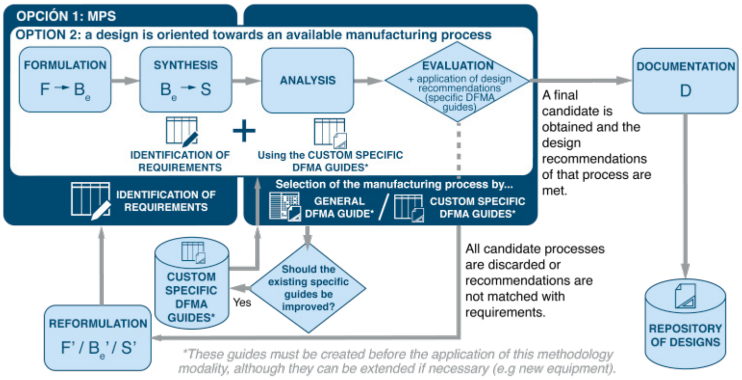
3.2. Adaptation of MPSIDP methodology in the University

The first version of the ITM had a complex structure and thick contents, which made understanding difficult. As a result of this, other adaptive learning strategies are being considered. In fact, in this 2018/19 academic year some measures have already been taken to achieve this goal (i.e. new course activity and tutorial videos). In this new course activity (Fig. 3), although the students consult the ITM independently (independent learning), they have a face-to-face class before applying the MPSIDP (practical lesson). This begins with a first partial delivery (1st phase) that gives them more time to raise concerns. These aspects are the main differences with the first activity proposal. In terms of facilitating the compression of teaching, several tutorial videos on the use of the CES for the MPSIDP have been created. These have already been used in practical lessons and students have some examples of the first application to guide their course work this year. Another measure, suggested by the results analysis is that tackling students' own designs would be more interesting. However, this option was discarded because the ITM is applied to an introductory course about manufacturing processes (called *Procesos Industriales*), and a semester is a short time. In the future, the application of the 3rd stage to a student's own design could be tackled in a subsequent course, as a continuation of this activity.

With regard to the MPSIDP methodology, the original version is still being used (without the use of the specific DFMA guides until the *Evaluation* stage) because the CES is licensed by the ULPGC library and there have not been enough loops in the spiral (academic courses) to generate enough specific guides. We anticipate an improvement in the adaptive characteristics of the ITM and the start of the Spiral of knowledge this year, with all the students following the *Procesos Industriales* course (and continuing in later courses).

3.3. Adaptation of MPSIDP methodology in the Industry

As a result of the first application, two profiles with different needs and interests are revealed, which forces us to adapt the application to each profile:



a.

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		x			4					1		x	4	2	9	11
Forge		x		x	4		x		x	5		x	3	5	12	17
Sheet forming	4	x	4		1	3	x	5		5	3	x	4	3	10	13
Conventional machining		x		x	4		x			5		x	2	4	11	15

Fig. 4. (a) new proposal of the methodology for profile 1 and (b) example of impact calculation.

- The local manufacturing companies (which have more manufacturing experience than design knowledge) have limited access to manufacturing technologies and they focus on advising their clients so that they can manufacture their designs. They only choose manufacturing process when the products are innovative. In addition, they need to reduce the time taken up by the application of the methodology in order to be effective. Therefore, several modifications are proposed regarding the first proposal (image-a Fig. 4). On the one hand, in the case of MPS, the general and custom specific guides (only from the manufacturing processes they have available) will be used, so, in the *Analysis* and *Evaluation*, the initial design requirements are compared with the capacities of each process. Candidates are selected according to the impacts (image-b Fig. 4) and the design considerations from the specific custom guides are applied. If the company is considering the acquisition of new technologies, it can put the available information in a specific guide. On the other hand, if a design is oriented towards an existing process, the stages of *Formulation*, *Synthesis* and *Analysis* become the method of identification of requirements together with a custom specific guide and the degree of compliance with the design considerations of that guide is then verified during the *Evaluation*. This profile is applicable to a highly experienced professional as opposed to one with low experience or an internship that would operate as the following profile.
- The professionals of Industrial Design (reverse situation) carry out MPS and record and collect their experience. Therefore, they follow a methodology similar to the first version (or generic use) of MPSIDP, except for the custom specific DFMA guides, which are created by this profile with the data of the collaborating companies. In addition, these guides would be applied from the *Analysis* and *Evaluation* stages. The creation of these custom guides can also be carried out by manufacturing companies that request services from other companies, because they also need to know their capabilities to be able to advise their clients with regard to their designs.

Although the creation of these custom guides is proposed for profile 2 (designers, low-experience employees or companies that request services), profile 1 can also be used to produce specific guides when developing projects or changing capabilities (e.g. new equipment). Thus, between these two profiles a "symbiosis" happens. The advantages of this new approach, for profile 1, are to reduce application time and have structured information about its capabilities. Meanwhile, for profile 2, if this is a designer, it saves on time needed to advise clients about manufacturing and, if this is a new employee or an internship student, they can get knowledge about the company's capabilities by generating documentation (based on veteran employees' experience). By suggesting this collaboration, integration along the whole value chain is expected; in this case, suppliers, manufacturing companies and client designers.

The creation of organisational knowledge (guides and projects in repository) supports the continual improvement process, but the need to propose a coding system for the name of the documentation and a change control, which could be included in a quality management system, also emerged. In fact, a first proposal has been done based on other mixed codes (hierarchical and chain coding) used for metrology and group technology and this uses the impacts of the general guide. Therefore, information on the FBS variables, manufacturing process, company (if applicable) and document version is given (e.g. DESREP/W3C6T4R3E2M12F2100A2/122/REP Aluminium bin rev01).

4. Conclusion

In conclusion, after detecting inadequacies in the current MPS methodologies and as a result of the search for Industry 4.0 objectives, a MPS methodology was proposed. It is integrated into a Design Process and it contains and generates DFMA guides that are used in the process from its early stages. In this way, the consideration of manufacturing when the design variables have already been established is avoided. In addition, the values recommended by these guides and the distinction between functional or not and the requirement level avoid restriction of the selection by non-functional variables. A highly valuable aspect of the MPSIDP is a result of the structuring of information: values of design variables are shown as ranges with a manufacturing impact that is expressed numerically. Thus, it can be integrated into a database in the future. No existing selection tools combine all these necessary aspects.

The first test, which is described in the paper also presented at this conference, led to modification of the methodology in order to adapt it to the needs of the university and industry. The first one needs an ITM more focused on adaptive learning. This academic year, a new course activity and tutorial videos are being implemented in order to achieve this. In the coming years, the results of this proposal will show new improvements and will initiate the Spiral knowledge. In the second context, the possibility of establishing a "symbiosis" or collaboration between designers and manufacturing companies emerged. In the future we will look for the best ways and computing platforms to achieve this.

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