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Methodology for capturing and formalizing DFM Knowledge

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ABSTRACT

Design for manufacturing (DFM) practices lead to more competitive products from the point of view of cost, development time and quality. However, the success of considering manufacturing issues during design process would be higher if manufacturing information was more readily available and designers needed less experience to select information relevant to DFM.

This paper presents a method for identifying and formalizing the relevant manufacturing information that designer should have available for DFM. The method is based on the Axiomatic Design theory [1]. It helps the designer capture the relationship between design and manufacturing information. The information related to obtaining the design parameters that achieve product functionalities is the most relevant DFM information. A case study where the method is applied to the design of a connecting rod for an alternative internal combustion engine is presented. The manufacturing processes considered were hot closed die forging and powder metallurgy.

1. Introduction

Design for manufacturing (DFM) considers design goals and manufacturing constraints simultaneously to identify and alleviate manufacturing problems while the product is being designed. As a consequence the lead time for product development is reduced the and product quality and cost are improved [2]. Several DFM techniques have been developed to assist the designer, such as manufacturing process selection methods [3,4], DFMA guidelines [5,6] and manufacturability analysis tools [2].

Consequently product competitiveness has been improved by applying these DFM techniques. Nevertheless, the decision-making process and the expertise of the designer continue to be the key aspects to ensure the success of DFM, due in part to the availability of DFM information. There are a variety of data and information associated with each manufacturing process, but little explicitly represented knowledge about how to use them in DFM. In addition, the different sources and formats make it difficult to access such information and knowledge when needed. This leads companies to develop their own particular DFM guidelines suited to their own needs [4].

Another reason that makes difficult DFM is the lack of systematic procedures for capturing, organizing and representing DFM knowledge and its associated rationale [4,7]. The relationship between DFM knowledge and design, and that it depends on collecting empirical data derived from years of experience, is obvious. Nevertheless, it is quite difficult to solve this problem from a theoretical point of view. On the other hand the lack of procedures to document and formalize the decisions taken during the design process, and more specifically in the initial design phases [8], does not help either. Although design models, such as the Pahl and Beitz model [9], indicate the steps needed to develop a design, there are a few formalized procedures to guide the designer and document the decisions taken during this process.

These issues have led to the main questions that motivated this work: which manufacturing information should be available to designers for DFM? How could expert designers be guided to capture and document the DFM information that they use in each design phase? How could this DFM information be reused in other designs?

This paper presents a methodology for identifying and formalizing the relevant manufacturing information that should be available in DFM, that is, the manufacturing information designers should take into account. This is achieved by developing a systematic procedure that guides designers in three ways: (1) to define and formalize the information generated during the design process; (2) to make explicit the relationship between this design information and essential DFM information; and (3) to define and formalize this DFM information. This methodology is based on the Axiomatic Design theory [1] and DFM techniques. It demonstrates how the Axiomatic Design theory can be used to support DFM.

As a result, applying the methodology provides explicit manufacturing knowledge related to design, as well as the

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relationship between this manufacturing knowledge and its corresponding design phase. This knowledge is based on the expertise and is essential for the future development of a software system that effectively provides necessary DFM information to designers. This means providing information for each of the design phases without saturating designers with unnecessary information.

Next, the research fields related to this work are discussed; including DFM techniques and the relationship between design methods and the manufacturing process that research has established and developed the theoretical fundaments of the proposed methodology. Finally, the methodology is validated with a case study: the connecting rod of an alternative internal combustion engine.

2. DFM techniques

Nowadays products are developed in concurrent engineering environments where integrating manufacturing into design is fundamental. For this reason the manufacturing process has to be considered in the design as soon as possible. Fig. 1 shows the relationship between the research fields for integrating manufacturing into design and the design phases [10]. DFM techniques include manufacturing process selection, DFM guidelines and manufacturability analysis.

In early design, the manufacturing process selection helps designers choose the manufacturing processes that are technically and economically suitable for a given design [3,4,11]. The choice is made by comparing the design specifications with the attributes of the manufacturing process. The process attributes are parameters that describe a process and its capabilities and allow direct, objective comparisons to be made [12]. In the preliminary selection the attributes are common to all processes, for example, the tolerance or roughness each process is able to obtain in a part. In a more detailed selection, the attributes are usually more specific and their values can be related to design requirements and other attributes or processing conditions [12]. Some selection tools, such as a CES Selector [13], PRIMA [4] and MAS [11], select from among all manufacturing processes. Other selection tools, such as the forging process selector [14], select from among specific processes.

When the set of processes has been limited, DFM guidelines become essential to evaluate the design according to manufacturing aspects [10]. Design guidelines suggest how to better design parts for a particular manufacturing process, and how this process may affect the shape, dimensions, material and internal structure of the part [6].

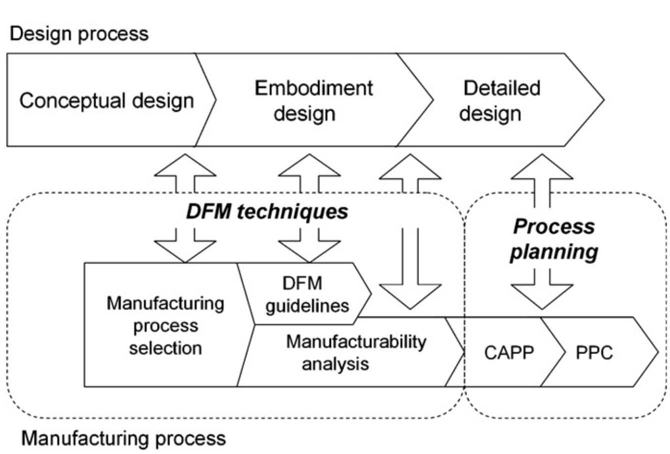

Fig. 1. Integrating manufacturing into the design process.

Most of the data and information related to these guidelines are available in handbooks, standards, and in-house guidelines. Nevertheless, the lack of systematic procedures for developing these guidelines may lead to incomplete knowledge, which makes it difficult to use them without prior experience [4,7].

Integrating DFM guidelines into a CAD system would help analyze the manufacturability automatically [2], identify the potential manufacturability problems and assess the manufacturing cost. This automatic analysis should make it unnecessary to study and memorize manufacturability checklists, and therefore allow designers to focus on the creative aspects of the design process [2]. Most of the literature reviewed focuses this manufacturability analysis on geometric issues. The main geometrical design features are recognized and their manufacturability is checked for a given process [2]. Geometric redesigns can also be proposed [15]. However, there is much more important manufacturing information for DFM that is not integrated enough, for example the roughness or the draft in the forging process. Manufacturability evaluation is also important in this research field. This evaluation reflects the ease or difficulty of carrying out the design technically [5] or economically [2,5].

When the design is quite detailed, integrating it with manufacturing is more focused on process and production planning than on DFM techniques, Fig. 1. Systems that integrate process planning and production planning are presented in [16,17].

3. Design methods and manufacturing process

Design methods also emphasize the relevance of manufacturing integration. Design models which structure the design process in phases establish that the manufacturing issues should start to be considered in the embodiment design phase, when the overall layout design (general arrangement and spatial compatibility) and the preliminary form designs (component shapes and materials) are being defined [9]. However, the Axiomatic Design theory [1] states that the manufacturing process should be considered during early design stages because the design evolves within the functional, physical and process domains at the same time. In spite of these differences, most design methods consider that the design has to satisfy product functionality [1,9]; therefore, the manufacturing process should produce a product that achieves such functionality. This relationship between functionality and the manufacturing process is stated explicitly in the Axiomatic Design theory [1].

The Axiomatic Design theory organizes the design process into four domains: customer [customer needs (CNs)], functional [functional requirements (FRs) and constraints], physical [design parameters (DPs)] and process [process variable (PVs)]. The information in each domain evolves in parallel by means of a mapping process between CNs and FRs, FRs and DPs, and DPs and PVs. For example, in the physical domain the design solution is defined by the set of DPs that satisfies the set of FRs specified in the functional domain. In the process domain the set of PVs used to produce the specified product (DPs) is identified.

The mapping relationships between domains are expressed by a matrix composed of 1s and 0s that shows, which DP affects each FR and which PV affects each DP. The relationships between the design information in each design level are stated explicitly in Eqs. (1) and (2).

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \dots \\ FR_n \end{Bmatrix} = \begin{pmatrix} 1 & 0 & . & 0 \\ . & 1 & . & 0 \\ . & . & . & 0 \\ . & . & . & 1 \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \dots \\ DP_n \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} DP_1 \\ DP_2 \\ \dots \\ DP_n \end{Bmatrix} = \begin{pmatrix} 1 & 0 & . & 0 \\ . & 1 & . & 0 \\ . & . & . & 0 \\ . & . & . & 1 \end{pmatrix} \begin{Bmatrix} PV_1 \\ PV_2 \\ \dots \\ PV_n \end{Bmatrix} \quad (2)$$

During the mapping process the independence axiom helps determine the right decisions to take in order to obtain a good design. This axiom states that when there is more than one FR, the design solution must be such that each of the FRs can be satisfied without affecting the other FRs. This means the correct set of DPs must be chosen to satisfy the FRs and maintain their independence [1]. This is achieved when the relationship between FRs and DPs results in a diagonal or triangular matrix, Eq. (1).

When several designs that satisfy the independence axiom are available, the information axiom can be used to select the best design. This axiom is related to design complexity and implies that the simplest design is the best [18]. It states that the design with the lowest information content is the best [1]. The information content is calculated by the probability of successfully achieving the design solutions that the FRs represent [1].

A zigzagging procedure between domains is used to break up the information in each domain. In this procedure the highest level DPs are used to state the FRs in the next level. In the same way the highest level PVs are used to define the DPs in the next level [1]. For example, when the forging process (PV) is chosen in the process domain, the DPs in the next level will be affected by this decision. The FR, DP and PV hierarchies are the result of this process.

Recent research studies have explored using the Axiomatic Design theory to integrate manufacturing issues. Gonçalves-Coelho [18] shows how Axiomatic Design principles can be used to select the manufacturing technology (PVs) that best obtains the product purposes, such as product cost or roughness. This study contributes to decision-making in DFM. However, the axiomatic design theory is used more often in manufacturing system design. For example, Houshmand [19] proposes an axiomatic model of a lean production system design and Suh [1] applies the theory to the design of manufacturing systems.

This paper proposes a procedure for determining the essential manufacturing information that should be available to designers to support DFM. The information available in DFM techniques, which is discussed in Section 2, is essential for explicitly representing the relationship between the design solutions and manufacturing processes.

4. Proposed methodology

4.1. Conceptual framework

The conceptual framework of the method is based on the axiomatic design theory and DFM techniques (Fig. 2). This framework includes three design domains: the functional, the physical and the process. It is assumed that the mapping between the customer domain and the functional domain has already been defined.

The axiomatic mapping between the functional and physical domains determines the design parameters (DPs) that satisfy the functional requirements (FRs) and the constraints (Cs) related to the product (see definitions in Table 1). A systematic method is proposed to formalize the FRs and DPs.

Next, a mapping procedure between these design parameters (DPs) and the manufacturing information available from the DFM techniques lead to identify the essential manufacturing information that should be available to designers. The essential DFM information shown in Fig. 2 includes the process properties (PPs) and the manufacturing defects (Dfs) (see definitions in Table 1). The PPs and the Dfs represent the capabilities and the constraints of each manufacturing process to obtain the DPs in the process domain. However, they are not process variables (PVs) because they do not represent how the manufacturing process should be

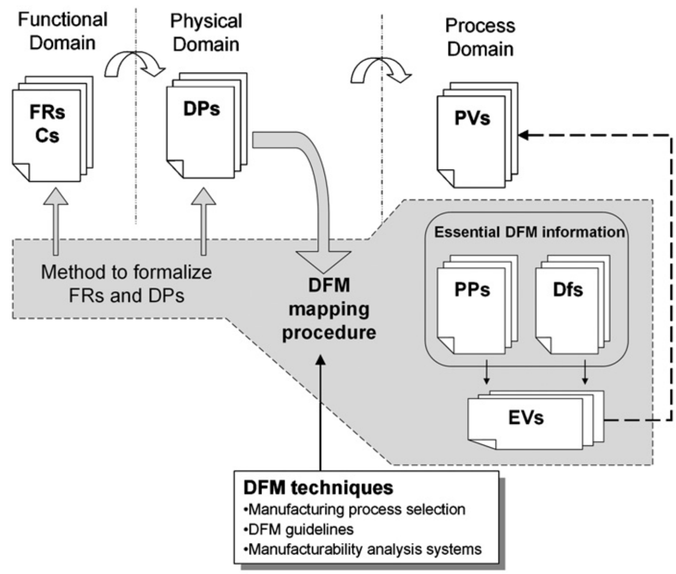

Fig. 2. Conceptual framework of the proposed methodology.

Table 1
Related terms.

Term	Definition
Functional requirement (FR)	It represents what the product must do independent of any possible solution [1,9,20,21]. It is a unique and unambiguous statement in natural language of a single functionality, written in a way that it can be ranked, traced, measured, verified, and validated [21].
Constraint (C)	It is a restriction that, in general, affects some kind of requirement, and it limits the range of possible solutions while satisfying the requirements. So, a constraint should be always linked to a requirement [20,21]
Design parameter (DP)	It is any physical property whose value shape the design solution and satisfy the functional requirements (FRs) established in the functional domain [1,21] (for example, weight, thickness or roughness)
Process attribute	It describes a process and its capability in order to allow direct, objective comparisons between the design specifications with the manufacturing process. They can be common among all processes (roughness, cost) or specific to some of them [12]
Process property (PP)	It is any process characteristic, which reflects the process constraint or requirement to get the design parameters (DPs). The process property (PP) is a type of process attribute, but the main difference is that the (PP) is only related to DPs and not to other design specification like the product cost [7].
Manufacturing Defect (Df)	It is a process failure or imperfection that can affect to obtain the design parameters (DPs) successfully. The failure occurs as a consequence of an incorrect control of the process execution variables (EVs), so the surface cracks in forging process. Nevertheless the imperfection is associated to the own manufacturing process, so the decarburization generated in forging process.
Execution Variables (EV)	It is the process parameters that should be controlled during the manufacturing process to obtain a specific value range of PP or to avoid a Df given successfully (for example, the work temperature in hot die forging process).

carried out, like deformation speed or working temperature in the forging process.

The relationship between the essential DFM information and PVs is established by the execution variables (EVs), which need to be controlled during the manufacturing process to obtain a specific range of process property values or to avoid a given manufacturing defect (Df) (see definitions in Table 1). The difference between EVs and PVs is that EVs do not ensure functional independence, although they are a good starting point for identifying them.

A systematic procedure is proposed to define and formalize this manufacturing information (PPs and Dfs) and the more relevant relationships between the design parameters (DPs).

4.2. Development of the methodology

The proposed methodology is divided into two phases: the Design information phase and the Manufacturing process information phase (Fig. 3). Phase 1: Design information aims to define and formalize the design parameters (DPs) that satisfy the functional requirements (FRs) and their constraints (Cs). Axiomatic Design principles are used to break down the FRs and DPs in this phase. Phase 2: Manufacturing process information aims to identify, define and formalize the essential manufacturing information that could affect the design parameters (DPs) to be obtained. This includes process properties (PPs) and manufacturing defects (Dfs).

Fig. 3 shows the steps included in each phase. These steps have to be applied in the different domains of the design process. The first step starts in the functional domain.

- In the functional domain, the functional requirements (FRs) are defined and formalized, using the functional needs and the product constraints as the initial information (Step I). To define a FR, the *action*, the *object* and the *qualifiers* need to be identified (Fig. 4a) [20]. The *action* represents the product function to be satisfied and is expressed with an active verb [9,20]. For example, an AICE connecting rod must carry out the action ‘‘to transmit’’. The *object* represents the entity in which the action is carried out on and is expressed with a name. For example, ‘‘the piston’s load’’ is the object that the connecting rod has ‘‘to transmit’’. The *qualifiers* represent the constraints (Cs) joined with the function and limit the possible design solutions [20,21]. The qualifiers are expressed by a name or adverbial groups and have been divided into four constraints: input, output, environment and design (Fig. 4a).
  - Input constraints are the restrictions that exist before the action is executed, for example, the load range that the connecting rod has to transmit [22].
  - Output constraints are the restrictions obtained after applying the action, for example, the number of cycles the connecting rod has to make to transmit this load [22].
  - Environment constraints are the restrictions that come from the conditions where the action is being carried out, for example, the temperature range in which the connecting rod works.

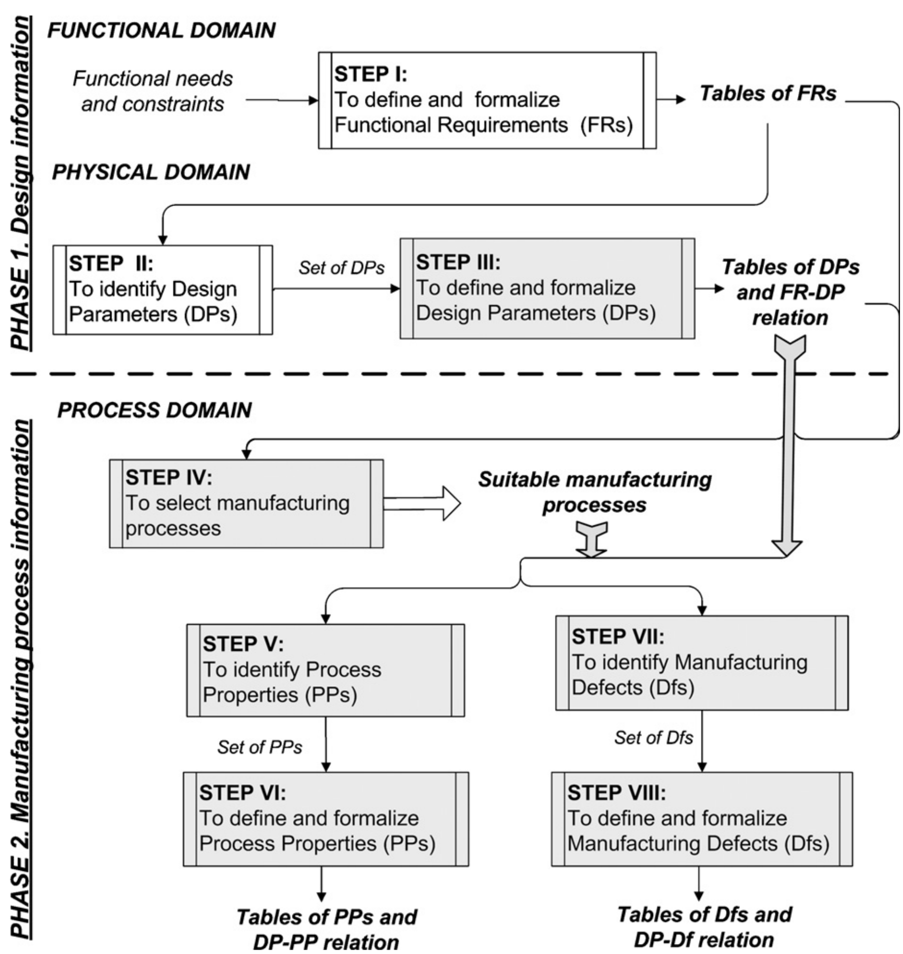

Fig. 3. Structure of the proposed methodology.

Functional Domain

Table of Functional Requirement (FR)

	FUNCION	
	Action	Object
Function	*To transmit*	*The piston's load*

QUALIFIERS				
Constraint	Description	Value	Units	Tolerance
Input	*Load*	*[25-35]*	*N*	*+/- 5*
Output	*Cycle number*	*10e6*	*cycles*	
Environment	*Temperature*	*[80-90]*	*ºC*	*+/- 10*
Design	*Mass*	*[0.5-0.7]*	*kg*	*+/- 0.05*

a

Physical Domain

Table of Design Parameter (DP)

DP-FR	Functional Requirement (FR)	*FR1*
	Description FR-DP	*Fatigue analysis*
DP	Chunk	*Beam*
	Product property	*Fatigue strength*
	Specification	*Numerical*
	– Value	*[90-100]*
	– Units	*MPa*
	– Tolerance	*+/- 5*

b

Process Domain

Table of Process Property (PP)

	Manufacturing process	*Hot die forging*
PP-DP	Design parameter (DP)	*Roughness*
	Description	*This is the limitation on surface finish of the part*
	Type of relation	*Primary*
PP	Property's name	*Roughness*
	Specification	*Numerical*
	– Value	*3.2-12.5*
	– Units	*µm*
	– Tolerance	*-*
	Dependence	*Processing conditions*

c

Table of Manufacturing Defect (Df)

	Manufacturing process	*Hot die forging*
Df-DP	Design parameter (DP)	*Fatigue strength*
	Description	*Breaks in the part*
	Type of relation	*Primary*
Df	Defect's name	*Superficial cracks*
	Execution variables (EVs)	*Temperature Deformation rate*

d

Fig. 4. Formalization Table: (a) FRs, (b) DPs, (c) PPs and (d) Dfs.

- ○ Design constraints are the limitations related directly to the component's physical definition, for example, the mass and cost limitation associated with the connecting rod [22,23].
- All the information associated with each FR is documented in a table shown in Fig. 4(a). As a result the set of formalized FRs the product must satisfy is obtained from the functional domain.
  - ○ In the physical domain the design parameters (DPs) that satisfy the functional requirements (FRs) formalized in Step I are identified. The traditional methods to search for solutions proposed in the design method [9], for instance literature searches, brainstorming, analogy, study of physical processes or the morphological method, can be used to carry out Step II. The Axiomatic Design principles are used to obtain the final set of DPs.

    The DPs obtained have to be defined and formalized in Step III. In order to define each of them, the *product property*, the *specification* and the *physical structure* need to be identified (Fig. 4b). The *product property* is the physical characteristic that defines the product in terms of material, dimensions, shape and surface finish. It is represented by a name, for example, the "fatigue strength" of the connecting rod beam used to transmit the piston's load (Fig. 4b). The *specification* represents the value or set of values that limit the product property, for example, the numerical value of this "fatigue strength". There are three types of specifications: numerical, selection or Boolean. The *physical structure* represents each functional chunk into which a product is divided, for example, a connecting rod has three physical structures: the "pin", the "beam" and the "crank" [22]. Each of these is embodied by design parameters so each DP has to belong to at least one physical structure.

    Fig. 4(b) shows the template for documenting the DP information, as well as the information that connects the FR and the DP (*Description FR-DP*).
- The process domain starts with the selection of the manufacturing processes to manufacture the product (Step IV). Any preliminary manufacturing selection tool mentioned in Section 2 could be used to do this.

  The necessary manufacturing information is identified and formalized by taking the suitable manufacturing processes and the DP formalized in Phase 1. It starts with the process properties (PPs) (Step V, VI) and continues with the manufacturing defects (Dfs) (Steps VII, VIII). The procedure proposed by Ferrer [7] is used to identify this manufacturing information. This procedure takes each formalized DP and proposes iterative searches in three basic sources: design and manufacturing experts, internal industry practices and specialized literature.

In order to define each process property (PPs) (Step VI) the *process property's name*, the *specification* and the *dependence* should be identified (Fig. 4c). The *process property's name* represents the proper name, for example, the "anisotropy" that the closed die forging process generates in the mechanical properties of the connecting rod or the "roughness" which can be obtained by this process (Fig. 4c). The *specification* represents the value or set of values that the manufacturing process can achieve in relation to this PP. The PP specification can also be: numerical, selection or Boolean. The *dependence* represents the design parameter (DP) or the process execution variable (EV) that can affect the range of the PP values, for example, the value range of the draft in forged parts depends on the type of material [6], whereas the roughness depends on the processing conditions [23].

To define the manufacturing defects (Dfs) (Step VIII) the *defect's name* and the *process execution variables* (EVs) must be identified. The *defect's name* is expressed by a name, for example, as the "superficial cracks" that a forging process could cause on the surface part (Fig. 4d). The *execution variable* (EV) is the variable, or set of variables, that has to be controlled during the process to avoid this defect or minimize the effects that it can generate in the DP.

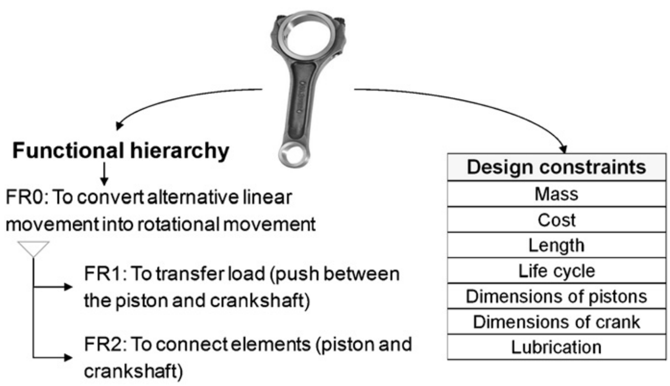

Fig. 5. Starting information: functions and product constraints of the connecting rod.

All the PP and the Df information is documented in Fig. 4. These tables also contain the information associated with the relationships between DPs and PPs, and DPs and Dfs. This information includes the *description* and the relation *type*. The *description* specifies how the process property (PP) and/or the manufacturing defect (Df) affects on the design parameter (DP). Whereas the relation *type* specifies how much they are affected. For example, the relation *type* is primary when the PP has to be fulfilled to obtain the DP by this manufacturing process because it could not be obtained by other manufacturing processes. It would be secondary when the DP can be obtained or refined by later manufacturing processes.

The final results are shown in the set of tables that document the essential DFM information (PPs and Dfs) that can affect each of the DPs that satisfy the FRs. It means the manufacturing information for DFM.

5. Case study

The method has been applied and validated by means of a case study using a connecting rod of an alternative internal combustion engine. The starting information includes the functions and the sub-functions that the connecting rod has to carry out and the design constraints derived from the mechanical system where it belongs (Fig. 5).

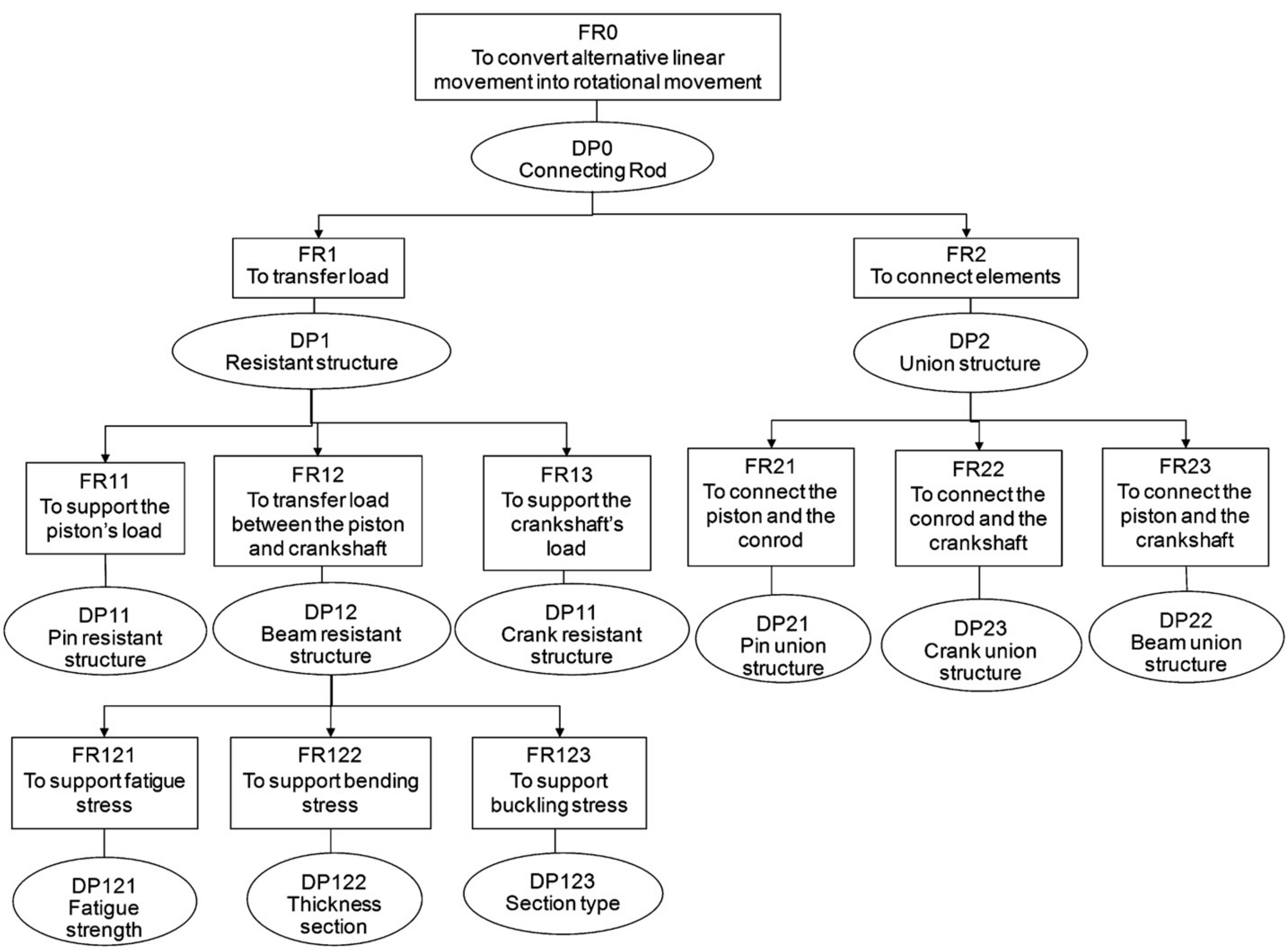

Fig. 6. Case study (Phase 1): FR and DP hierarchies.

Functional requirement table (FR12)

Requirement number	FR12
Description	To transfer load between the piston and the crankshaft

FUNCTION		
	Action (verb)	Object (Flow)
Function	To transfer	Load

QUALIFIERS				
Constraint	Description	Value	Units	Tolerance
Input	Load of the conrod - Direction - Sense - Value range	Parallel to conrod longitude +/- (alter) [20-30]	N	*
Output	Ultimate strength	*	Pa	*
	Reliability	>10e6	cycles	*
Environment	Temperature	[80-90]	ºC	+/- 10
Design	Space in piston - Direction X - Direction Y - Direction Z	* * *	mm mm mm	* * *
	Space in crank - Direction X - Direction Y - Direction Z	* * *	mm mm mm	* * *
	Mass	[0.5-0.7]	kg	*
	Cost	[150-200]	€	*

Fig. 7. Case study (Phase 1): example of formalized FR.

Fig. 6 shows some of the results obtained in Phase 1: Design information. The functional and physical domains have been broken down to the minimum DP level, which allows Phase II of the methodology to be applied at the material, shape and geometry levels. In Fig. 6 the FRs are represented by squares and the DPs by ellipses.

All the decomposition levels guarantee the functional independence of FRs on diagonal matrices, although this action becomes more difficult in lower levels of the hierarchy. Fig. 6 shows how the "DP12—beam resistant structure" has to support fatigue and bending and buckling stress [22,24]. Several DPs could be defined to satisfy these FRs but considering that this component has to support fatigue and the Axiomatic Design principles, the three DPs chosen, were: "DP121—fatigue strength", "DP122—thickness section" and "DP123—section type". The relationship between FRs and DPs in this case is established by a triangular matrix (Eq. (3)):

$$\begin{Bmatrix} FR\,121\text{—fatigue stress} \\ FR\,122\text{—bending stress} \\ FR\,123\text{—buckling stress} \end{Bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} * \begin{Bmatrix} DP\,121\text{—fatigue strength} \\ DP\,122\text{—thickness section} \\ DP\,123\text{—section type} \end{Bmatrix} \quad (3)$$

Each of the FRs and the DPs shown in Fig. 6 has been formalized according to the indications of the methodology. Fig. 7 shows the result of formalizing FR12. The numerical design properties obtained when the DPs that characterize the "DP12—beam resistant structure" are formalized are "DP121—fatigue strength" and "DP122—thickness section" (Fig. 8). Consequently the value or value range, the units and the tolerance that each of them takes has been documented. The "DP123—section type" is a selection type property so its value has been assigned by referencing an established list of values. The DP values are refined as the design process progresses.

Phase 2 of the method begins with the selection of the viable manufacturing processes for producing the connecting rod. The CES Selector 4.5v [13] was used in this case study. The process attributes considered to make the selection were the shape (3D), the material type (metal), the mass range (0.3–0.9 kg), the tolerance ($<$ 0.5 mm) and the batch size ($>$ 100,000 units). According to the CES Selector 4.5v there are ten technically viable manufacturing processes for making an AICE connecting rod (Fig. 9). The shadowed square in Fig. 9 shows the range of mass and tolerance related to the connecting rod.

In Fig. 9 each process occupies a particular area of the chart, which reflects the capacity of the process for obtaining designs in a given range of mass and tolerance. The processes capable of providing a better precision range are located on the left of the chart (for example, cold closed die forging [0.1–0.3] mm, powder metal forging [0.06–0.5] mm or high pressure die casting [0.12–0.5] mm). Despite that the cost related to these processes is usually higher; selecting them could avoid secondary operations, which would increase the final cost, to achieve further tolerances in the design. The processes that occupy the largest areas in the tolerance range provide greater tolerance variations but less precision (for example, Cosworth casting [0.2–3] mm and hot closed die forging [0.4–2] mm). These processes are generally cheaper but when the tolerance requirements of the design are too near to the lower range, secondary operations could be needed, leading to an increase in the final cost of the design.

Currently the main manufacturing processes used to manufacture this component are hot closed die forging (H/F) and powder metal forging (P/F) [22,23]. Paek et al. [25] have demonstrated that less secondary operations were needed when using the powder metal forging process than when using the hot closed die forging process, and consequently the product cost was lower too. Considering the CES results and the current trend, the method has been applied to hot closed die forging (H/F) and powder metal forging (P/F).

Next, the DFM information for manufacturing the connecting rod with the hot closed die forging process (H/F) and with the powder metal forging process (P/F) was determined. Fig. 10 shows some of the process properties (PPs) of the two different manufacturing processes that should be considered to decide on the DPs formalized in Phase 1, such as "DP121—fatigue strength" and "DP122—section thickness". For instance, the relationship between "DP121—fatigue strength" and "PP-anisotropy" means that the H/F process causes anisotropy in the fatigue strength, which will have to be taken into account when the designer makes decisions about the fatigue strength values in the design. In the same way, the designer will also have to remember that this process has a limitation on the"PP-material type" that will also limit its value. The value range that each process property can take has also been formalized, as has the information that describes the relationship between the DP and PP, including a description and the relationship type (Fig. 10).

Fig. 11 shows two manufacturing defects that have to be considered when using the H/F and P/F processes to successfully obtain the "DP121—fatigue strength" of the connecting rod. These defects are "Df-cracks" and "Df-decarburization" [26]. The cracks can be avoided by controlling the execution variables of work temperature and deformation rate. However, if cracks appear they are very difficult to eliminate. As a result the DP–Df relationship is considered to be of primary importance. Decarburization is a defect associated with the deformation process but it can be minimized by controlling the temperature range and heating time. This defect is generally eliminated by means of a shot peening treatment [22,26] and consequently the DP–Df relationship is considered to be of secondary importance.

Table of DP121-fatigue strength

DP-FR	Functional Requirement (FR)	FR121
	Description FR-DP	Fatigue analysis
DP	Chunk	Beam
	Product property	Fatigue strength
	Specification	Numeric type
	– Value	[80-100]
	– Units	MPa
	– Tolerance	0/+5

Table of DP123-section type

DP-FR	Functional Requirement (FR)	FR121, FR122, FR123
	Description FR-DP	Axial static analysis, Bending analysis, Fatigue analysis, Buckling analysis
DP	Chunk	Beam
	Product property	Section type
	Specification	Selection type
	– Value	I type

Table of DP122-section thickness

DP-FR	Functional Requirement (FR)	FR121, FR122
	Description FR-DP	Axial static analysis, Bending analysis, Fatigue analysis.
DP	Chunk	Beam
	Product property	Section thickness
	Specification	Numeric type
	– Value	8
	– Units	mm
	– Tolerance	0/+0.04

Fig. 8. Case study (Phase 1): example of formalized DPs.

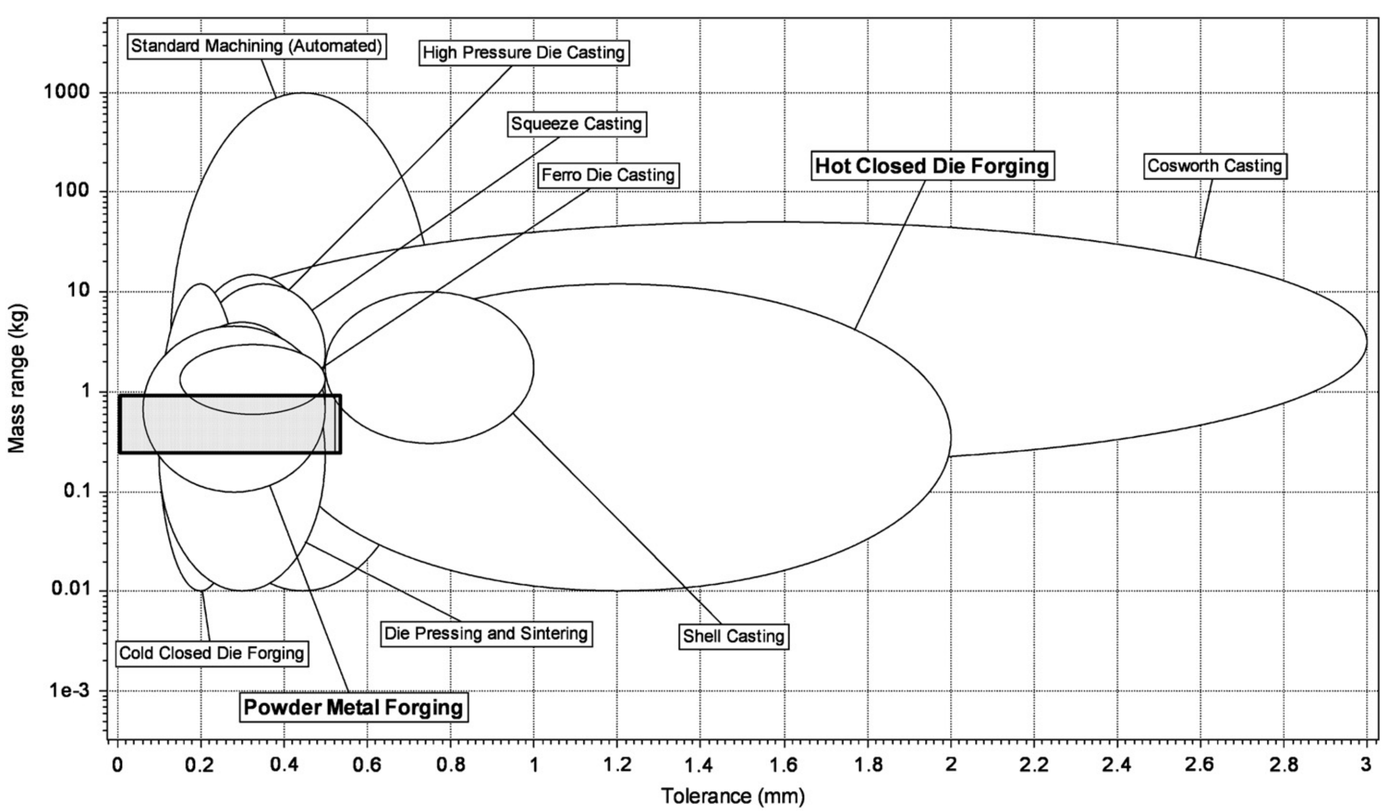

Fig. 9. Case study (Phase 2): viable processes (source from [13]).

6. Conclusions

A methodology for capturing and formalizing the relevant manufacturing information for DFM and its corresponding relationship to the design process (FRs and DPs) has been presented. This methodology guides the designer through the decisions of the design process, from the functional to the process domain. It includes systematic procedures for defining and

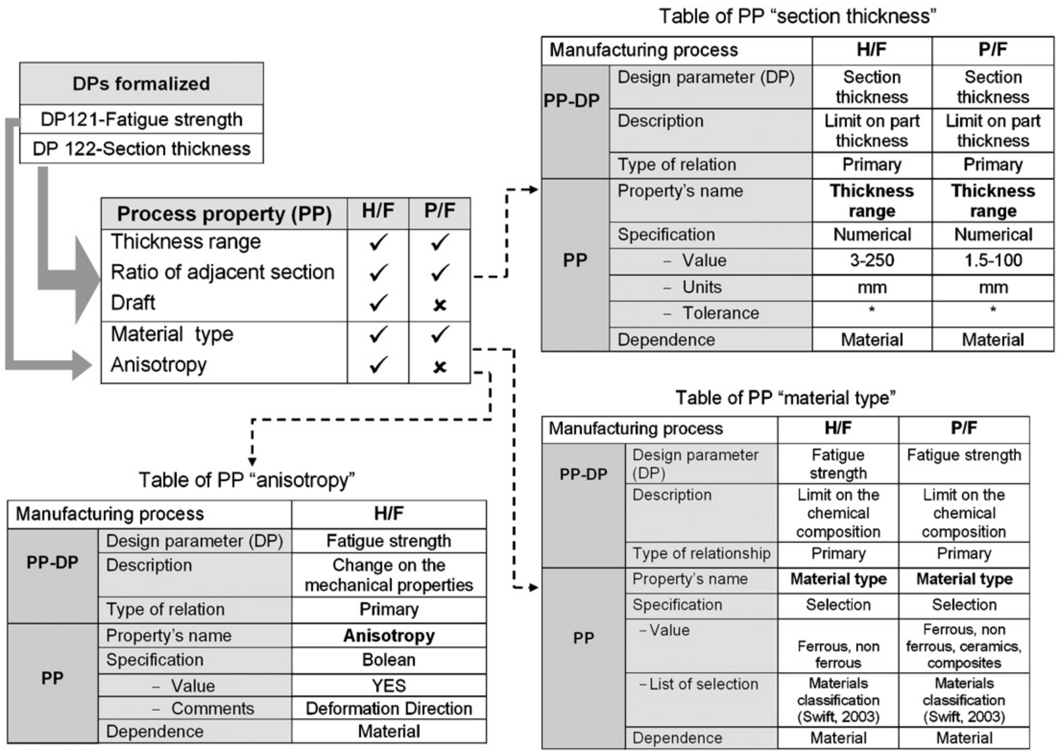

Fig. 10. Case study (Phase 2): example of formalized PPs.

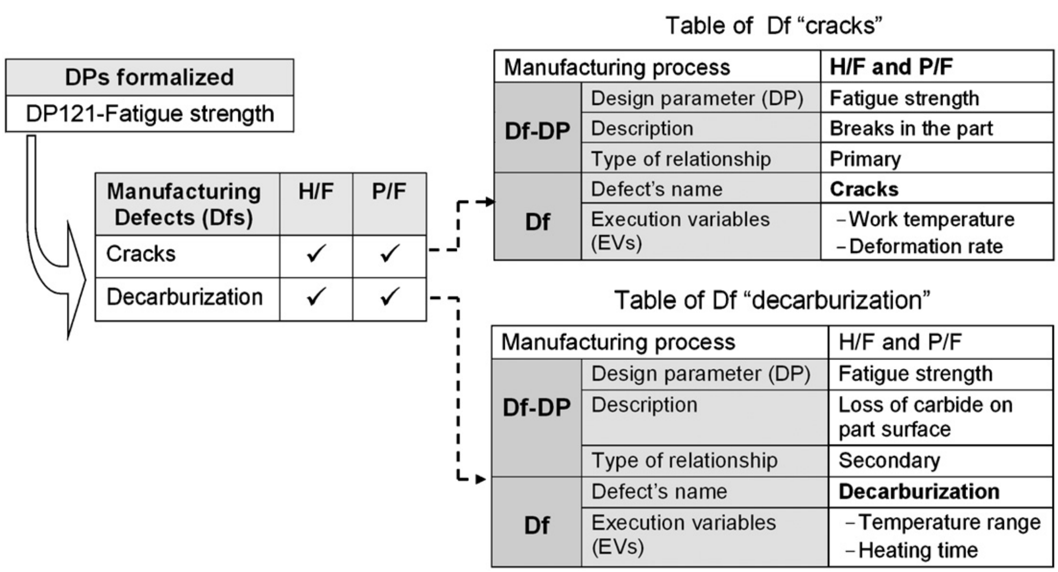

Fig. 11. Case study (Phase 2): example of formalized Dfs.

formalizing the design information (FRs and DPs), DFM information (PPs and Dfs) and the more relevant relationships between the design parameters (DPs).

The work presented here is a first step towards developing a software application capable of providing DFM knowledge to the designer when needed. Thus the designer could be advised to check the part manufacturability before making certain design decisions in order to avoid later re-design tasks and reduce the development time. For this reason the methodology, its application and the results were widely discussed with design and manufacturing experts. As a consequence it can be concluded that:

- Using the Axiomatic Design theory to capture design for manufacturing information helps to determine the information that is essential for satisfying the product functionality. Using the set of DPs that satisfy the functional independence reduces DFM information indirectly. This theory also helps to explicitly state the connection between this DFM information and DPs and FRs in each level of design decomposition.

- The methodology developed proves that in the DFM environment, the mapping between the physical domain and the process domain should be completed by a DFM mapping procedure, and that PPs, Dfs and EVs should be added to the process domain, as they show the relationship between the Axiomatic Design theory and DFM techniques more clearly.
- In this approach the DFM mapping procedure determines the process properties (PPs) and manufacturing defects (Dfs) of each manufacturing process that should be considered to achieve the DPs in the physical domain. Several PPs and Dfs can be used to make decisions on each DP. Nevertheless, applying this method to a real design proves that the design process generates a large amount of information that increases considerably when manufacturing issues are introduced. For this reason it would be appropriate to develop an additional method to determine how important the PPs and Dfs are in each DP. Such a method would minimize the DFM information in each design level.
- The case study revealed that designer expertise and knowledge continue to be essential for carrying out both tasks. However, the explicit knowledge obtained from applying DFM reduces the expertise required in other designs.

The systematic structures proposed for defining and formalizing information—FRs, DPs, PPs and Dfs—should be represented in a data structure model and further implemented in a software application. This software application should guide the designer through the process of defining information and storing it, so that it would be easier to apply the method. First of all this software application would automate the design process and guide the designer through the processes of defining and storing FRs and DPs as well as the relationships between both. Using a CAD system as a platform this information could be connected with the geometrical feature so that the design information would not get lost and could be used in new redesigns. And next, the software should automate the DFM process and guide the designer through the processes of defining and storing PPs and Dfs and providing the corresponding DFM rules to the designer when needed.

The proposed method has three main advantages. First, it makes it easier to integrate design and manufacturing. Second, it encourages defining and formalizing design and manufacturing information as DFM. Finally, it motivates the development of software based on real knowledge to assist in the design process. In future work it is necessary to develop a software application to apply the methodology and a systematic procedure for reusing the design and DFM information after it has been applied.

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