Robotics & Computer-Integrated Manufacturing, Vol. 1, No. 2, pp. 181–190, 1984
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0736-5845/84 $3.00 + 0.00
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A TWO-PHASE ANALYTIC APPROACH TO ROBOTIC SYSTEM DESIGN

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A two-phase analytic approach to robotic system design is presented. The first phase evaluates the robotic technological classes according to their functional adequacy; the next phase specifies the desired robotic configuration. The methodology developed here is demonstrated for the case of installing a robot in an automated investment casting shelling production line.

1. PROBLEM STATEMENT

The industrial robot is defined as a commercially available programmable manipulative device. In this sense, robots fill the gap between automatic machines, performing a single task, and human operators who can handle a variety of jobs.[6] The advent of industrial robots has signalled new opportunities in industrial automation that stem from an on-going evolution in computer science, machine design and control theory.[5] Recent studies have indicated that robotic technology is becoming a significant factor in the design of modern data-driven facilities such as flexible manufacturing systems (FMS) and automatic storage and retrieval systems.[2]

In recent years a wide variety of robotic systems and supporting equipment of varying capabilities have appeared on the market. It is likely that, for the same industrial application, various vendors may propose robotic systems which may be quite different both from a technology viewpoint and the adaptability of the automated system to the industrial environment. Most acquisitions of robotic systems are directed at "turn key" projects, where the complete installation is designed and backed by one source. In these cases one has to evaluate several distinct robotic configurations proposed by various vendors. These configurations may differ greatly in their potential performance and technical characteristics.[7,28] When none is clearly superior in all respects, a method for evaluating the various characteristics to arrive at a measure of overall performance is required.[18]

Recent studies regarding the selection of specific industrial robots tend to focus either on the *economic* aspects or on the *prescriptive* or technical aspects of this decision problem. The *economic* approach attempts to identify and to measure the relative savings or the gains from various robotic configurations. Hasegawa[11] has conducted an industrial survey in order to identify the cardinal reasons for the introduction of robotic technologies. His study indicates that, for certain industries, the cardinal reasons were the need for labor cost-savings, improvements in the quality of work conditions and increasing production flexibility. In a similar study, Froehlich[10] claims that robots' contribution to productivity gains can be realized through technological advancement of the manufacturing processes and by improved capital and labor allocation.

Several economic decision models are presented by Ciborra,[4] Owen,[21] Engelberger,[7] Tanner,[29] Knott and Getto,[13] Fleischer[9] and by Dorf.[6] Ciborra[4] develops a model for evaluating both tangible and intangible installation costs. Performance measures considered are production lead times, economic life of the robot and parts flexibility. Owen[21] points out to labor cost savings and raw material waste reduction as the two major justification factors. Knott and Gett[13] describe a model for evaluating altern-

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Acknowledgement—The authors would like to thank Professor G. Halevy from the Technion, Israel Institute of Technology and Hal-Robotics Ltd., Tel-Aviv, Israel, for useful discussions.

Received for publication 18 June 1984.

ative robot systems under uncertainty. The variance of the net present value is used as a risk measure. Most of the other studies use the internal rate of return or the pay-back period justification techmiques. Industrial examples of economic case studies include spray coating,[3] drilling, broaching and grinding[14] and a batch machining system.[12]

Various *prescriptive* models for robotic systems evaluation have been published. For example, Vukubratovic[30] specifies a check-list with eleven groups of technical criteria including such factors as multifunctionality, reliability, structural kinematic adaptivity, indispensability and the degree of anthropomorphicity. Other studies[7,20,27] have proposed additional factors such as interface compatibility, sensory perception and inherent safety.

Basic industrial robot classification schemes, work abilities and techniques for analyzing industrial robot systems are reported by Weill[32] and by Fisher *et al.*[8] Recently, Warnecke and Schraft[31] and Nof[18] presented several new prescriptive models for planning industrial robot operations. These models focus on workplace analysis and on various design aspects for effective robot selection and utilization.

While several papers are treating the comparative performance evaluation issue, no particular methodology has emerged as being capable of dealing with both the managerial, technical and functional aspects of this problem. Most of the prescriptive models lead to some conceptual solution while the economic models tend to address a single financial objective. Moreover, the economic models cannot distinguish among the technological levels of robots. Thus they compare different systems on equal basis and therefore can yield an increasing risk in the long run. On the other hand, the technological models ignore the economic issues and therefore cannot be considered by themselves, and additional information is needed.

This paper presents a multi-attribute decision methodology for evaluating and selecting an industrial robot. This methodology aids in structuring the decision process and in establishing order of priority for alternative designs for manufacturing automation.[26]

Section 2 outlines the methodology used in the paper. Section 3 presents the selection of the robotic technological class. Section 4 outlines the robotic configuration selection and section 5 provides the concluding discussion.

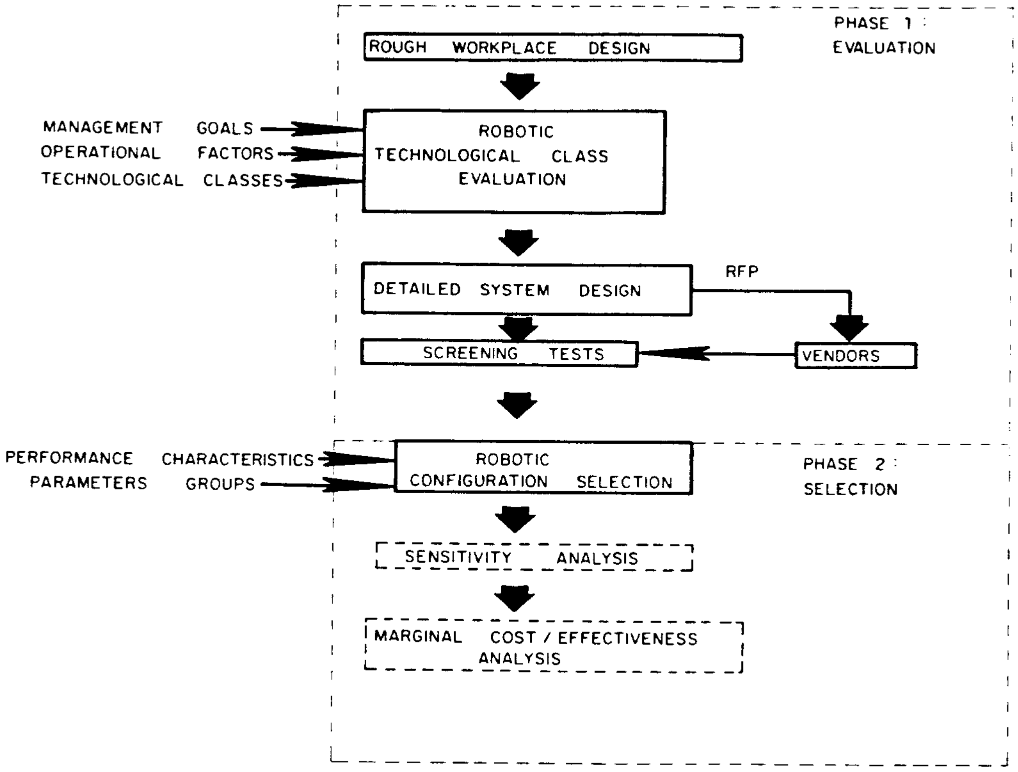

Fig. 1. The robotic system design process.

2. THE DECISION METHODOLOGY

Selecting a robot for industrial application is a complex, multi-attribute, decision problem. A particular technology selected for the robot is influenced by a number of managerial and technical considerations. In many cases these considerations will be in conflict with each other; that is, attaining one may be achieved at the expense of the other. In addition, choosing the most advanced technology may not always lead to the most appropriate solution in a particular setting.[33] For example, by using a fixed or a variable sequence robot technology, one may obtain better output uniformity than by using the more advanced numerically controlled robot.[19] Therefore, the choice of a particular robot has to be preceded by a choice of a specific technology that is the most appropriate to the particular application and, thus, leading to a two-phase decision problem. In the first phase a particular *technological class* is selected followed, in the second phase, by selecting a specific robot *configuration* from this technological class. The overall two-phase decision process is depicted in Fig. 1.

The decision process used for this evaluation and selection problem should be capable of handling multi-criteria and multi-parameters by providing a systematic and consistent way of prioritizing them. Such a methodology is offered through the Analytic Hierarchy Process (AHP) developed by T.L. Saaty.[23] This methodology has been successfully applied in various applications[24,34] and recently in a number of technology-based decision problems.[1,26]

This approach is based on three major components:

(1) The AHP starts by decomposing a complex decision problem into a hierarchy; each level consists of a few manageable elements and each element is, in turn, decomposed into another set of elements. The process continues down to the most specific elements of the problem, typically the specific courses of action considered, or the decision variables, which are represented at the lowest level of the hierarchy.

(2) A measurement methodology is used to establish priorities among the elements within each stratum of the hierarchy.

(3) A measurement theory is used to establish the priorities of the hierarchy and the consistency of the judgemental data provided by the group of respondents.

Deriving the actual local priorities of members in each level is done through a pairwise comparison between each member of the level, relative to a member of the adjacent upper level. These pairwise comparisons are summarized in an $n \times n$ comparison matrix A given by

$$A = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \vdots & & & \vdots \\ w_n/w_1 & w_3/w_w & \dots & w_n/w_n \end{pmatrix} \qquad (1)$$

The information displayed in this matrix is interpreted as follows: every element a_{ij} of the matrix A shows the relative contribution to the objective of the i-th activity compared to the j-th activity, i.e.

$$a_{ij} = w_i/w_j \qquad 1 < i < n, \qquad 1 < j < n. \qquad (2)$$

The actual entries are derived by using the scale described in Table 1.

Matrix A is a *reciprocal* matrix, i.e. $a_{ij} = 1/a_{ji}$. Therefore, whenever the ij-th element of the matrix is specified, the ji-th position is automatically determined by its reciprocal value. To actually recover the weights, w_i, rather than their ratios that are given in (1), we proceed as follows. Note that the matrix A in (1) is of unity rank and, therefore, $(n - 1)$ of its eigenvalues are equal to zero, furthermore,

$$\sum_{i=1}^{n} \lambda_i = \text{trace}(A) \triangleq \sum_{i=1}^{n} a_{ii} = n \qquad (3)$$

and therefore the nonzero eigenvalue is equal to n. It is easily verified that $Aw = nw$ from which it follows that w is the (normalized) eigenvector associated with the largest eigenvalue of the matrix A in (1). The case shown in (1) represents the perfectly consistent case where $a_{ij} = a_{ik}a_{kj}$, $\forall\, i, j, k$. In practice, the elements of the matrix A in (1) are estimated through the use of the scale whose values are given in Table 2. In general the elements of (1) satisfy $a_{ij} = w_i/w_j + \varepsilon_{ij}$ where ε_{ij} is some error that represents inconsistencies in judgement and then $a_{ij} \neq a_{ik}a_{kj}$. It can be shown that the largest eigenvalues of the matrix A, $\lambda_{\max}$, satisfies $\lambda_{\max} \geq n$ where equality holds for the perfectly consistent case only. A *consistency index* is now defined as

$$\text{C.I} = (\lambda_{\max} - n)/(n - 1) \qquad (4)$$

which is zero in the perfectly consistent case. To assess the consistency derived in (4) we compare it to the worst case which will be the case of a pairwise com-

Table 1. Comparison scale

1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent scale values

parison matrix whose entries are filled at random. Doing it for many samples and for various matrices, Saaty has obtained the following:

n	1	2	3	4	5	6	7	8	9	10
R.I	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

where n represents the dimension of the matrix and R.I. is the *random index* evaluated through (4) for these random matrices. Now one defines the *consistency ratio* (C.R) as

$$\text{C.R.} = \text{C.I/R.I} \tag{5}$$

which is required to be less than 0.1 for acceptable results.

The decision problem formulated and analyzed in this paper addresses a common application for robotic usage offered in the area of ceramic mold making in investment casting foundries. In this process a robot is introduced to handle clusters of patterns by putting them through various steps such as dipping in ceramic slurry pots; following the slurry coating process each cluster is then sanded in a rainfall sander or a fluidized bed. The robot is also used to assist in loading and unloading the three conveyors involved.[15,17] A schematic view of such an operation is shown in Fig. 2.

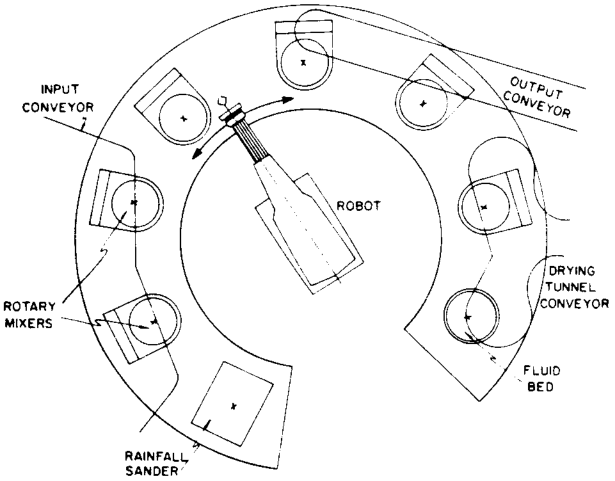

Fig. 2. Ceramic mold-making robotic cell.

3. TECHNOLOGICAL CLASS EVALUATION

Starting to construct the AHP decision hierarchy recall that the installation of a robotic system should support the basic *management goals* considering improvements in resource utilization and product lines. The *resource utilizations* goals are concerned with cost reductions efforts through the optimal usage of the available manpower, manufacturing hardware, raw materials and the buffer inventories. In addition, *products line* goals include enhanced design options for current and future parts, better marketing support and improved outgoing quality. Next, one considers the *operational factors* in measuring how well these management goals are addressed. The *production capacity* factors include two major subsets: the first subset is the stated manufacturing volume; the second is the potential for capacity growth in the future. The *production support* factors are related to the output uniformity, scheduling and control options, delivered precision level and the ability to cope with parts' flexibility. The production infrastructure factors refer to the degree of material handling flexibility, maintenance and safety aspects as well as to the required layout accommodation for the robotic installation. Lastly, in the operational factors, one considers the *production effectiveness*; it is determined by means of the required supervision, the set-up times between single-model parts and between different models, and by the aggregate production lead times, from customer's order to delivery. Finally, the bottom level of the hierarchy is concerned with the relevant *robotic technologies*.

Following the general scheme of the *Japanese Industrial Robot Association* (JIRA),[32] the robotic population is partitioned into five major subsets according to the nature of their input requirement and control scheme. The *Fixed Sequence* robot is designed to operate according to a present sequence of positional changes. Often very small drift with high speed can be obtained with this technology. The *Variable Sequence* robot operates similarly but it can be reprogrammed easily and its operator can control it during the duty cycle. *Playback* robot is taught by a human trainer automatically to repeat a sequence of activities. This sequence is stored in a digital file. Numerical control programs (NC) and direct numerical control systems (DNC) drive the *numerically Controlled* robot. *Intelligent/Adaptive* robot is characterized by the capability to logically interact the external sensors, to recognise changes and to continuously respond by changing its trajectories and its sequence of acts.

The hierarchical framework established in this section is used next in the determination of the priorities associated with the candidate robotic technologies. This determination facilitates the selection of the most appropriate robotic technological class for the specific application in question. The complete hierarchy describing the evaluation elements and their interconnections is depicted in Fig. 3. Note that these interconnections, from one level to the other, are flexible in the sense that they

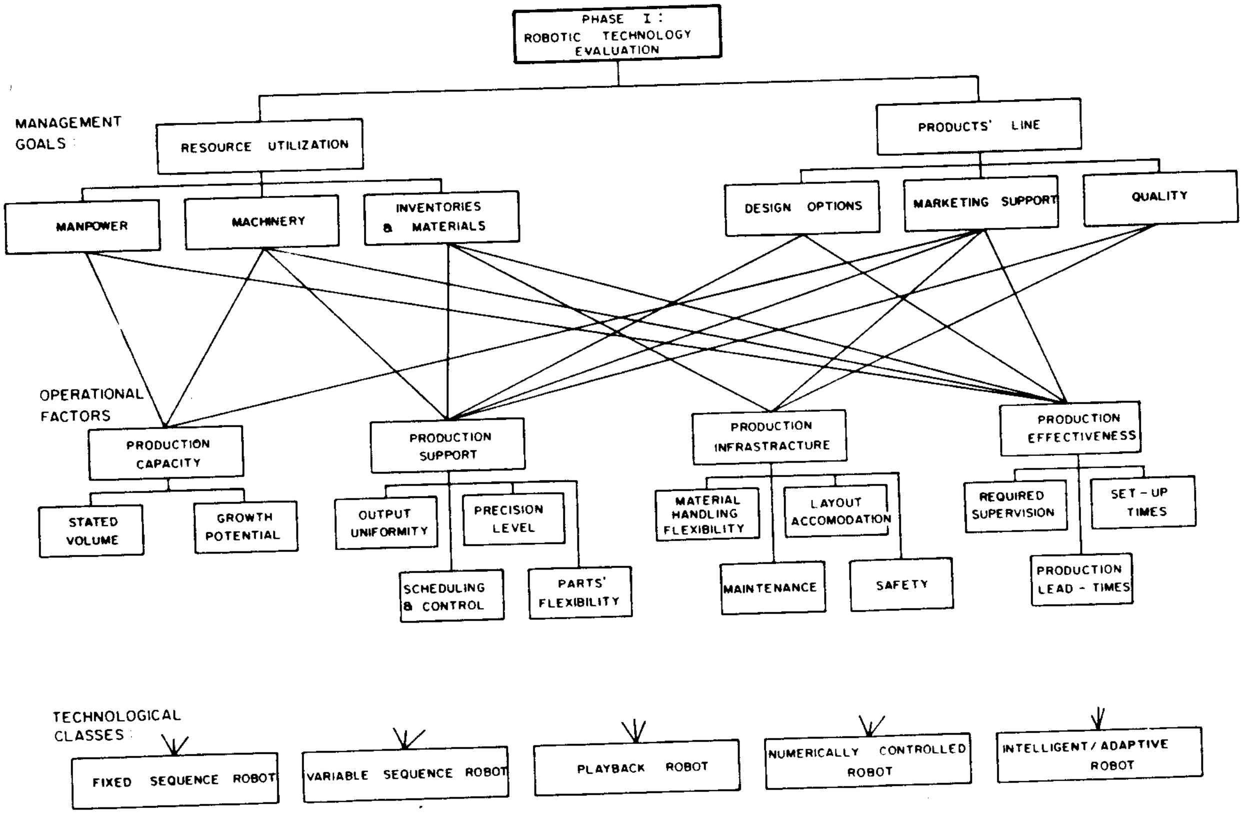

Fig. 3. The technology class evaluation hierarchy.

describe a specific industrial application and should be modified to reflect another.

In order to select the most appropriate technological class for a particular application, the elements depicted in the hierarchy of Fig. 3 have to be prioritized. The prioritization process starts by pairwise comparisons of the elements in the first level and progresses downwards until the last level is reached and the specific priorities for each of the robotic technological classes are computed.

The AHP methodology performs these comparisons of elements in one level with regard to a single element in the level immediately above it. Such a comparison results in the *local priorities* of these elements reflecting their relative contribution to the subject of comparison. The assessment process will not be presented here in detail. Instead, the prioritization scheme will be outlined in order to illustrate some major aspects of the evaluation process.

The pairwise comparison process of the management goals and their subsets might lead, therefore, to the comparison matrix shown in Table 2.

Table 2. Management goals

	(1)	(2)	Local priority
Resource utilization (1)	1.0	3.0	0.75
Products line (2)	0.33	1.0	0.25
C.R. = 0.0			1.00

The elements of the matrix are answers provided by the team responsible for the decision and are interpreted as follows. In comparing "Resource Utilization" vs "Products Line" the former was judged to be moderately more important and hence the entry (3) in the first row–second column position (w_1/w_2) in the table; the symmetric position (w_2/w_1) is, of course, its reciprocal value (cf. section 2). This simple case (simple since it involves a single question) results in the priorities shown in the last column of Table 2. The local priority vector (0.75 for resource utilization and 0.25 for product's line) reflects management's assessment of the importance of cost reductions through improved resource utilization in the investment casting process illustrated here. Both resource utilization and product's line goals are further subdivided (Fig. 3). Performing the pairwise comparisons of each of these subdivisions results in Tables 3 and 4.

The pairwise comparisons summarized in Tables 3 and 4 and the derived priority vectors agree with the

Table 3. Resource utilization elements

	(1)	(2)	(3)	Local priority	Global priority
Manpower (1)	1.0	4.0	6.0	0.701	0.526
Machinery (2)	0.25	1.0	2.0	0.193	0.145
Inventories (3) & materials	0.17	0.5	1.00	0.106	0.079
C.R. = 0.007933				1.00	0.75

Table 4. Product's line elements

	(1)	(2)	(3)	Local priority	Global priority
Design options (1)	1.00	2.00	0.25	0.2	0.050
Marketing support (2)	0.50	1.00	0.20	0.117	0.029
Quality (3)	4.00	5.00	1.00	0.683	0.171
				1.0	0.25

Table 5. Operational factors relative to machinery

	(1)	(2)	(3)	Local priority
Production capacity (1)	1.00	2.00	0.33	0.249
Production support (2)	0.5	1.00	0.33	0.157
Production effectiveness (3)	3.00	3.00	1.00	0.594
C.R. = 0.04625				1.00

Table 6. Production support elements

	(1)	(2)	(3)	(4)	Local priority
Output uniformity (1)	1.00	5.00	1.00	3.00	0.417
Scheduling & control (2)	0.20	1.00	0.33	0.50	0.091
Precision level (3)	1.00	3.00	1.00	2.00	0.332
Parts' flexibility (4)	0.33	2.00	0.50	1.00	0.160
C.R. = 0.01258					1.00

earlier gross statements regarding the design priorities. That is, improved resource utilization through labor reduction; thus reduction of labor is the most significant element contributing to better resource utilization. In terms of product's line quality improvements is the most significant element. Weighting the local priorities by the priority of the higher management goals, one converts these local priorities to *glocal* priorities. Thus the last columns in Tables 3 and 4 were obtained by multiplying the local priorities by (0.75) and by (0.25), respectively.

Next, the operational factors are prioritized. This is done by considering the relative contribution of the four operational factors with respect to each subset of the management goals. Therefore, in considering *operational factors* relative to machinery one obtains the results summarized in Table 5.

The prioritization is continued by computing the priorities within each subset of the operational factors. Table 6 illustrates the pairwise comparison with respect to the production support factors.

Once this is done, direct comparison of specific technological classes is carried out. Following the same prioritization level as discussed above one derives first the local priorities of the technological classes with respect to each subset of the operational factors. For example, in considering the five technological classes relative to maintenance and setup times one obtains the results summarized in Tables 7 and 8.

Observing Tables 7 and 8 one detects a clear shift of priorities. In terms of maintenance, highest priority has been given to the variable sequence robotic technology; on the other hand, the numerically controlled technology has emerged with the highest

Table 7. Technological classes relative to maintenance

	(1)	(2)	(3)	(4)	(5)	Local priority
Fixed sequence R. (1)	1.00	0.33	0.50	3.00	4.00	0.190
Variable sequence R. (2)	3.00	1.00	2.00	4.00	5.00	0.417
Playback R. (3)	2.00	0.50	1.00	2.00	3.00	0.233
Numerically controlled R. (4)	0.33	0.25	0.50	1.00	2.00	0.098
Intelligent/adaptive R. (5)	0.25	0.20	0.33	0.50	1.00	0.062
C.R. = 0.037961						1.00

Table 8. Technological classes relative to set-up times

	(1)	(2)	(3)	(4)	(5)	Local priority
Fixed sequence R. (1)	1.00	3.00	2.00	0.25	0.33	0.154
Variable sequence R. (2)	0.33	1.00	2.00	0.33	0.50	0.109
Playback R. (3)	0.50	0.50	1.00	0.33	0.50	0.087
Numerically controlled R. (4)	4.00	3.00	3.00	1.00	3.00	0.425
Intelligent/adaptive R. (5)	3.00	2.00	2.00	0.33	1.00	0.225
C.R. = 0.094102						1.00

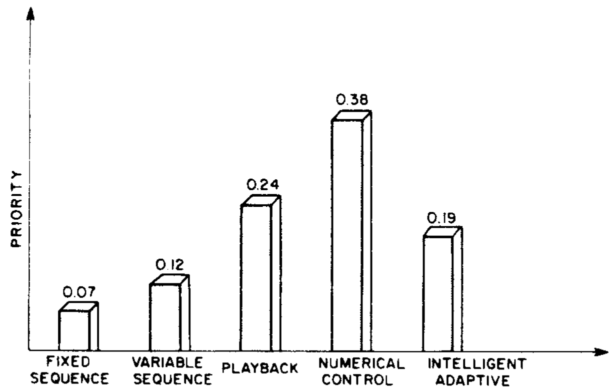

Fig. 4. Global priorities of technological classes.

priority relative to set up times. Following these pairwise comparisons of the robotic technologies one applies the global priorities of the individual subsets of the operational factors, thus obtaining the global priorities for the technological classes. These global priorities are depicted in Fig. 4.

4. ROBOTIC CONFIGURATION SELECTION

As outline in Fig. 1 the robotic evaluation model is composed of two phases: the evaluation of the technological class, discussed in section 3, and the robotic configuration to be discussed here. At this stage, one considers these decision factors having a bearing on the problem of incorporating an industrial robotic system within the realm of a specified technological class. The various performance characteristics and parameter groups relevant to the candidate configurations are analyzed by the AHP following the general outline of the technology evaluation model (Fig. 5). Major performance characteristics consist of *manipulative ability*, *accuracy*, *operational integrity*, *plant compatibility*, *product adaptability*, *tool velocity and required support*. These performance characteristics were judged to be relevant for the investment casting application discussed here. Other performance characteristics, such as required customizing, are added when necessary. The next level in the hierarchy consists of nine parameter groups supporting the relevant performance characteristics: *kinematic attributes*, *robot–plant interaction*, *computer controls*, *system reliability*, *local vendor*, *external sensors*, *dynamic parameters*, *geometric attributes*, *and special operations*. These parameters and a partial list of their subdivisions are shown in Fig. 5. It should be pointed out that the list of the specific parameters groups outlined in the hierarchy does not claim to be exhaustive. The current structure of this hierarchy should reflect the local nature of the design issues

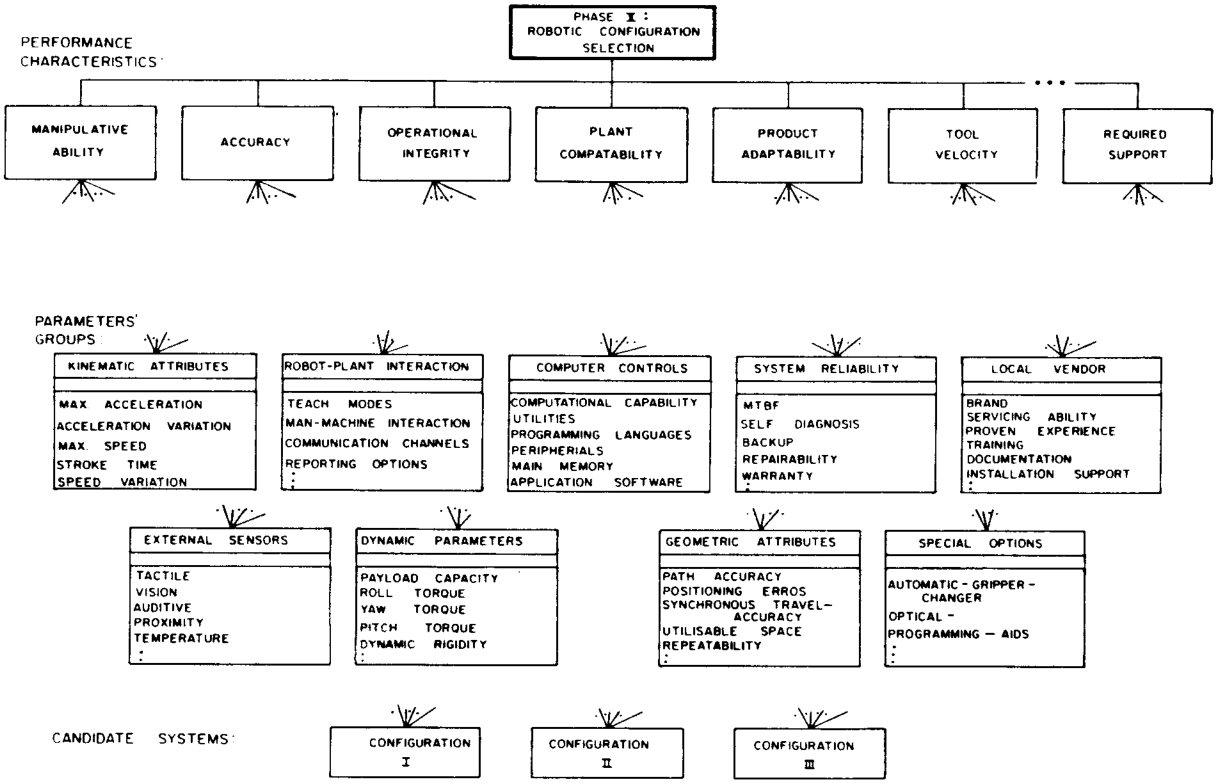

Fig. 5. The robotic configuration selection hierarchy.

Table 9. Performance characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	Local priority
Manipulative ability (1)	1.00	0.50	0.33	0.33	0.17	0.25	0.20	0.037
Accuracy (2)	2.00	1.00	0.50	0.50	0.20	0.33	0.25	0.055
Operational integrity (3)	3.00	2.00	1.00	0.50	0.20	0.50	0.33	0.080
Plant compatibility (4)	3.00	2.00	2.00	1.00	0.33	0.50	0.33	0.103
Product adaptability (5)	5.00	5.00	5.00	3.00	1.00	0.50	2.00	0.278
Tool velocity (6)	4.00	3.00	2.00	2.00	2.00	1.00	0.50	0.211
Required support (7)	5.00	4.00	3.00	3.00	0.50	2.00	1.00	0.236
C.R. = 0.049836								1.00

Table 10. Dynamic parameters

	(1)	(2)	(3)	(4)	(5)	Local priority
Payload capacity (1)	1.00	0.50	2.00	2.00	3.00	0.259
Roll torque (2)	2.00	1.00	2.00	2.00	3.00	0.344
Yaw torque (3)	0.50	0.50	1.00	1.00	2.00	0.155
Pitch torque (4)	0.50	0.50	1.00	2.00	2.00	0.155
Dynamic rigidity (5)	0.33	0.33	0.50	0.50	1.00	0.087
C.R. = 0.01605						1.00

and the industrial environment; only the particular elements relevant for that setting should be addressed. For example, programmable velocity, traverse base or multiple-handed grippers may be important for a particular setting but irrelevant to another.

The prioritization process of the robotic configuration hierarchy starts by prioritizing the major performance characteristics. In the particular application discussed here this has resulted in the comparison matrix shown in Table 9.

The next level deals with the specific robotic systems parameters. Following the same prioritization scheme as done in the technological class hierarchy one derives first the local priorities of the parameters groups with respect to each performance characteristic and then, using the priorities of each performance characteristic, one derives the global priorities for the parameters. Once the global priorities for each parameter group are determined, comparison matrices are applied to aid in the determination of priorities of specific parameters. For example, the parameters group labelled "Dynamic Parameters"[22] may result in a global priority of 0.15. This particular group has five members whose relative importance in this group is shown in Table 10. Note that, due to process requirements, the roll torque (Fig. 6) has been given the highest priority (0.344) while the yaw and pitch torque have been assigned equal (0.155), but lower, priorities.

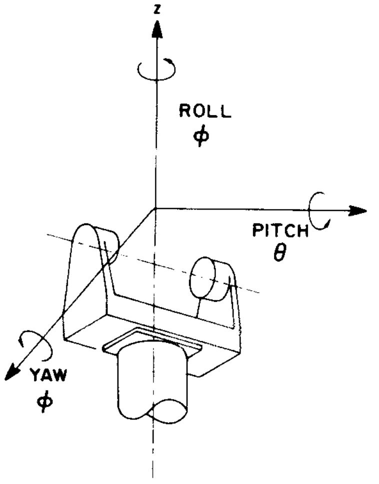

Fig. 6. The roll, pitch and yaw vectors.

Following this analysis for all parameter groups one is in a position to conduct direct comparisons of candidate robotic configurations based on the prioritized parameters. To carry out these comparisons, performance levels of all candidate configurations in each of the parameters have to be established. Such comparisons may rely on technical data that is either directly available through the vendors' proposals (e.g. max. speed, positioning errors and teach modes) or has to be assessed by the decision maker. In the last group some assessment can be made *directly* (e.g. vendors' training capabilities), while other assessments can be arrived at *indirectly* through special tests (e.g. synchronous travel accuracy or the ease of the man–machine interaction). This point is of particular inportance in robotics because of the newness of this technology and the absence of sufficient measurement methods and acceptance guidelines based on them.[31]

It should be emphasized, however, that only configurations whose performance levels *exceed* the threshold requirements (defined by the RFP) enter this comparison stage. In comparing the vendors' proposals with respect to each of their parameters, both descriptive terms and quantitative data are used. Table 11 describes dynamic parameters of three candidate configurations.

Table 11. Dynamic parameters of candidate configurations

Parameters	Configuration I	Configuration II	Configuration III
Payload capacity (kg)	36	50	36
Roll torque (kg.m)	14.4	10.4	9.1
Yaw torque (kg.m)	32.5	29.3	44.3
Pitch torque (kg.m)	80.7	125.9	110.0
Dynamic rigidity	good	very good	very good

Table 12. Payload capacity priorities

	(1)	(2)	(3)	Local priority
Configuration I (1)	1.00	0.50	1.00	0.25
Configuration II (2)	2.00	1.00	2.00	0.50
Configuration III (3)	1.00	0.50	1.00	0.25
C.R. = 0.00				1.00

Table 13. Yaw torque priorities

	(1)	(2)	(3)	Local priority
Configuration I (1)	1.00	1.50	0.33	0.24
Configuration II (2)	0.67	1.00	0.50	0.21
Configuration III (3)	3.00	2.00	1.00	0.55
C.R. = 0.063373				1.00

In comparing these configurations with respect to, say, payload capacity and yaw torque one may arrive at the comparison matrices shown in Tables 12 and 13.

Examining Table 13 one observes that the yaw torque of configuration I was judged to be slightly better than that of configuration II and that the yaw torque of III is moderately better than that of II. These judgement matrices represent the point of view taken by the system designer in judging these proposals in light of a specified application.

Repeating this process of comparing the three configurations relative to all their parameters and weighting their local priorities by the global priorities of the parameters reveals the global priorities of the three candidate configurations. The preferred configuration is the one dominating with the highest global priority. It represents the candidate with the best balance of characteristics.

Before a final installation decision is made, a sensitivity analysis may be performed. This calls for varying the relative importance assigned to various members of the hierarchy. Such an analysis results in a range of priorities indicating the preference domain of the selected configuration.

The selection of the configuration with the highest priority is based on the assumption that all candidate configurations are of relatively equal cost. When this assumption does not hold, one computes cost priorities for these systems depicting their relative costs and then makes the choice using the usual marginal cost/effectiveness analysis,[25] with the effectiveness priorities derived above for the competing configurations.

5. SUMMARY

Once a decision to install a robot was made, one meeds a comprehensive model for evaluating and comparing candidate robots. This paper presents an analytic methodology for the problem of selecting a robot—within a technological class—to automate a particular industrial process. The methodology integrates managerial and technical considerations by using experts from these two, sometimes different, perspectives. The analytical process provides quick and effective means to ensure consistently of judgement and adherence to stated objectives.

It should be noted that starting with a simple decision model does not make the analysis coarse or incomplete. Subsidiary models can be developed to ensure any desired level of detail and sophistication. Our industrial experience has shown that using an interactive program for computing the priority vectors and the consistency ratios makes this methodology an attractive decision aid to industrial managers and system designers alike.

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