A Decision-Analytic Feasibility Study of Upgrading Machinery at a Tools Workshop

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Abstract— **This paper presents the evaluation, from a Decision Analysis point of view, of the feasibility of upgrading machinery at an existing metal-forming workshop. The Integral Decision Analysis (IDA) methodology is applied to clarify the decision and develop a decision model. One of the key advantages of the IDA is its careful selection of the problem frame, allowing a correct problem definition. While following most of the original IDA methodology, an addition to this methodology is proposed in this work, that of using the strategic Means-Ends Objective Network as a backbone for the development of the decision model. The constructed decision model uses influence diagrams to include factual operator and vendor expertise, simulation to evaluate the alternatives and a utility function to take into account the risk attitude of the decision maker. Three alternatives are considered: Base (no modification), CNC (installing an automatic lathe) and CF (installation of an automatic milling machine). The results are presented as a graph showing zones in which a particular alternative should be selected. The results show the potential of IDA to tackle technical decisions that are otherwise approached without the due care.**

Keywords-decision analysis; equipment replacement; integral decision analysis; maximum expected utility

I. INTRODUCTION

This work presents a study of the feasibility of the inclusion of automated equipment into an existing metal manufacturing workshop located near México City. The feasibility analysis is approached from a Decision Analysis (DA) perspective. DA is a discipline which aims to bring clarity, insight and definition to messy decision situations [1-3], and has been viewed as a mixture of Systems Analysis and Decision Theory [1]. It´s usage for decision making guarantees the satisfaction of a set of desiderata (axioms) of rational choice [4].

In the context of DA, several methodologies for problem analysis have been proposed, as is the case of the PrOACT [5], the Integral Decision Analysis (IDA) [2] and Value Focused Thinking (VFT) [6]; similar methodologies are discussed in [7]. These methodologies aim to convert an initially blurry situation (in which the stakeholders don´t know exactly which consequences they care about or what can be done), into a structured decision model, in which alternatives and objectives have been clearly defined and measured [7].

The IDA consists of the following steps: 1) Problem Framing; 2) Analysis of Objectives; 3) Creation of Alternatives; 4) Identifying Uncertainties; 5) Decision Modeling; 6) Alternative evaluation; 7) Alternative selection and 8) Implementation. A distinct feature of the IDA is its careful determination of the decision frame, involving the creation of several frames of different sizes and emphases, using a graphic tool called diagram of decision frames.

There is a vast body of work related to the problem of finding an optimal replacement policy of industrial machinery [8-17]. A more complicated problem arises when incorporating the effects of technological change [18-20], inflation and taxes [21], a limited budget [22], imperfect repairs [23-24] or warranties from the equipment supplier [25-27]. Other researchers have approached the problem through fuzzy models [28-29] or treated the replacement of several equipments [31-32]. The consideration of several objectives can be found in [33-39] while the introduction of risk attitude is shown in [40].

The decision treated here is whether or not to include new equipment at a workshop, and it can be considered equivalent to the problem of determining a policy of equipment replacement. However, the above mentioned research starts with a problem that is already structured, that is, objectives and alternative courses of action are taken as a given. Related to this, a four-step method for selecting a model for a replacement problem is shown by Fraser and Posey [41] while Hart and Cook [42] propose a systematic approach to the decision process with stages of objective identification, indicators of achievement, alternatives and problems of implementation. These methodologies, however, do not treat problem framing explicitly and don´t take advantage of any of the well-established tools of the DA discipline.

By contrast, in a real life situation, once the idea of replacing equipment comes to mind, the engineer should proceed to carefully define a decision frame for the situation, so relevant objectives and alternatives are uncovered. These steps are omitted in the previous works and are presented here, as they are part of the IDA methodology. Also, in this work, relevant uncertain knowledge from the plant engineers and vendors are expressed as subjective probabilities and incorporated to the model. In this respect, except for Arueti and Okrent [39], none of the previous authors explicitly use subjective probabilities in the decision.

Finally, while this work follows the original IDA methodology for the most part, the IDA methodology is here expanded by adding the usage of the strategic Means-Objectives Network as a map for decision-model building. To the best of our knowledge, there are no reports of the application of the IDA, or other DA methodology with a similarly careful procedure for problem framing, to an industrial equipment replacement problem.

II. Problem Statement

The workshop under study is located near the town of Chalco, México. It produces several types of iron and steel tools: manual and bench drills, vises, clamps, etc. Its customers are mainly local carpenters and the nearby wood furniture industry. The main concern of the manager is a perceived low efficiency in the processing of bench vises, which happens to be the top seller product of the company. One proposal for improving this situation is to substitute old equipment with modern one, thus allowing operation with fewer workers and an increased productivity, as the modern machinery is more automated. Several issues need to be settled so the problem can be modeled correctly

1. The metric over which the modifications should be evaluated: It can be productivity, production costs or profits. The adequate metric depends on the manager's objectives.

2. The modifications that are to be considered when evaluating each proposal (i.e. are changes in inventory or layout to be considered in the decision?)

3. Are there any uncertainties that should be considered in the model? If so, the stakeholder´s dislike of uncertainty should be introduced in the model.

In the following we apply the IDA steps to the problem, showing how it helps to clarify the decision. All shown tables and figures are the authors' own production.

III. Development and Results

A. Problem Framing

In order to define a decision frame (what to decide and with which objectives), several frames should be explored. This can be conveniently done using a frames diagram. The construction of this diagram starts with the Base frame, which represents the current understanding of the decision situation, and then several other frames are defined by changing the amplitude and emphasis of the Base frame. Figure 1 shows a decision frames diagram, whose parts are explained below.

Base Frame: The trigger of the decision is the idea of automating the manufacture process, thus this frame is stated as: Deciding the automation of the manufacture process. It comprises the decision of whether or not to automate, and the type and size of the new machines. Its objective is to maximize the plant productivity.

Narrow Frames E1 and E2: The decision frame E1 is *Deciding the degree and extent of the automation* and E2 is *Deciding the equipment provider*. The objective of E1 is to maximize productivity and that of E2 is to minimize the time and costs involved in fixing possible equipment failures.

Wide Frame A1: *Deciding about improving the manufacture process* contains the base frame plus other alternatives, like modifications of inventory, staff, policies of inspection and outsourcing. The objective of this frame is to maximize product quality and to minimize costs.

Frames B1, B2, B3, B4 and B5: These frames are contained into A1, so their amplitude is similar to that of the Base Frame but their emphases are different: B1 emphasizes layout, B2 inspection, B3 staff, B4 inventory and B5 outsourcing. The objectives of B1-B5 are means of the objective of A1, related to the scope of each frame.

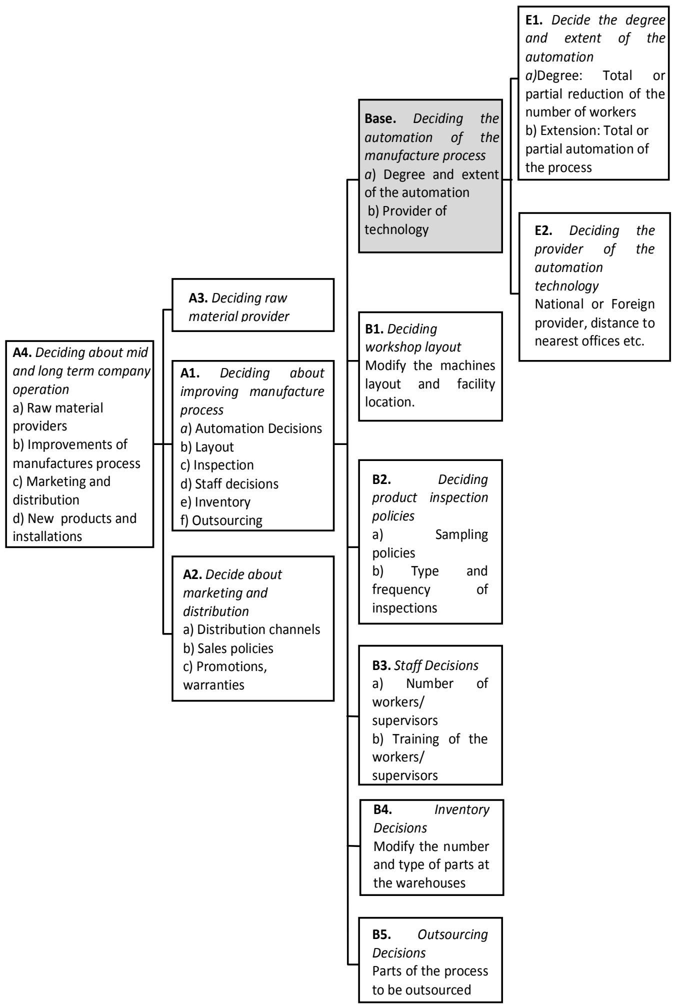


Fig. 1 Diagram of Decision Frames

Wide Frames A2 and A3: These frames shift the focus to different aspects of plant operation. A3 is *Decide about raw material procurement* and A2 is *Decide marketing and* *distribution policies*. The objectives of A3 are to minimize purchase costs, maximize availability and quality of raw material while those of A2 are to maximize sales and minimize marketing and distribution costs.

Wide Frame A4: A4 is the widest frame to consider, including frames A1, A2 and A3 plus additional decisions, like the installation of more workshops and new product development. A4 objective is to maximize profits.

Once the Decision Frames Diagram is complete, the generated frames are analyzed. A key element of our problem is that we haven´t decided whether or not to automate the process, and the automation will proceed only if it has a reasonable chance of generating economic benefits. Thus we discard the narrow frames E1 and E2, as these assume that it has been decided to automate the process.

The objective of the base frame is to increase productivity. While automating the process may increase productivity, the costs of the new equipment may outbalance the economic benefits of that increase. This would be an unacceptable scenario for the stakeholders, so the objective of the base frame is inadequate, as it doesn´t refer to costs.

Frame A1 objective (maximize quality and minimize costs) is more appropriate than the objective of the Base Frame. However, not all the decisions of A1 are to be considered in the present problem: we are not allowed to change inventory, inspection or outsourcing. By pruning the decisions of A1, we produce the frame A1* which has the same objective of A1 but only decisions in the context of our problem (Figure 2). A1* is not yet adequate, as the decisions should be assessed by their economic implications and A1* has the objective of maximizing quality and minimizing costs. A4 has the adequate objective (maximize profits) but the decisions included in it are too wide. We thus define A4*, eliminating the decisions of A4, not included in A1*. The decision frame to be used A4*, shown in Figure 3.

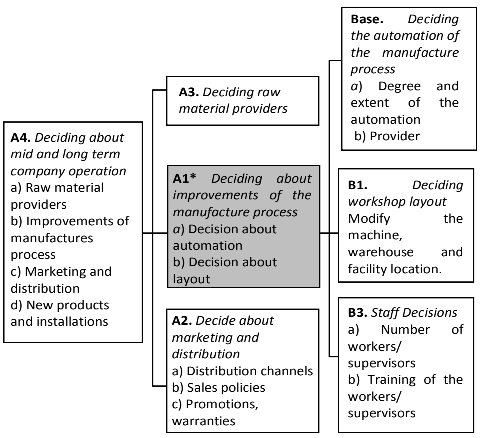


Fig. 2 Reduced Diagram of Decision Frames

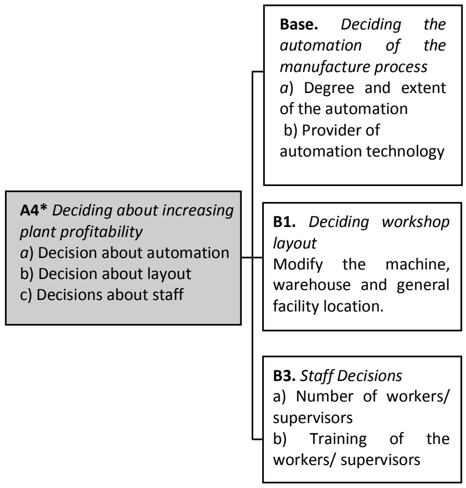


Fig. 3 Final Decision Frame

B. Objective Analysis

The first stage of the clarification of objectives is their identification [6]. To do so we begin with a “wish list” that provides the following 19 objectives

1. Maximize profits
2. Minimize total costs
3. Maximize incomes
4. Maximize sales
5. Maximize product quality
6. Minimize the number of jobs that need re-work
7. Maximize productivity
8. Minimize process times
9. Minimize transport time
10. Minimize delivery times
11. Minimize raw material waste
12. Optimize facility lay-out
13. Minimize required man-hours
14. Minimize inventory costs
15. Minimize inspection cost
16. Maximize market share
17. Maximize competitiveness of company
18. Maximize skill of work force
19. Minimize delays in product delivery

One of the most important steps in a DA approach to problem solving, is to understand the relationships among the identified objectives. The objectives that are important by themselves are called Fundamental Objectives, and are organized into a hierarchy shown in Figure 4. The objectives of the wish list that are not fundamental should either be equivalent to a fundamental objective, or be a mean to accomplish one. In this latter is true they are called Means Objectives and are structured in the Mean-End Objectives Network of Figure 5.

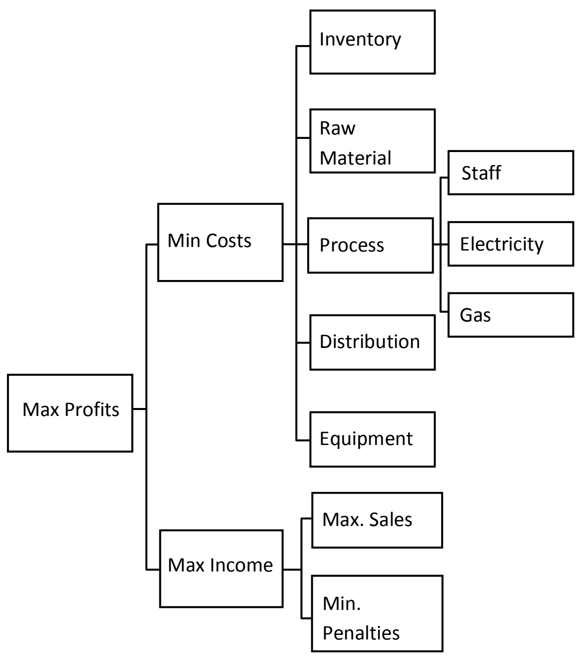
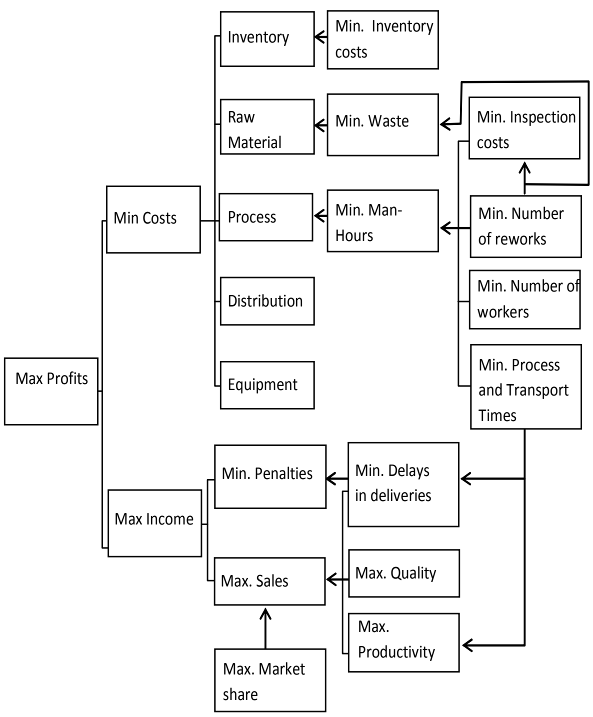


Fig. 4 Hierarchy of fundamental Objectives



Fig, 5 Mean-Ends Objective Network

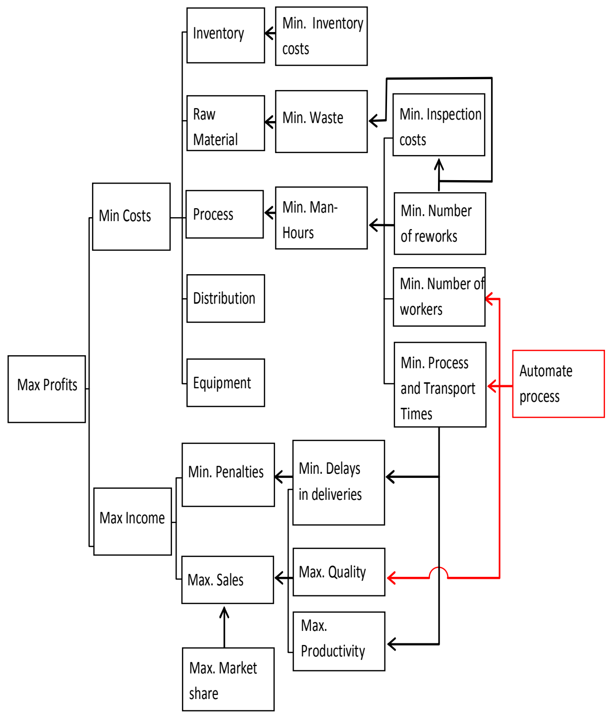


Fig 6. Alternatives and Mean-Ends Objectives Network

C. Alternatives

The Means-Ends Objective Network is useful for generating alternatives; however, in this case the class of alternatives to be considered has already been identified by the framing process. The alternative "Automating the process" implies either the introduction of automated machines that substitute the workers in a part of the process or changing the existing machines for new automated ones that require less supervision or fewer workers. This alternative implies purchase, installation, start up and maintenance costs, and, potentially, costs of worker training. To indentify all effects of this alternative on the objectives, we locate the alternative to the right of the Mean-Ends Objective Network and draw arrows to the objectives affected (Figure 6)

Once the general class of alternatives has been set, the following three concrete alternatives are defined for further consideration

1. **CNC**: Introduce an automatic Lathe.
2. **CF**: Introduce an automatic Milling Machine.
3. **Base**: Keep using the current machinery

D. Analysis of Uncertain Events

The main uncertainties to be considered can be identified from the Means-Ends Objective Network of Figure 6. The decision should be valued by its economic implications, so we´ll need to model the arrow paths that go from "Automate Process" to "Max. Profits". The arrow between "Max. Productivity" and "Max. Sales" and that between "Min. Process and Transport times" and "Max. Productivity" represent uncertain relations. While the latter may be dealt with by a simulation model, for the former we will likely have to rely on subjective probabilities from the vendor staff.

E. Decision Modeling

As the decision should be justified economically, it should be evaluated by its effect on profits

$$Profits=Income-Cost \quad (1)$$

Income equals the number of tools (vises) sold N_V (vises/day) times the selling price of each vise P_V (\$/vise).

$$Income=N_V \times P_V \quad (2)$$

If N_M is the size of the vise market (the maximum number that can be absorbed by the market on a daily basis) and N_{PROD} the daily production then N_V=min(N_M , N_{PROD}). The expertise of the company vendors can be used to construct the following contingency table of N_V.

TABLE I. EXAMPLE OF CONTINGENCY TABLE FOR N_V

N_M	Probability of $n_{M,k}$	N_V
$n_{M,1}$	p($n_{M,1}$)	$n_{M,1}$
$n_{M,2}$	p($n_{M,2}$)	$n_{M,2}$
:	:	:
$n_{M,i}$	p($n_{M,i}$)	$n_{M,i}$
$n_{M,i+1}$	p($n_{M,i+1}$)	N_{PROD}
:	:	:
$n_{M,n}$	p($n_{M,n}$)	N_{PROD}

Being $n_{M,i}$ such that $n_{M,i} < N_{PROD} < n_{M,i+1}$. The daily costs for each automation option are

$$Cost = \left[\frac{C_{EQ}}{360 \times V_{EQ}} \right] + N_{PROD} \times \left(C_{MAT} + C_{EN} \right) + C_{MAN} \quad (3)$$

Where C_{EQ} and V_{EQ} are respectively the total cost and the life span (in years) of the new equipment, C_{MAT} and C_{EN} are the raw material and energy costs of manufacturing one vise. C_{MAN} is the daily staff cost and depends on the number of workers n_T and the daily wage S_{WORK} (\$/day-worker)

$$C_{MAN}= n_T \times S_{WORK} \quad (4)$$

If the process is automated, the required number of workers changes, whereas both the automation and number of workers affect the productivity. These relations are uncertain and are modeled as follows: For an automation option, let $N_{PROD,MAX}$ be the maximum achievable daily productivity. Using the expertise of the plant engineers, a contingency table is elicited, in which different levels of N_{PROD} are defined as fractions of $N_{PROD,MAX}$. The table shows, for the relevant automation option, the probability of the N_{PROD} levels conditional on the number of workers. The structure of such a table is shown in Table 2, for a high ($n_{T,\ HIGH}$), medium ($n_{T,\ MED}$) or low ($n_{T,\ LOW}$) number of workers.

TABLE II. EXAMPLE OF CONDITIONAL PROBABILITIES OF N_{PROD} FOR A CHOICE OF MACHINERY UPGRADE

		Number of Workers		
		$n_{T,LOW}$	$n_{T,MED}$	$n_{T,HIGH}$
N_{PROD}	$0.8 \times N_{PROD,MAX}$	--	--	--
	$0.9 \times N_{PROD,MAX}$	--	--	--
	$N_{PROD,MAX}$	--	--	--

The actual values of $n_{T,LOW}$, $n_{T,MED}$ and $n_{T,HIGH}$ depend on which automation choice is being considered. As summary, an influence diagram of the model is shown in Figure 7. In this diagram rectangles represent decisions; ovals mean uncertain variables and double-bordered ovals stand for deterministic calculations. The value of $N_{PROD,MAX}$ is obtained by simulating the system for the proposed automation choice. Finally, the risk attitude of the company is introduced by translating the Profits into a utility using an exponential risk averse function (5)

$$U = 1 - \exp\left(\frac{Profit - Profit^0}{R} \right) \quad (5)$$

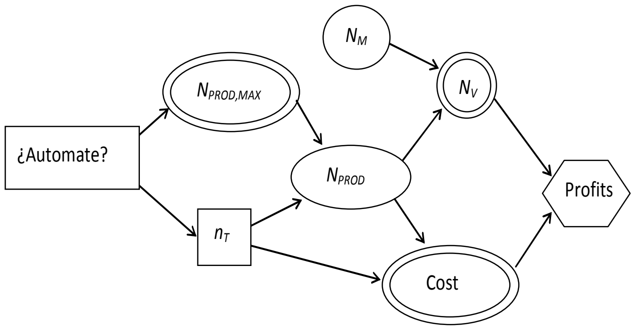


Fig. 7. Influence Diagram for Profits

Profit^0 is the minimum *Profit* that can happen and *R* is the risk tolerance. The alternative to be selected is the one that has the maximum expected utility [43].

F. Assessment of alternatives

The manufacture of vises, as currently done, is shown in Figure 8. The name of the operation, the tag of the equipment used, and the mean time (minutes) of the operation are also shown, while the name of each vise part is shown in the arrow-like shapes at the left. To calculate the maximum number of vises produced daily, ARENA [44] simulation models of the original and modified systems were set up.

The model of the CNC option is produced by substituting the lathes (1-M, 2-M, 3-M, 5-M and 7-M) by a single one that processes each part in half the time [45]. The CF option is modeled by taking out the existing milling machines of the model (5-F, 4-F and 3-F) and introducing a single one that can process the parts twice as fast as the formers [46]. The simulated maximum number of vises per day is shown in Table 3. It is interesting to note that the CNC option did not increase the productivity, as did the CF option. This is because the lathes are not an important bottleneck in the process. Probabilities of N_{PROD} and N_V, elicited from the plant engineers and vendors, respectively, are shown in Tables 4-7.

TABLE III. SIMULATED $N_{PROD,MAX}$ FOR CHOICE OF AUTOMATION

	BASE	CNC	CF
$N_{PROD,MAX}$	10	10	15

TABLE IV. CONDITIONAL PROBABILITIES OF N_{PROD} FOR BASE CASE

		Number of Workers		
		10	*12*	*14*
N_{PROD}	$0.6\times N_{PROD,MAX}$	0.5	0.2	0.1
	$0.8\times N_{PROD,MAX}$	0.4	0.6	0.1
	$N_{PROD,MAX}$	0.1	0.2	0.8

TABLE V. CONDITIONAL PROBABILITIES OF N_{PROD} FOR UPGRADE CHOICE "CNC"

		Number of Workers		
		6	*8*	*10*
N_{PROD}	$0.6\times N_{PROD,MAX}$	0.2	0.0	0.0
	$0.8\times N_{PROD,MAX}$	0.3	0.3	0.1
	$N_{PROD,MAX}$	0.5	0.7	0.9

TABLE VI. CONDITIONAL PROBABILITIES OF N_{PROD} FOR UPGRADE CHOICE "CF"

		Number of Workers		
		8	*10*	*12*
N_{PROD}	$0.6\times N_{PROD,MAX}$	0.5	0.2	0.1
	$0.8\times N_{PROD,MAX}$	0.4	0.6	0.3
	$N_{PROD,MAX}$	0.1	0.2	0.6

TABLE VII. PROBABILITY OF VISE MARKET LEVEL

N_M	Probability
6	0.2
9	0.3
12	0.4
15	0.1

The values of P_V, (C_{MAT} + C_{EN}), S_{WORK} and V_{EQ} are respectively \$1000, \$300, \$100 and 15 years. The risk tolerance (R) was evaluated as \$3000, using the method in [3].

G. Selection of alternatives

The results are shown in Figure 9, which is a graph over possible values of equipment cost per day ($C_{EQ}/360\times V_{EQ}$) for the CNC and CF alternatives. The graph shows zones in which the decision should be "CNC", "CF" or leave the system as it is ("Base"). For example, if the cost per day of the CNC is \$700 or more and that of CF is more than \$600, the best choice is to leave the system as it is, while if both the CNC and CF cost \$400, then the best choice is CNC.

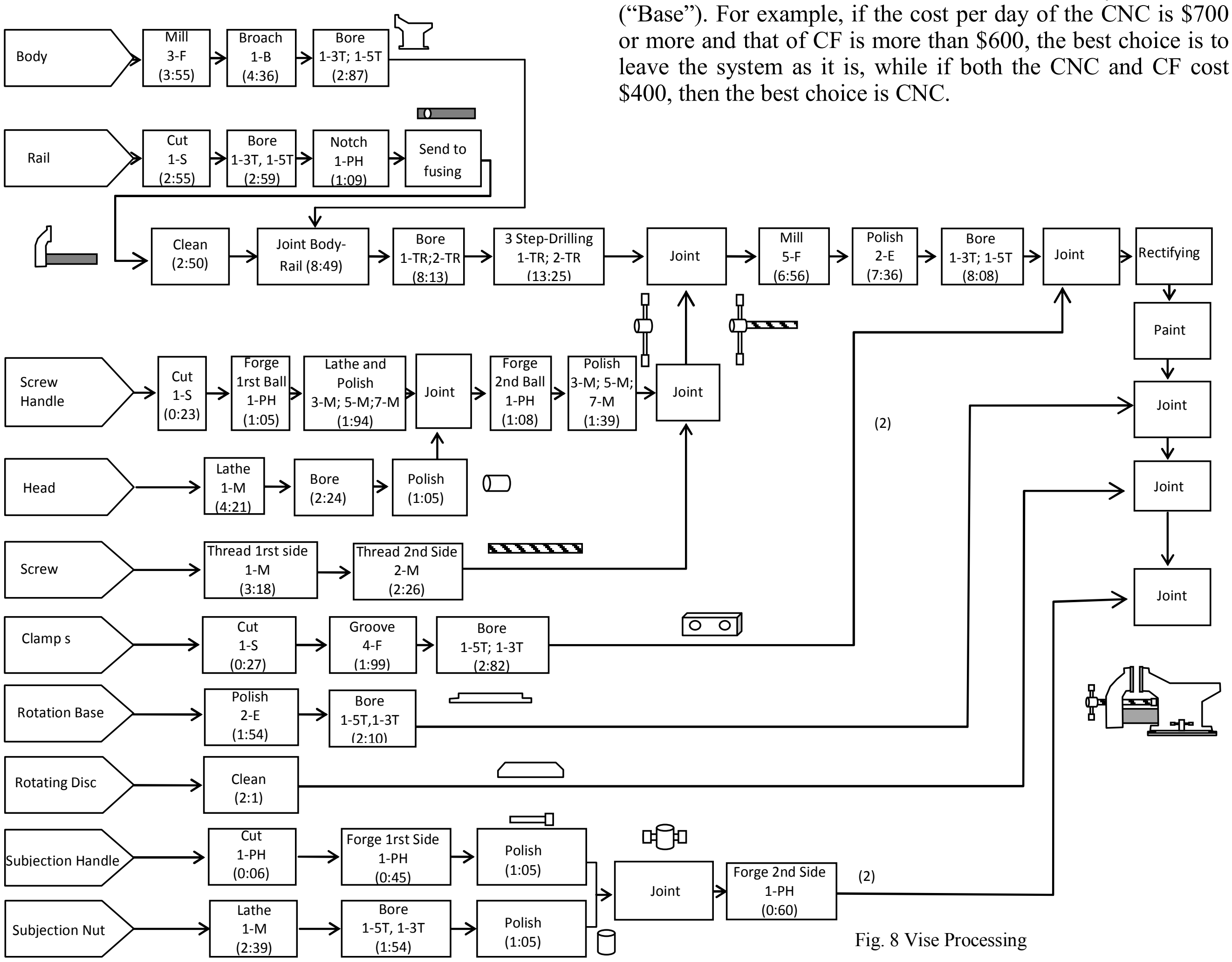


Fig. 8 Vise Processing

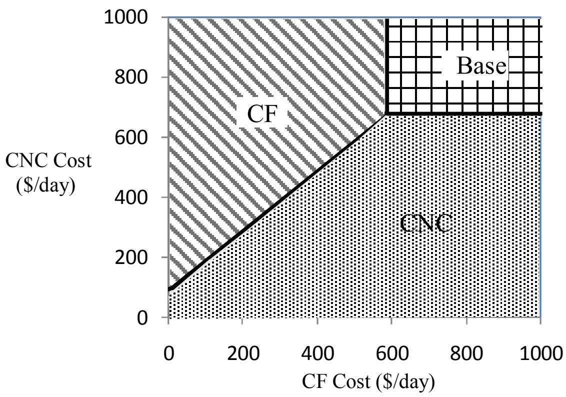


Fig 9. Feasibility zones for choices "CNC", "CF" and "Base"

IV. CONCLUSIONS AND FURTHER WORK

From the application shown here, it can be concluded that the IDA, proposed by Ley-Borrás [2], is a valuable tool in the clarification and structuring of real life engineering problems. By following its steps, it guarantees that the correct decision is tackled and that the adequate objectives, risk attitude and factual information are included and modeled.

It was also shown how two of the steps of the IDA methodology ("Alternatives" and "Analysis of Uncertain Events") can be improved by using the Means-Ends Objectives Network to identify the relations and uncertainties that should be modeled. Thus, the Means-Ends Objectives Network provides a blueprint for the construction of the decision model.

Currently, the simulation model is being extended with probabilistic vise process times. Also, a decision model that considers decisions about the layout of the workshop simultaneously with decisions of equipment replacement is being developed.

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