# A model to build manufacturing process chains during embodiment design phases

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The methods for manufacturing process selection from early design phases avoid later mistakes and ensure the success during product manufacturing. Currently, the majority of the products need more than one manufacturing process to become finished parts. This is known as a manufacturing processes chain, and it is important that this manufacturing chain is well designed. This paper presents the bases and the activity model (IDEFØ) to develop a decision support system that helps designers and manufacturing engineers to configure manufacturing process chains while the product is being designed. The model schematizes all the activities and information involved in obtaining reliable manufacturing process chains. The support system has been applied to an air-bending die design process to be used to perform either air bending or bottoming.

Keywords: Manufacturing process; process selection; activity model; decision support system.

## 1. Introduction

In a context of profound changes in industrial markets—in relation to globalization and delocalization—the main challenge for all industries is to remain competitive [1]. In this context, companies need to focus on satisfying as much as possible the product requirements demanded by the market. During the first stage of product development—the design process—many decisions are made to meet these requirements; however, such decisions also affect on other issues, such as process planning, manufacturing, assembly or recycling of the product. Considering these issues during the design stage is important because wrong decisions can have serious effects on development time, cost, and product quality [2, 3]. Given that manufacturing issues must be taken into account at the initial stages of design [3, 4], the designer should know the manufacturing processes or sequence of processes (i.e., the manufacturing process chain) that may be used to manufacture what they are designing. This, however, is not an easy task. First, there is a large variety of manufacturing processes; second, the knowledge associated with each process is abundant; and, finally, the increasing trend towards relocating and separating manufacturing and design centers from each other has led to a decline in designers’ understanding of manufacturing processes by making them less accessible.

To solve this problem, several methods and tools have been developed to help designers select suitable manufacturing processes during product design.

Manufacturing process selection tools help designers choose the most technically and economically suitable manufacturing process to obtain a product [3, 5]. Most of the work developed is based on quantitative analysis. In manufacturing process selection-based on quantitative analysis (MPS-BQA), the choice is made by comparing the design parameters or specifications with the attributes of the manufacturing process. Process attributes describe the capabilities of the process in terms of material, shape, size, tolerances, production rate, cost, and environmental impact, allowing direct, objective comparisons to be made [5], for example, of the tolerance or roughness each process is able to obtain in a part. Some relevant examples of these research studies are: CES [6] , MAS 2,0 [7], , WiSeProM [8], and WebMCSS [9]. These tools may be applied from the preliminary design stages, in which there is already a rough idea of design parameters, such as shape, material and weight, as well as of product restrictions, such as production volume or cost limit. The tools result is a list of manufacturing processes which are able to achieve the basic product form but designer have to chose only one manufacturing process option (a, b, c, d and e in Figure 1) without combining more than one process as a chain derivation allows. To obtain manufacturing process chain two basic requirements have to be considered. First, how much and in what way a product is modified during each process in the manufacturing process chain needs to be considered, thus revealing what remains to be done in the following processes. Second, the compatibility of different manufacturing processes needs to be considered to develop manufacturing process chains that are technically feasible. This means ensuring that a particular process is compatible with the subsequent process.

The process chain can be defined from early design using a selection process or during detail design using a configuration process (Figure 1). The manufacturing process chain selection comprises all the manufacturing processes—taken as a sequence of processes—that meet all the product requirements [10]. For example, chains I and II in Figure 1. By other hand, configuring the manufacturing process chain means choosing the machinery, tools, and other production parameters that will meet the product quality requirements [10].

(See chains III and IV in Figure 1.) Therefore, the configuration takes place at the process planning level.

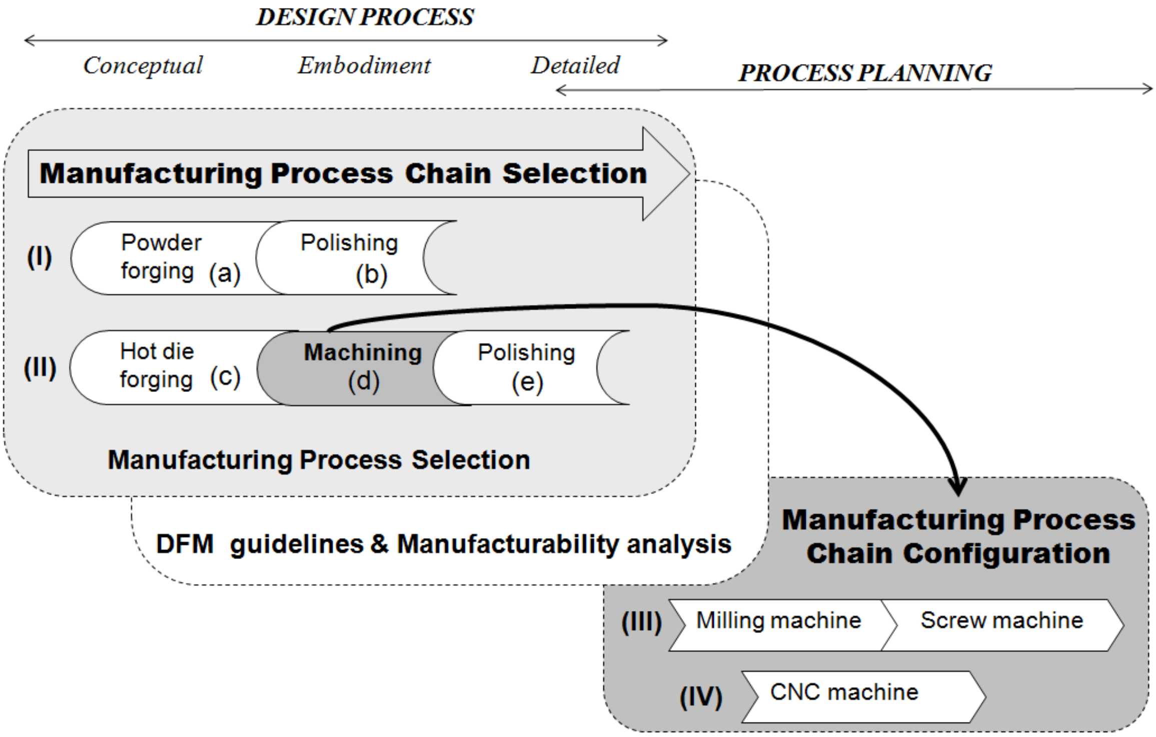


Figure 1. Manufacturing process chain related to the design process.

This research is intended to develop a decision support system to help designers or manufacturer engineers know the sets of manufacturing process chains that could be used to manufacture the products being designed during early design. It is assumed that each chain is able to manufacture the product in its entirety. However, paper presents the first stages in the development of this system. First of all, the framework approach on which the system is based is described. Second, the IDEFØ activity model, in which all the activities, information, and knowledge involved in obtaining a set of viable manufacturing process chains are gathered, is presented to help select manufacturing process chains. Finally, an example that shows the application of the model is explained in detail.

There are three main advantages of such a method. First, the design parameters are better adapted to the manufacturing requirements and there is a better validation of the manufacturability of the design for all the processes involved in its manufacture; second, any problems during the manufacturing phase arising from an unsuitable design are reduced since these problems are detected during the design process; and, finally, production costs can be calculated and compared for various manufacturing process chains.

# 2. Framework approach

The manufacturing process chain is defined as a process map that describes how the initial product blank is transformed into the final product. To get a manufacturing process chain capable of producing a product, a *manufacturing process chain derivation method* is used, which is the core of the method described in this research study (Figure 2). The derivation method which will be presented next is based on both design information and the capabilities of the processes for transforming the products, and provides as a result the set of viable manufacturing process chains that will produce the product. It is focused on mechanical products.

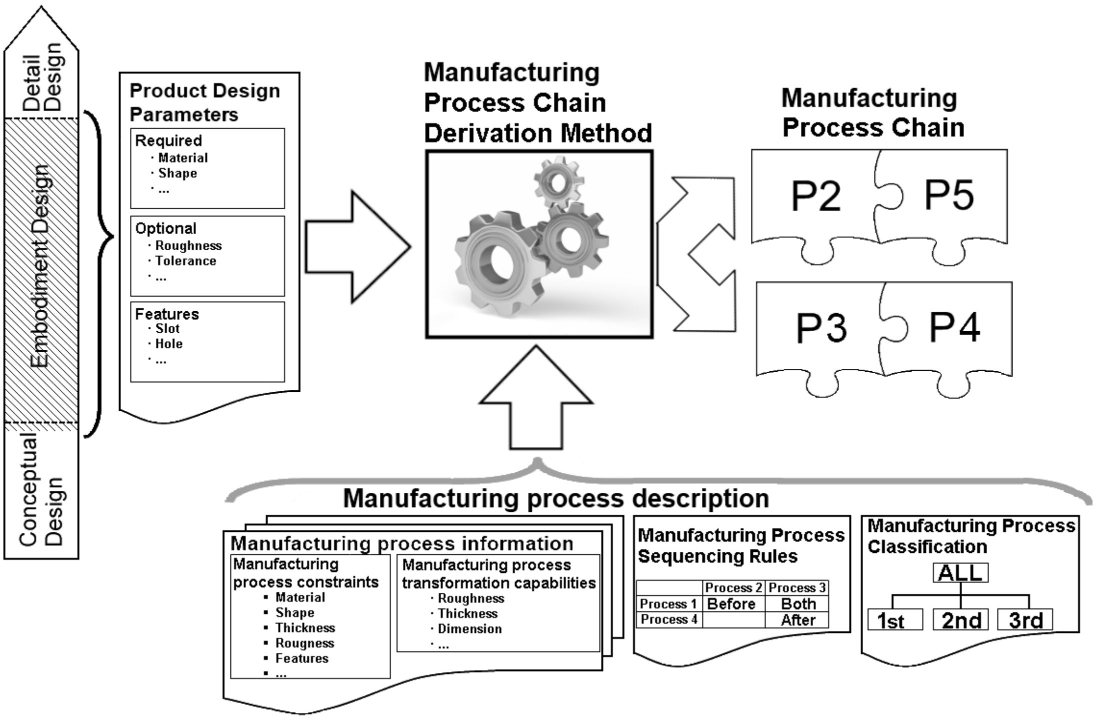


Figure 2. Manufacturing process chain derivation.

As shown in Figure 2, the *manufacturing process chain* must begin to take shape during the embodiment design phase [9, 11], when the requirements and the functionality are defined, and a preliminary draft is written. All this design information has to be compiled in the *product design parameters*, which are a qualitative description of the designed product. Basically, these parameters have been extracted from research works related to MPS-BQA [6, 7, 12] , but they have been classified into three lists: required, optional, and feature design parameters, which are explained in detail in section 3.

The *manufacturing process chain derivation method* requires concise information about the manufacturing processes, especially regarding their capacity to modify the product with respect to the design parameters. This information has to be comparable with the product information in order to create viable manufacturing process chains from a technological point of view. The *manufacturing process description* is divided into three parts (Figure 2):

- The *manufacturing process information* concerns manufacturing process data related to product design and is divided into *manufacturing process constraints* and *manufacturing process transformation capabilities*.
    - The *manufacturing process constraints* are attributes that describe the manufacturing processes and their ability to meet the product design parameters. These constraints include process capabilities related to material, shape, geometrical dimensions (e.g., thickness or tolerance), roughness, geometrical features, and production rates, which also define the product, allowing direct and objective comparisons to be made between design and manufacturing information. They are, therefore, the same as process attributes defined by Lovatt and Shercliff [5].
    - The *manufacturing process transformation capabilities* represent the capability of each manufacturing process to modify the product design parameters from the initial stage or to modify the product design parameters that have been modified by previous manufacturing processes. These capabilities are defined using maximum values of transformation, which quantify how much a manufacturing process can change a product parameter.  Furthermore, the differences regarding manufacturing process constraints will be discussed further.
- The *manufacturing process sequencing rules* define technological constraints among different manufacturing processes so that it is possible to distinguish between viable and non-viable manufacturing process chains, because not all process combinations are viable as a manufacturing process chain [11]. Therefore, for each manufacturing process, it needs to specify all the other compatible manufacturing processes that can be carried out before it, after it, or both (Figure 3). Figure 3 shows an example of the sequencing rules for the milling process. It shows that, during the manufacturing of a part, the processes of casting and powder metallurgy must always take place before milling, whereas bending or drilling processes (labeled ‘both’ in the figure) can take place either before or after milling. The polishing process, however, must take place after milling.

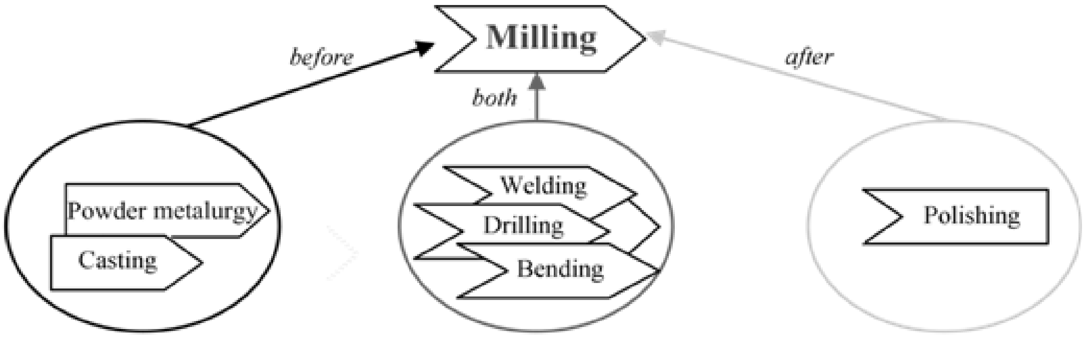


Figure 3. Example of milling process sequencing rules.

- The *manufacturing process classification* classifies manufacturing processes that vary according to the objective pursued with this classification. The manufacturing process classification proposed by Lovatt and Shercliff [5] is used in this work. The processes are classified according to the extent to which they can transform the part and are classified as [5]: primary, secondary, and tertiary. The "primary processes" take unshaped material (liquid metal, or a powder, or a solid ingot) and give it shape. Thus, molding, casting or machining processes are primary. The "secondary processes" modify, add, or refine features to an already-shaped body, such as fine machining and polishing. And finally, the "tertiary processes" add quality either to the bulk or to the surface of a component, for example, shot-peening of surfaces. Although this classification is not absolute, since a particular process, such as machining, may belong to more than one group, the use of this process classification reduces the complexity of the problem and limits the number of candidate processes for manufacturing at each level of the product design. Therefore, it limits the number of processes that need to be analyzed in order to configure each step of the manufacturing process chain.

## 3. Process chain derivation model

Modeling knowledge and information used to integrate design information with manufacturing information has been extensively studied and is still a very active field, as confirmed by the following studies. Skander et al. [1] modeled all the product information, the manufacturing constraints related to design, and the required rules to implement a method that integrated process selection and manufacturing constraints into the design. Ferrer et al. [13] proposed a method to formalize the most relevant design information related to manufacturing that should be made available to the designer to design for manufacturing of new designs. Ciurana et al. [14] modeled the process planning activities in sheet metal processes and the model was implemented in a computer-aided tool. Guerra-Zubiaga and Young [15] show different ways to model manufacturing knowledge and how to make it available when needed. Thibault et al. [16] propose an integrated product–process approach to evaluate its consistency and is useful in selecting suitable forging process and product design parameters. Yuh-Jen Chen [17] modeled the process for conventional molding product design and process development by using the process modeling technique IDEFØ. And finally, Mauchanda et al. [18] model the knowledge and information to develop a tool to calculate the manufacturing cost from conceptual design.

In accordance with the framework approach presented in section 2, an activities model using IDEFØ methodology has been developed as skeleton of a decision-support system to obtain a process chain. The purpose is to schematize all the activities involved in obtaining the viable manufacturing process chains to manufacture a given design from the designer's point of view, i.e., to derive the process chain (Figure 4).

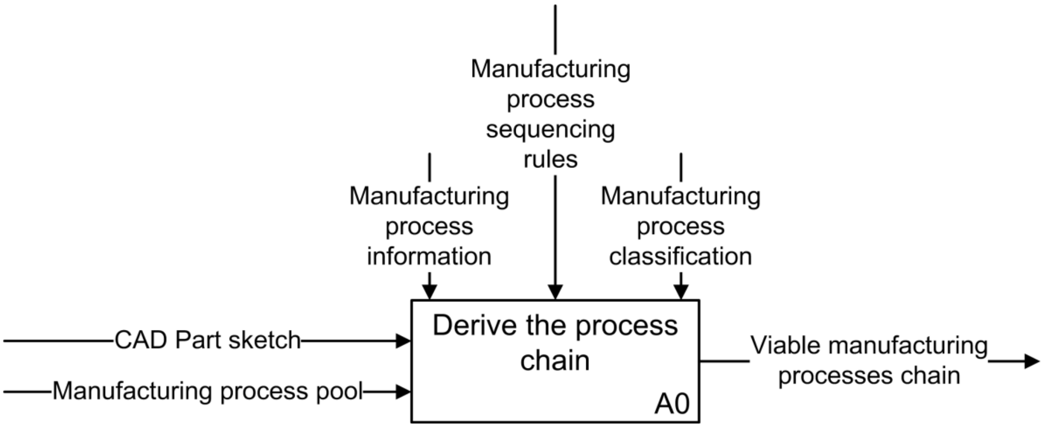


Figure 4. The basic derivation of the process chain A-0.

The inputs required to carry out the main activity are the *CAD part sketch* and *the manufacturing process pool*, whereas the output will be the set of *viable manufacturing process chains*. *Manufacturing process information, manufacturing process sequencing rules*, and *manufacturing process classification* act as controls. The *manufacturing process pool* represents the whole set of manufacturing processes that are considered for the selection. It may be wider or narrower depending on the scope. This main activity, A0, is broken down into four specific activities, A1, A2, A3 and A4, shown in Figure 5, which will now be described in detail.

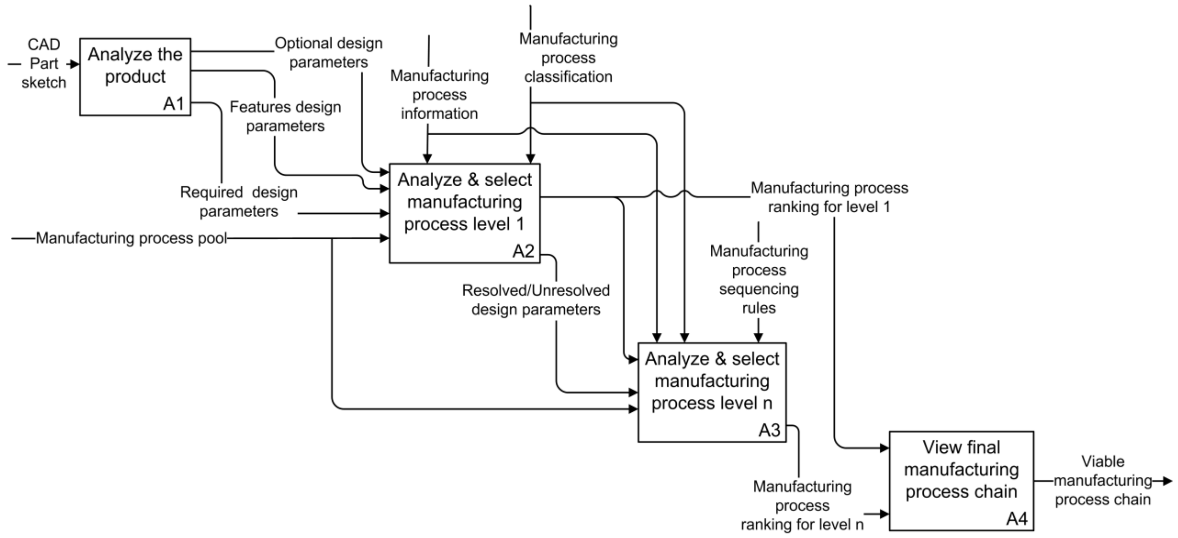


Figure 5. Detailed derivation of the process chain.

## Activity A1. "Analyze the product"

In this activity, the designer has to analyze the product information from the *CAD part sketch* and classify it into three lists of design parameters (see Figure 5): required, optional, and feature design parameters. In this way, the design parameters are organized in terms of how they can be obtained by the manufacturing processes that will form part of the chain, which is important to establish process chains. The first list consists of the *required design parameters*, which are those that all the manufacturing processes in the process chain have to be able to deal with. These parameters are exclusive, which means that a process is excluded when it is not able to process with this property, for any step of the process chain. The second list is the *optional design parameters*, which are product parameters that may be transformed by various manufacturing processes until the final optional design parameter is reached. Finally, the third list is the *feature design parameters*, where a feature refers to the significant processing of portions of the geometric shape of a part or assembly. Neither optional nor features are exclusive because they can be obtained along the process chain.

## Activity A2. "Analyze and select manufacturing process level 1"

The goal of this activity is to analyze and select the first manufacturing process in the process chain from the *manufacturing process pool*, using the *required, optional* and *feature design parameters* as inputs, and both *manufacturing process information* and *manufacturing process classification* as controls (Figure 5). Two outputs are obtained: a set of manufacturing processes ranked according to which should occupy the first position of the process chain, called *manufacturing process ranking for level 1*, and a list of *resolved/unresolved design parameters*. The *resolved design parameters* are those which will have been completely transformed or changed by the selected process whereas the *unresolved design parameters* are those which will require further manufacturing processes. Activity A2 is further broken down into four sub-activities, shown in Figure 6.

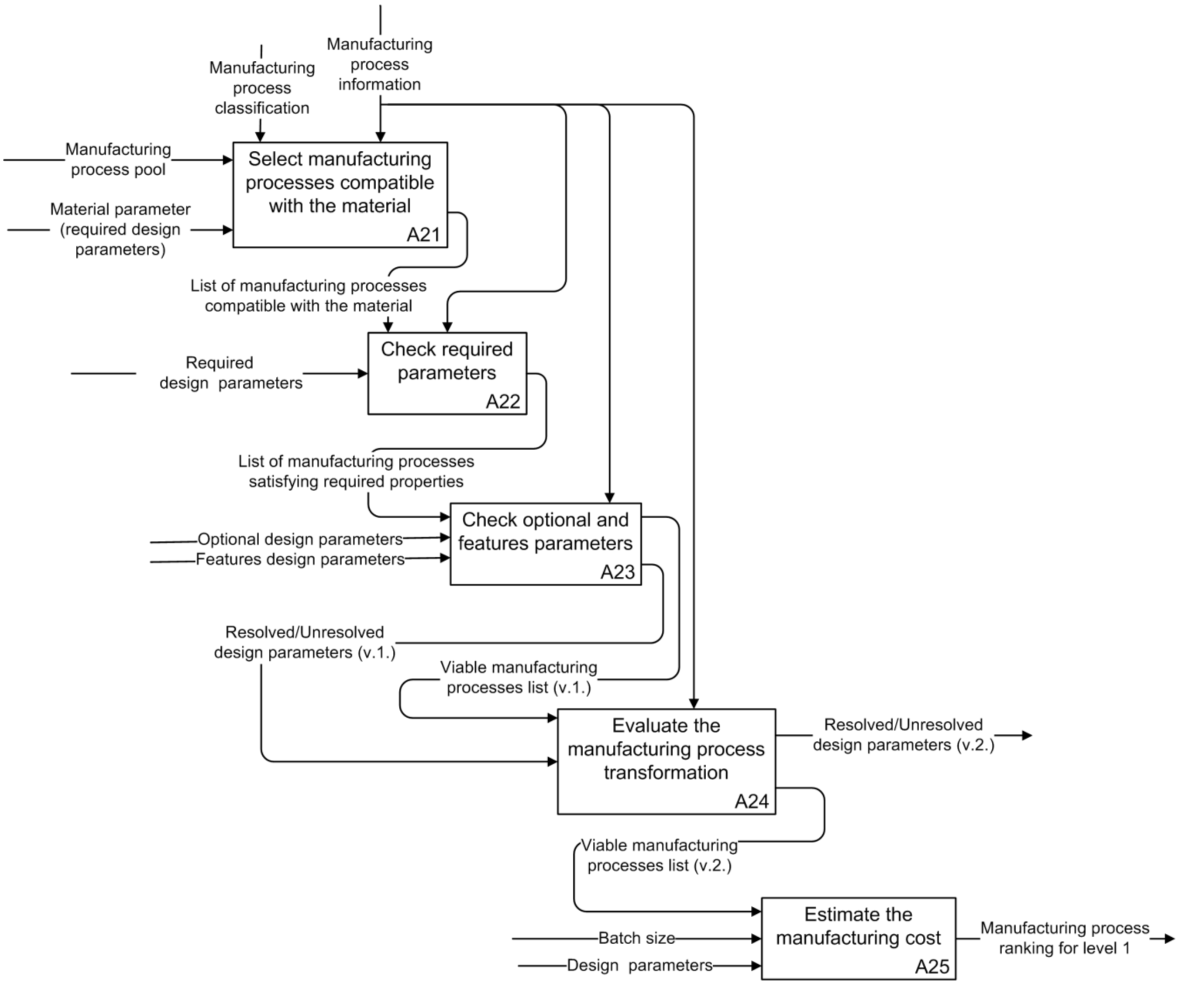


Figure 6. Details of Activity A2 - Analysis and selection of manufacturing process level 1.

### A2.1. “Select manufacturing processes compatible with the material”

The inputs for this sub-activity are the *manufacturing process pool* and the *material design parameter*. The material of the product is compared to the set of materials with which each process is able to work, thus the result obtained is a list of manufacturing processes compatible with the material. The material for required design parameters was chosen as the first discriminatory step because this parameter is the most restrictive in terms of selecting manufacturing processes and it reduces the search range for the next steps [5, 9]. It means that choosing the material for the first step a lot of processes can be excluded since the product cannot be obtained.

### A2.2. “Check required parameters”

This sub-activity checks whether or not the processes in *the list of manufacturing processes compatible with the material* (from activity A2.1) are able to manufacture the other *required design parameters*. These parameters are compared to the manufacturing process constraints of each process. When the process is able to obtain all the parameters from the list of *required design parameters* then the process is kept on the list; otherwise it is excluded. The result is the *list of manufacturing processes satisfying required properties*.

### A2.3. “Check optional and feature parameters”

In this activity the lists of optional and feature design parameters are checked. The result is the *viable manufacturing process list* and a first version of the list of *resolved/unresolved design parameters* indicating which processes are able to transform the part according to those parameters and which ones are not.

### A2.4. “Evaluate the manufacturing process transformation”

As stated in section 2, transformation is the capability of each manufacturing process to modify the parameters of the product either from the initial stage or after a previous manufacturing process has already modified them. It means that achieving the values of a given parameter depends on the starting value of this parameter on the part. To evaluate the manufacturing process transformation, the method needs to calculate the transformation required in the product parameters by comparing the status of these parameters from one manufacturing process to the next. Subsequently, the values obtained for the required product transformation must be compared with the transformation capabilities of the particular manufacturing process. When the calculated values are less than or equal to the manufacturing process transformation capabilities, the manufacturing process is deemed able to transform all the ‘resolved design parameters’ of the part and therefore there is no need to update the list of *resolved/unresolved design parameter*s. Otherwise, when the calculated values are greater than the manufacturing process transformation capability, the list of *resolved/unresolved design parameters* will be updated accordingly.

### A2.5. “Estimate the manufacturing cost”

In the fifth and last sub-activity of A2 the viable manufacturing processes are ranked according to economical criterion. Several methods have been developed for manufacturing cost estimation from early design stages, for example CES [6] and Swift and Booker [19] method. These methods are based on three main elements: material and consumables, tooling and equipments, and investment, where the batch size becomes a key factor. Depending on the value of the batch size the manufacturing cost changes considerably. In addition some processes that may be viable from technological point of view become non viable from economical point of view depending on the batch size.

When A2 activity is complete, it might be that a single manufacturing process can make the entire part or, in contrast, that it is necessary to continue building the chain of manufacturing processes. This decision is determined by the list of *resolved / unresolved design parameters*. If all design parameters are resolved, the chain of manufacturing processes is complete and activity A4 will be implemented, showing the first result. If they are 'unresolved' and there are still some parameters that have not been achieved or only partly achieved, activity A3 continues the elaboration of the chain of manufacturing processes until all the design parameters are resolved.

### Activity A3. “Analyze and select process level n (A3)”

In this activity, the *manufacturing process ranking for level 1* from the activity (A2) is used to evaluate new manufacturing processes for the next step in the process chain. In addition, a new control is used: *manufacturing process sequencing rules*. These rules validate the technological feasibility of each combination of manufacturing processes. Although the procedure of this activity is similar to that of the previous activity (A2), there are two main differences. The first change is the starting point, since now it has the list of *resolved and unresolved parameters* from the previous activity, representing the design properties carried out by the previous process and those pending in the next one. This list will be updated until the manufacturing process chain resolves all the unresolved parameters. The second difference is that the transformation calculation is carried out using the lists of *resolved and unresolved parameters* from the previous manufacturing process as well as the process currently being checked.

### Activity A4. "View final process chain (A4)"

This activity provides a list detailing the selected manufacturing processes that make up the process chain.

## 4. Application of the proposed model

The developed model was applied to a selected set of mechanical parts. However, in this work the design process of an air-bending die (Figure 7) to be used to perform either air bending or bottoming is discussed in detail. The manufacturing processes are reduced in this sample to 'powder metallurgy', 'machining', 'polishing', 'hot closed die forging' and 'roll forming'. Nevertheless, the model developed is also applicable for other mechanical parts than this sample and whole manufacturing processes feasible for mechanical parts being manufactured. Following the proposed IDEFØ diagram and based on the current version of the 'CAD part sketch' (Figure 7), the designer or manufacturing engineer has to extract the design parameters and classify them into required, optional and feature design parameters. Table 1 shows these three lists and the values of the parameters for the case study. The lists are produced during activity A1, as shown in Figure 5.

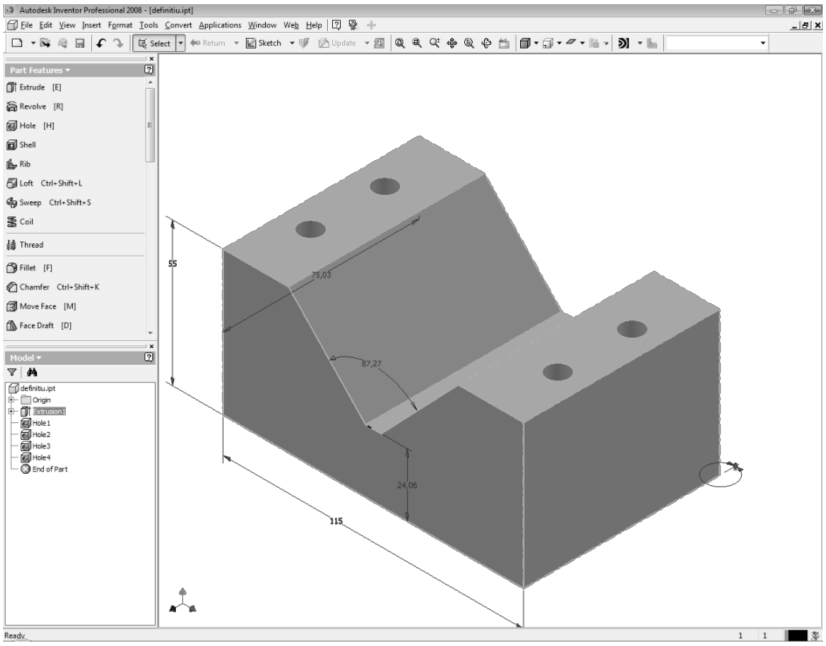


Figure 7. CAD sketch of the die used in the case study.

| Product design parameters | | |
|---|---|---|
| *List* | *Parameter* | *Value* |
| Required design parameters | Material | Iron |
| | Shape | Prismatic – non-axisymmetric - solid |
| | Length (X) | [75;75] mm |
| | Width (Y) | [115;115] mm |
| | Height (Z) | [24;55] mm |
| | Weight | 3 kg |
| Optional design parameters | General roughness | 10 µm |
| | Specific roughness | 5 µm |
| | General tolerance | 10 |
| | Specific tolerance | 0.5 |
| | Corner radius | 1 |
| Feature design parameters | Type | Hole |
| | Diameter | 8.5 mm |
| | Height (Z) | 55 mm |
| | Roughness | 0.1 µm |
| | Tolerance | 0.002 |

Table 1. Product design parameters of the case study.

In activity A2 (Figure 5), the lists of *product design parameters* from Table 1 and the *manufacturing process pool* are used to produce two outputs. The first one is the list of processes that can be used as the first manufacturing process of the process chain which will initiate production of the part, i.e., 'hot closed die forging', 'powder metallurgy', and 'machining'. The second output is the list of *resolved/unresolved parameters*, which it will be explained later. Nevertheless, to achieve these outputs, the A2 sub-activities must first be carried out. Figure 8 shows in detail the results of these A2 sub-activities for the die case study.

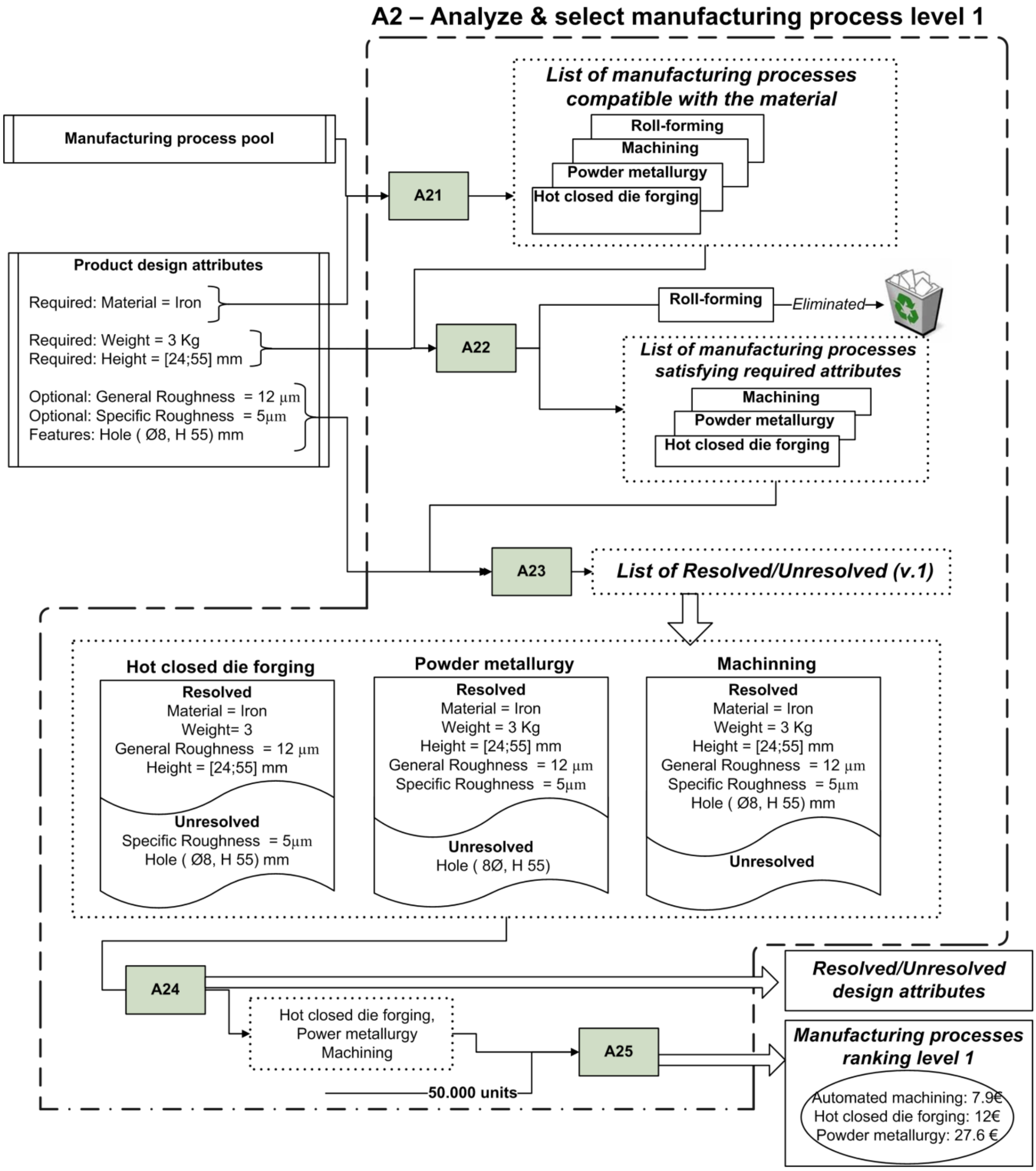
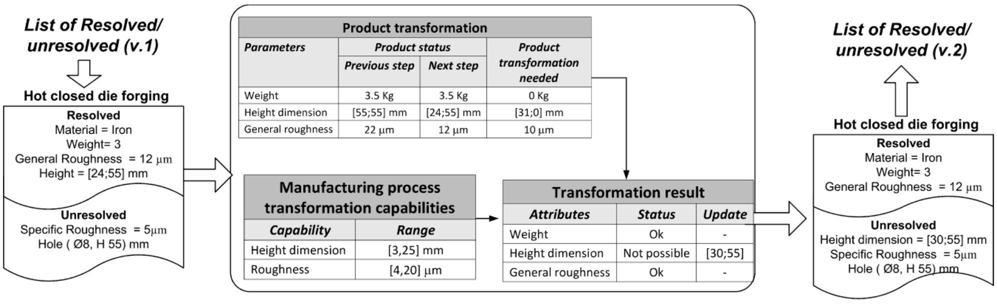


Figure 8. Flow chart of Activity A2.

Initially, the A2.1 sub-activity gives a list of all the manufacturing processes capable of working with the *material* of the product in question, comparing the product material with the set of materials that each process is able to manufacture. 'Hot closed die forging', 'powder metallurgy', 'machining', and 'roll-forming' make up the *list of manufacturing processes compatible with the material.* Subsequently, these processes are further filtered by sub-activities A2.2 and A2.3. Activity A2.2 checks the *list of manufacturing processes compatible with the material* to see which ones satisfy the other required parameters, which in the example are *weight* and *height*. Both are numeric parameters and it is checked that its value is included in the range of values that each process is able to achieve, according to its manufacturing process constraint. The 'hot closed die forging', ‘powder metallurgy’, and 'machining' processes meet these requirements and are therefore allowed to continue as input for the next activity, A2.3. In contrast, the 'roll forming’ process cannot achieve the required *height* and is removed from the list. Now, activity A2.3 checks the list to see if these processes are capable of manufacturing the *optional* and *feature* design parameters, which in this case include *general roughness, specific roughness,* and *hole*.

As shown in Figure 8, the process 'hot closed die forging' can meet the material, weight, general roughness and height requirements, but not the specific roughness and hole requirements. Choosing this process would require a subsequent manufacturing process to complete the part. In contrast, 'machining' is able to resolve all the design parameters, which suggests that, for this case study, this process would be sufficient to produce the part. However, following the model proposed here, it is necessary to analyze whether each process can transform the objectives set out in the list of design parameters (sub-activity A2.4).

At this point, the method has evaluated the capacity of the processes to meet the product design parameters taking into account the manufacturing process constraints. However, activity A2.4 assesses the capability of the manufacturing processes to transform the parameters from the output list of activity A2.3. Figure 9 shows the results of activity A2.4 for the process 'hot closed die forging'. The process 'hot closed die forging' has to transform the parameters of *weight, height* and *general roughness* from an initial status (previous step) to a final status (next step). In that case, the initial status corresponds to the material blank, which is considered as the volumetric space of the part. Therefore, the values for *weight* and *height* take it into account. The final values of these parameters appear in the next step. The parameters are quantified with a numerical value—as the weight—or using a range that shows the maximum and minimum values the parameter takes in the part—as the height dimension. The result of this transformation is described in the *product transformation needed* column in the *product transformation* table. The resulting values must then be compared with the range of transformation values found for 'hot closed die forging' in the list of *manufacturing process transformation capabilities*. The result of this comparison is shown in the *transformation result* table, which notes whether or not the process 'hot closed die forging' can sufficiently modify the parameters of the product. If a parameter cannot be transformed by the manufacturing process, such as *height* in this case, its value is adapted in relation to the transformation capacity of the process. In this case, the 'hot closed die forging process' cannot reduce the height of the part from an initial 55 mm to a final 24 mm because the maximum process transformation capability for height is 25mm. Therefore, after this process the height of the part will be 30 instead of 24 mm. Thus, this parameter, which seemed to be resolved at the beginning of activity A2.4, in *resolved / unresolved design parameters, version 1* (Figure 9), is classified as unresolved at the end of it. When a parameter such as *roughness* can be transformed by the process, it is kept as 'resolved' in the list. The *weight* parameter is not affected by this manufacturing process capability. The outputs of Activity A2.4 are, first, an update that gives us *resolved/unresolved design parameters (version 2)* for each manufacturing process and, second, the *list of selected manufacturing processes*, as shown in Figure 8.



**Product transformation**

| *Parameters* | *Product status* | | *Product transformation needed* |
|---|---|---|---|
| | *Previous step* | *Next step* | |
| Weight | 3.5 Kg | 3.5 Kg | 0 Kg |
| Height dimension | [55;55] mm | [24;55] mm | [31;0] mm |
| General roughness | 22 μm | 12 μm | 10 μm |

**Manufacturing process transformation capabilities**

| *Capability* | *Range* |
|---|---|
| Height dimension | [3,25] mm |
| Roughness | [4,20] μm |

**Transformation result**

| *Attributes* | *Status* | *Update* |
|---|---|---|
| Weight | Ok | - |
| Height dimension | Not possible | [30;55] |
| General roughness | Ok | - |

Figure 9. Evaluating the manufacturing process transformation capability (A2.4).

Next the manufacturing cost is estimated according to the batch size. Considering the Swift & Booker cost method [19] when the batch size is lower than 1.000 units only manual machining is viable and the estimated cost is 21 € per part. Neither 'hot closed die forging' nor 'powder metallurgy' are viable from economical point of view. Otherwise when is higher than 1.000 units 'hot closed die forging', 'powder metallurgy', and 'automated machining' continuing being viable. The estimated costs for 10.000 units are 30, 97.6 and 13.7 € per part, respectively, whereas for 50.000 units the cost is 12, 27.6 and 7.9 € per part, respectively. The Figure 8 shows the processes ranked according to this result.

At this point the first manufacturing process chain for the manufacture of the die, consisting simply of 'machining', is achieved. However, for the manufacturing processes with unresolved parameters, the manufacturing process chain must continue to be constructed. This means carrying out Activity A3 which, in the case of ‘powder metallurgy’ produces the chain ‘powder metallurgy – machining – polishing’ and in the case of ‘hot closed die forging’ produces the chain ‘hot closed die forging – machining – polishing’.

# 5. Conclusion

This paper presents the bases for developing a decision support system that would help designers and manufacturing engineers know which manufacturing process chains can be used to manufacture a product. The main research contribution of this work is to help designers to define the set of useful manufacturing processes chains thus the designer could select for manufacturing a mechanical part based on cost estimation and technical feasibility. Then result is based on showing all the activities, information, and knowledge involved in obtaining a set of viable manufacturing process chains to manufacture a product through the method by utilizing IDEF0. To reach this purpose detailed novelties are:

- The model makes it possible to control the properties modified in each step of the process chain and to know if the properties are partially or completely obtained.
- New classification of design properties identifying those which are exclusive (required properties) and those which are not (optional and feature properties), and a procedure to assess the manufacturing process transformation capability have been proposed.
- Definition of manufacturing sequencing rules to consider the compatibility among manufacturing processes to obtain viable manufacturing process chains is created.
- the research is validated by applying the method to an air-bending die case study

The proposed model certainly makes it easier to develop manufacturing process chains, however, the next step in this research is focused on the development of a decision-support system to select the manufacturing process chain. The model should be integrated in a CAD system making the model useful, reliable and feasible for industrial application.

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