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SELECTION OF ROBOT FOR CONTOUR CRAFTING USING ANALYTICAL HIERARCHY PROCESS

Senthilraja SHANMUGASUNDARAM [1], Raja Muthaiah MURUGAN CHIDHEMBARAM [2]
[1] Department of Mechatronics Engineering, SRM Institute of Science and Technology, Kattankulathur, India
[2] Department of School of Architecture and Interior Design, SRM Institute of Science and Technology, Kattankulathur, India

Abstract

The use of robotic equipment and a new technique called contour crafting allows for the construction of buildings at lower labor and material costs. The selection of the type of robot is an important factor that affects the overall performance of the contour crafting (CC) system. Various robot configurations, such as gantry, cylindrical, and SCARA, may be employed for contour crafting. There are benefits and drawbacks to using different types of robots for various tasks, including cost, work volume, material compatibility, and precision. Identifying a proper robot using the multi-criterion decision-making (MCDM) technique is crucial for successful building automation. This article uses the analytical hierarchy process (AHP) method to rank the best robots according to several characteristics. Cartesian robots, cylindrical robots, and SCARA robots were evaluated based on cost, accuracy, work volume, surface finish, type of profile, and speed. The results showed that the gantry-type robot is the most suitable option, while the cylindrical robot is unsuitable for building construction due to lower accuracy.

Keywords: multi criteria decision making (MCDM), contour crafting, analytical hierarchy process (AHP)

1. INTRODUCTION

The increasing cost of labor, rising energy expenses, and a shortage of available workers have all contributed to the growing adoption of automated technologies in the construction industry in recent years. The integration of advanced technology and robotics in building applications can help alleviate these challenges. Contour crafting (CC), owing to its numerous attractive features, has garnered significant attention from both academic researchers and industry professionals, aiming to enhance the efficiency of various building systems. CC is a construction technique designed to automate the building of structures, offering the potential for faster and more cost-effective construction processes. This method applies 3D printing principles, utilizing robots to extrude materials like concrete and

[1] Corresponding author: Department of Mechatronics Engineering, SRM Institute of Science and Technology, Kattankulathur, India, srm.senthil@yahoo.com, +91 8015058258.

systematically constructing large structures layer by layer in the construction field. CC represents a form of additive manufacturing that receives digital instructions in STL format and builds physical objects in successive layers [1]. The process involves a robotic system, hopper unit, nozzle unit, trowels, etc. Fig. 1 illustrates the operational process of a typical contour crafting robot.

Various types of robots, including Spherical coordinate robots, Cartesian coordinate (Gantry) robots, and cylindrical coordinate robots, can be employed in contour crafting applications. However, the selection of an appropriate robot is critical to improving surface finish, enhancing the quality of the finished product, and reducing production costs. Therefore, this research aims to utilize the Analytic Hierarchy Process (AHP) to systematically choose the most suitable robots for contour crafting (CC). The objective is to identify a robotic solution that enhances CC processes, ensuring high-quality construction output, cost-effectiveness, efficiency, and improved performance, making it applicable to various construction scenarios.

Fig. 1. Contour crafting Process [2]

Several methodologies have been employed in this study to determine the suitable robot category for collaborative building in the construction field. Thus, understanding user preferences is crucial before selecting a CC machine, and qualitative information plays a vital role in sustaining competitiveness within the industry. The decision-making and robot machine selection process involve a combination of user expectations and mathematical factors. This paper amalgamates the aforementioned facts to guide researchers and engineers in selecting an appropriate and user-friendly robot. The study addresses considerations influencing the choice of CC robots, incorporating the integration of qualitative and quantitative data for more informed decision-making. These approaches include a combination of criteria assessment, optimization techniques, and consideration of the specific requirements of the construction process.

One of the Multi-Criteria Decision Making (MCDM) methods, such as the Analytic Hierarchy Process (AHP), is employed to systematically evaluate and prioritize different robot types based on multiple criteria. These criteria encompass cost, dimensional accuracy, surface finish, complex profile, work volume, and speed. AHP provides a structured framework for decision-makers to compare and rank various options.

2. LITERATURE REVIEW

2.1 Recent Trends in CC

To fabricate large-scale structures with high accuracy, the scientist Khoshnevis used a rapid prototyping technology coined as ‘Contour Crafting’ [3,4]. Despite a surge in research on automated CC machines, their widespread adoption has been gradual over the last decade. Considering this, numerous researchers are striving to integrate various cost-effective technologies into CC machines. Rouhana et al. [5] assert that using CC has the potential to greatly reduce building time. Hwang et al. [6] studied the feasibility of wall fabrication using CC technology with a gantry-type robot. After the study, the researchers discovered a few restrictions, including material deposition speed and settling time. Khoshnevis et al. [7] carried out an experimental study using ceramic materials such as clay and plaster in CC and found the pressure between the trowel and top layer is the primary factor that affects the quality of the product. Bosscher et al. [8] developed a new kind of cable-suspended robot for CC and discussed the forward and inverse kinematics analyzed. Khorramshahi and Mokhtar [9] reviewed the details of automated construction using CC technology and concluded that CC technology will be a promising technology for constructing a building with less cost and time. Khoshnevis et al. [10] developed an automated system and studied the feasibility of sulfur in CC experimentally. They found the concrete made of sulfur using CC technology can be stable after 500 h of work and concluded that this method is suitable for construction.

Kevin Subrin et al. [11] discussed the application of foam additive manufacturing for 3D printing using mobile robots and explored the determination of the best location for the robot. Zhang and Khosnevis [12] proposed a planning framework with potential application in future research involving mobile robotics in the construction processes of CC. Zhang and Khosnevis [13] outlined a systematic approach for process planning and optimization in large-scale structure construction using CC systems, leveraging their speed and use of in-situ materials. Valente et al. [14] discussed the variations in additive manufacturing technologies in architecture and construction, focusing on differences in printing apparatus, materials, and potential construction projects also described aspects like structural robustness, material selection, curing mechanisms, and admixture choices are crucial for successful construction. Zareiyan and Khosnevis [15] investigated the structural integrity of contour-crafted structures using experimental methods. Develops a concrete mixture with enhanced strength through adjustments in aggregate size and ratio. Yeh and Khosnevis [16] introduced principles of geometric conformity for assessing deviations between designed and fabricated surfaces. Derives equations to calculate ruled surface areas and volumes of 3D slices in object models. Khoshnevis et al. [17] focused and summarized the construction and operation details of the fabrication machine and presented the experimental results. Khoshnevis et al. [18] analyzed the essentials of the CC process, research and development status, experiments with thermoplastics and ceramics, engineering analysis, and potential application areas. Lieyun Ding et al. [19] explored a new BIM-based automated construction system (BIMAC), covering composition, execution setup, data considerations, and a filling layer algorithm. Provides examples of highly customized printed building components. Sakin and Kiroglu [20] discussed the potential of integrating BIM methodology with 3D printing modeling for energy efficiency, improved design, cost reduction, and structural insulation. Omid et al. [21] proposed a software platform, Planning and Operations Control Software for Automated Construction (POCSAC), for efficient data retrieval and analysis from BIM models to integrate BIM and CC.

From the above literature, it can be found that contour crafting technology possesses many advantages than the conventional techniques. However, the optimization of process parameters and selection of suitable robot are required to improve the performance of the system. For this purpose, in this research, multi-criteria decision-making (MCDM) was used to select the suitable robot for contour crafting technology. The structure of this article is as follows. Section 2 presents the Literature Review of CC technology, MCDM methodologies, and the AHP process. The key features and phases of AHP are described in this Section. An overview of Robot types is given in Section 3. The details of AHP hierarchy, pairwise matrix, and the methodology adopted for AHP analysis in this study are provided in section 4. Findings from this research are addressed in detail in Section 5. Section 6 summarizes the key findings, while Section 7 discusses research limits and future initiatives.

2.2 Multi Criteria Decision Making (MCDM) And Analytic Hierarchy Process (AHP)

The process of choosing an appropriate robot for a specific application has become a challenging task in modern times due to several contributing elements. The performance of a robot system may be influenced by various aspects, including but not limited to cost, accuracy, work volume, etc. Within the context of many Criteria Decision Making (MCDM) challenges, researchers evaluate numerous possibilities based on a range of criteria to identify the most optimal alternative(s). MCDM, or Multiple Criteria Decision Making, is a discipline focused on aiding decision-makers when faced with complex scenarios involving diverse and often conflicting criteria. The objective is to systematically evaluate and compare alternative courses of action to identify the most optimal solution.

Singh and Malik [22] highlighted that Multiple Criteria Decision Making (MCDM) has evolved into a powerful tool, making the process of choice not only easier but also more accurate. Hagag et al. [23] conveyed that there is a noticeable rise in the utilization of MCDM techniques for machine selection problems in manufacturing and construction fields. Numerous MCDM tools have been used in different applications. Some of the popular MCDM tools are as follows: Analytic Hierarchy Process (AHP), analytic network process (ANP), Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), etc. [24]. In this research, the AHP MCDM tool has been used to select the suitable robot for CC application. The Analytic Hierarchy Process (AHP), introduced by Thomas L. Saaty in 1970, utilizes the Saaty scale for pairwise comparisons [25]. MCDM models consist of 6 important key elements, namely decision variables, alternatives, criteria, outcomes, preferences, and decisions. Panagis et al. [26] introduced a modified AHP process to boost the automation and efficiency in construction using additive manufacturing techniques.

Chan Hua Go [27] proposed a robot selection model utilizing the Analytic Hierarchy Process, integrating inputs from multiple decision-makers and considering both subjective and objective criteria in the manufacturing sector. Repeatability, cost, load capacity, and velocity were chosen as criteria for the robot attributes. The novelty in using the Analytic Hierarchy Process (AHP) for selecting a robot for CC lies in its systematic and transparent approach to complex decision-making. AHP allows for the integration of both qualitative and quantitative factors, providing a structured framework to assess criteria, make informed comparisons, and arrive at a rational decision. The customization of criteria specific to CC, coupled with the ability to explicitly express preferences, fosters collaboration and enhances the credibility of the decision-making process. The method's adaptability to the unique requirements and challenges of CC adds a novel dimension to the robot selection process. Breaz et al. [28] highlighted that MCDM methods, with a focus on the widely used Analytic Hierarchy Process (AHP), are the prevalent approach for ranking robots, especially in determining criteria weights for robot selection decisions. Şenim Özgürler et al. [29] addressed the industrial robot selection problem, employing AHP and TOPSIS as multicriteria decision-making methods. Bhattacharyay et al. [30] used, the Quality Function Deployment method to pinpoint technical requirement criteria, while AHP is utilized to assess the priority of each criterion in robot selection.

The Analytic Hierarchy Process (AHP) used in this research consists of the 7 steps outlined below, which were derived from previously published data [31 – 33]. The stages of AHP are presented in Fig. 2. The identification of a problem is a critical stage in the process of making informed decisions. This process may include the act of choosing the most optimal alternative, assigning priority to various factors, or deciding between many competing possibilities. The subsequent stage involves the formulation of a fundamental hierarchical framework for the specified issue. The developed hierarchical structure consists of 3 levels. Level 1 indicates the goal of the problem; Level 2 indicates the criteria considered in this research, and Level 3 indicates alternatives based on criteria. The third and fourth steps of the analysis included building a pairwise matrix and assigning relative importance to each criterion and alternative. In the AHP procedure, it is vital to verify the consistency of the weight. In the fifth stage, the consistency index and consistency ratio were computed for this purpose. If the weights are consistent, the sixth stage involves developing the pairwise matrix for each criterion and calculating the corresponding weights. Finally, the decision matrix was formed, and the rank was assigned based on the priority value.

3. OVERVIEW OF GANTRY, SCARA AND CYLINDRICAL ROBOT

When considering robotic solutions for various applications, three primary types—Cartesian, SCARA (Selective Compliance Articulated Robot Arm), and cylindrical robots—offer distinct advantages and considerations. Cartesian robots operate through linear movements along the X, Y, and Z axes, providing high precision and simplicity in design. Gantry robots belong to a distinct category within Cartesian robots. SCARA robots, employing Selective Compliance Articulated Robot Arm technology, excel in speed, compactness, and precision, making them suitable for confined spaces. Cylindrical robots, characterized by simple cylindrical movements, are cost-effective and easy to implement. Each type has its strengths, such as precision and simplicity, and limitations, such as restricted workspace or limited reach. The choice among these robotic systems should be guided by the specific needs of the application, balancing factors like workspace requirements, task complexity, and the desired level of precision. The Fig. 3 illustrates the typical configurations of Cartesian, SCARA, and Cylindrical Robots.

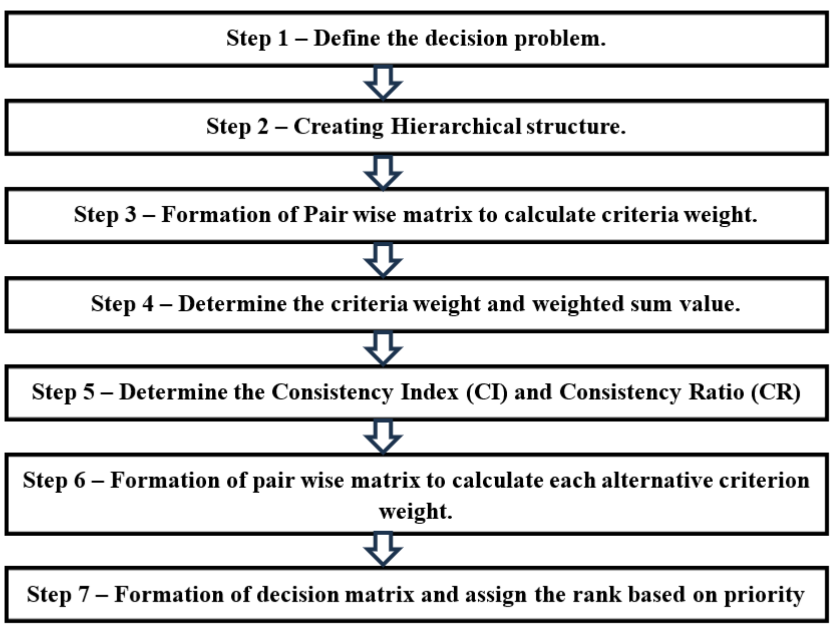

Fig. 2. Adopted steps in AHP method

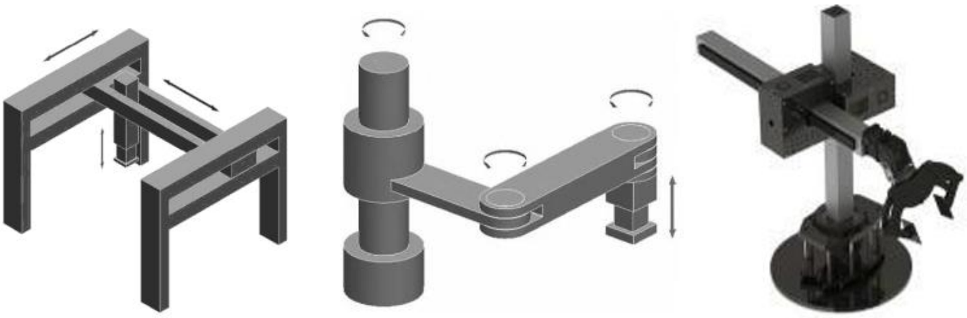

Fig. 3. a) Gantry Robot [34] b) SCARA Robot [34] c) Cylindrical Robot [35]

4. AHP PRELIMINARIES

4.1 Hierarchy, scale and pairwise comparison matrix

As discussed in the previous section, the hierarchical structure of the defined problem was prepared and presented in Fig. 4. The figure displays the hierarchical structure for selecting the robot for contour crafting with 6 criteria: cost, speed, dimensional accuracy, surface finish, work volume, and 3 alternatives: Cartesian, SCARA, Cylindrical robot. These hierarchical elements in a pairwise matrix was compared using the nine-point scale (Saaty scale – Table 1) to assess the relative importance or preference of elements in pairs. Values for inverse comparisons were 1/3, 1/5, 1/7, 1/9. Values between (2, 4, 6, 8) represent varying degrees of importance. For instance, if one element is strongly favored over another in a specific criterion, the expert assigns a value of 5 on the Saaty scale. These Saaty scale values are crucial for constructing matrices, which are normalized to determine overall priorities in the Analytic Hierarchy Process (AHP).

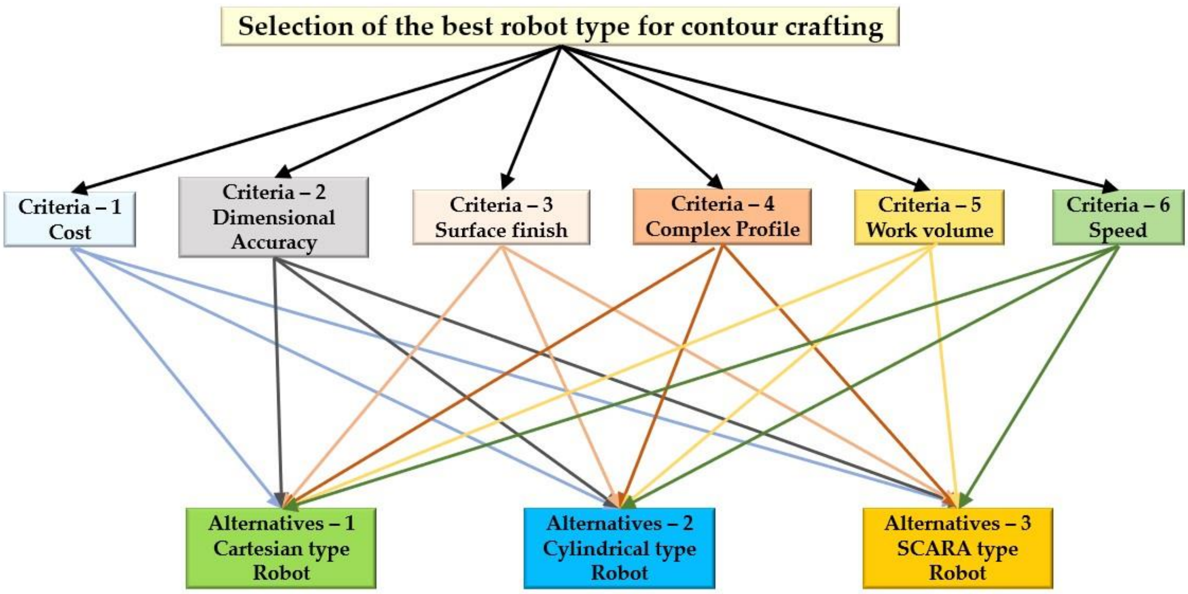

Fig. 4. Developed Hierarchical structure to select the robot for contour crafting

Table 1. Relative scale of criterion importance Saaty scale [1]

Scale	Numerical assessment
Equal Importance	1
Moderate Importance	3
Strong Importance	5
Very strong Importance	7
Extreme Importance	9
Intermediate values	2,4,6,8
Values of inverse comparison	1/3, 1/5, 1/7, 1/9

4.2 Data collection

In the dynamic field of construction for CC, a diverse group of experts contributes to the advancement of this innovative technology. Construction engineers, architects, project managers, material scientists, and robotics specialists are among the key stakeholders, each playing a unique role. To gather valuable insights from these experts, a comprehensive questionnaire has been crafted and sent to the identified professionals for the selection of a robot. A total of 80 responses were received, reflecting diverse expertise in the field. The breakdown includes 15% from Construction Engineers, 12% from Architects and Designers, 10% from Project Managers in Construction, 8% from Material Science Researchers, 10% from Robotics and Automation Specialists, 12% from Civil Engineering Professionals, 8% from Sustainability and Green Building Experts, 10% from Construction Technology Researchers, 5% from Urban Planning professionals, 7% from Building Information Modeling (BIM) Experts, 8% from Safety Compliance Specialists in Construction, and 5% from Users and Operators of CC. Six criteria such as cost, dimensional accuracy, surface finish, complex profile, work volume, and speed were selected.

Experts were asked to express their preferences for a specific criterion using a Saaty scale. The obtained results are presented in Fig. 5 – 10, with the percentage values and the number of respondents for each scale shown above each segment in the graph. The importance of the cost of a robot is represented in Fig. 5. The result from this figure reveals that approximately 30% of respondents, specifically 24 individuals out of 80, attributed high importance to the given factor. The dimensional accuracy and surface finish are important criteria in CC. As expected, around 41% of respondents selected very strong importance for dimensional accuracy. Surface finish, rated at 30% with very strong importance by respondents, emphasizes the significance of achieving a refined and high-quality surface appearance.

The development of a complex profile is another factor that needs to be considered while selecting the robot for CC application. Based on the survey result, 35% of respondents preferred strong importance. The work volume of the robot decides the size of the structure and cost of the system. For these criteria, around 34% of respondents preferred moderate importance. The speed of the robot is another factor that decides the cost of the structure directly. Hence, around 31% selected extreme importance.

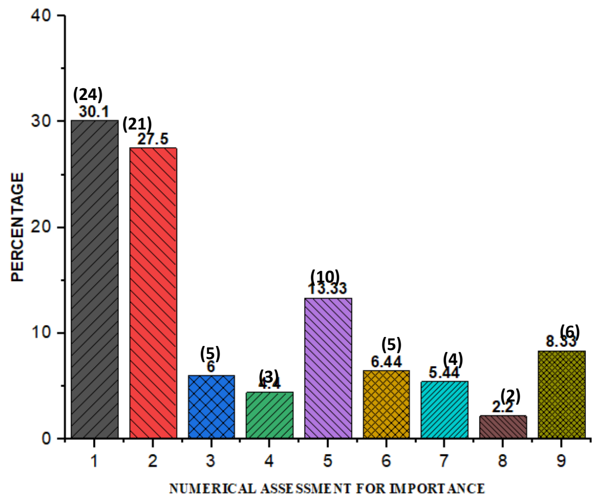

Fig. 5. Importance of cost of robot for CC

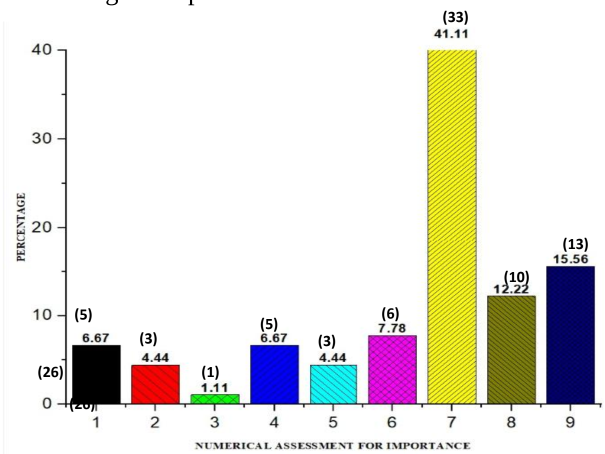

Fig. 6. Importance of dimensional accuracy of robot for CC

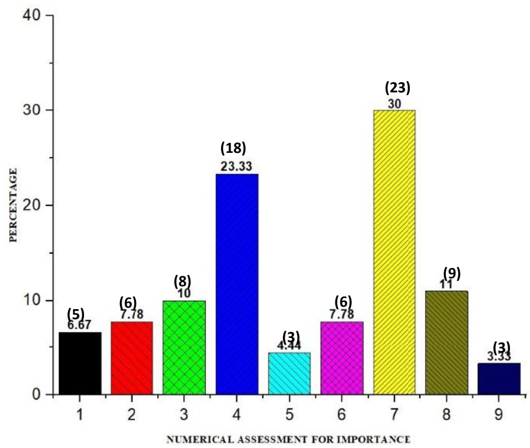

Fig. 7. Importance of surface finish of robot for contour Crafting

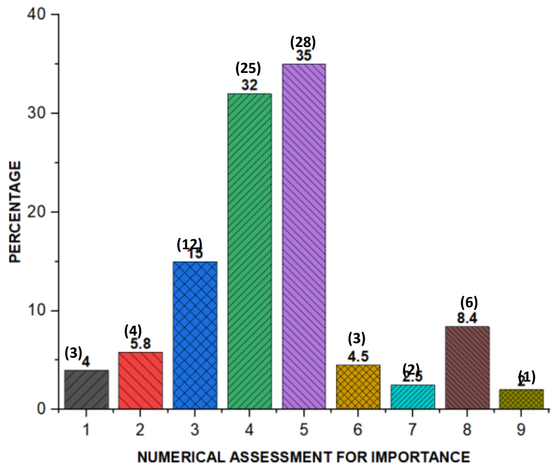

Fig. 8. Importance of complexity of profile for CC

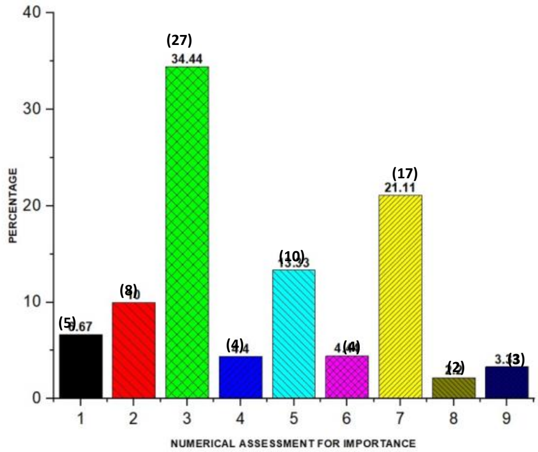

Fig. 9. Importance of work volume of robot for CC

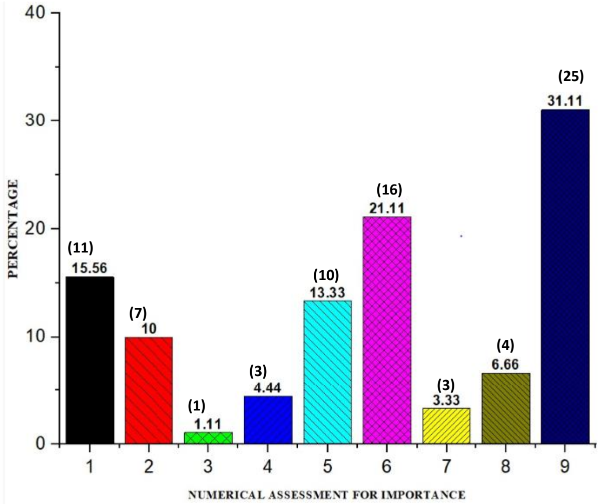

Fig. 10. Importance of speed of robot for CC

4.3 Pairwise comparison matrix

In this study, participants were surveyed to collect pairwise comparisons for each criterion using the numerical scale designed by Thomas L. Saaty, which ranges from 1 to 9, through a Google form. They were asked to assess the significance of alternatives in pairs, covering all possible combinations within each criterion. The general pairwise comparison matrix with the 'n' elements is given in equation (4.1).

$$X = \begin{pmatrix} 1 & X_{12} & X_{13} & \ldots X_{1n} \\ X_{21} & 1 & X_{23} & \ldots X_{2n} \\ . & . & 1 & . \\ . & . & . & . \\ X_{m1} & X_{m2} & X_{m3} & \ldots 1 \end{pmatrix} \quad \begin{matrix} X_{ii} = 1 \\ X_{ji} = \dfrac{1}{X_{ij}} \quad X_{ij} \neq 0 \end{matrix} \tag{4.1}$$

in this matrix, 'X_{ij}' represents the significance of the i^{th} element relative to the j^{th} element. The above-mentioned pairwise matrix 'X', derived using the Saaty scale from the data provided by respondents, will be utilized in determining the criteria weights. This method is used to quantitatively compare subjective opinions. Based on the survey results, a pairwise comparison matrix was developed considering 6 criteria such as cost, dimensional accuracy, surface finish, complex profile, work volume, and speed, and presented in Table 2.

Table 2. Pair-wise comparison matrix

Criterion	Cost	Dimensional accuracy	Surface finish	Complex profile	Work volume	Speed
Cost	1	1/7	1/7	1/5	1/3	1/9
Dimensional accuracy	7	1	3	7	9	5
surface finish	7	1/3	1	3	5	5
Complex profile	5	1/7	1/3	1	3	1/2
work volume	3	1/9	1/5	1/3	1	1/3
Speed	9	1/5	1/5	2	3	1

This approach aimed to collect comprehensive and detailed insights for subsequent analysis and decision-making. For example, a value of 1/7 in row 1 indicates a very strong preference for dimensional accuracy over cost, and a value of 9 in row 2 signifies an extremely strong preference for accuracy over work volume. Each cell contains the assigned values for each pair from the responders. Using AHP, these pairwise comparisons help derive overall priorities, aiding decision-making based on preferences.

4.4 Criteria Weight Calculation

The criteria weight was calculated by adding the row values and normalizing the values from the pairwise comparison matrix. Table 3 illustrates the pairwise matrix that has been resolved through the following procedure to derive the criteria weights:

Summation of Column Values: Calculate the sum of values in each column for every criterion.

Normalization of Importance Values: Divide each importance value within a column by the total sum of that column.

Row Summation for Criterion Weight: Lastly, the sum of values in each row represents the weight value for each criterion.

Table 3. Pair-wise matrix with Criterion weight

	Cost	Dimensional accuracy	Surface finish	Complex profile	Work volume	Speed	Criteria weight (sum of Row/6)
Cost	0.031	0.074	0.029	0.015	0.016	0.009	0.029
Dimensional accuracy	0.219	0.518	0.615	0.517	0.422	0.419	0.452
surface finish	0.219	0.173	0.205	0.222	0.234	0.419	0.245
Complex profile	0.156	0.074	0.068	0.074	0.141	0.042	0.092
work volume	0.094	0.058	0.041	0.025	0.047	0.028	0.049
Speed	0.281	0.104	0.041	0.148	0.141	0.084	0.133

The weighted sum value of each criterion was calculated and presented in Table 4. The values in the matrix were obtained by multiplying the pairwise comparison matrix values of each criterion from Table 2 with its corresponding weight value, and the sum of each row gives the weighted sum value for each criterion. The obtained weight for each criterion, presented in Table 5, represents the tabulation of each criterion and its weightage. It's found that dimensional accuracy has the most weightage among the six criteria.

Table 4. Pair-wise matrix with Weighted sum value

	Cost	Dimensional accuracy	Surface finish	Complex profile	Work volume	Speed	Weighted Sum
Cost	0.029	0.065	0.035	0.018	0.016	0.015	0.178
Dimensional accuracy	0.203	0.452	0.736	0.647	0.438	0.665	3.141
surface finish	0.203	0.151	0.245	0.277	0.243	0.665	1.785
Complex profile	0.145	0.065	0.082	0.092	0.146	0.067	0.596
work volume	0.087	0.050	0.049	0.031	0.049	0.044	0.310
Speed	0.261	0.090	0.049	0.185	0.146	0.133	0.865

Table 5. Criteria and criteria weight

	Cost	Dimensional accuracy	surface finish	Complex profile	work volume	Speed
Criteria weight	0.029	0.452	0.245	0.092	0.049	0.133

4.5 Calculation of Consistency Index and Consistency Ratio

The following formula may be used to calculate the consistency index (CI) and consistency ratio (CR).

$$CR = \frac{CI}{RI} = \left[\frac{\lambda_{\max} - n}{n-1}\right] \times \frac{1}{RI} \tag{4.2}$$

Where ‘n’ is the number of criteria, ‘RI’ is the random Index depending on the number of criteria can be found in Table 6.

Table 6. Random index

(N)	1	2	3	4	5	6	7	8	9	10
(RI)	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

N- Number of criteria, RI- Random Index

λ is the maximum Eigan value and can be found as

$$\lambda_{\max} = \left[\frac{Addition\,of\;weighted\;sum\,value}{Criteria\,weight}\right] \tag{4.3}$$

The same weights may be used for further computations if the resulting CR is less than 0.1. If not, the preceding procedures should be repeated until consistency is achieved. The ratio of the weighted sum value of each criterion by its respective criteria weight is calculated as shown in Table 7. ‘λ_{max}’ is derived by summing the column of ratio values and then dividing it by the number of criteria.

Table 7. Pairwise matrix with ratio

	Criteria weight	Weighted sum	Ratio
Cost	0.174	1.07	6.149
Dimensional accuracy	2.71	18.861	6.96
surface finish	1.472	10.717	7.281
Complex profile	0.555	3.582	6.454
work volume	0.293	1.861	6.352
Speed	0.799	5.191	6.497
		λ_{max}	6.616
	Consistency Index (CI)		0.123
	Consistency Ratio (CR)		0.099

$$\lambda_{\max} = \left[\frac{0.178+3.141+1.785+0.596+0.310+0.865}{6}\right] = 6.616 \tag{4.4}$$

Subsequently, the consistency index (C.I) is obtained using the subsequent formula:

$$Consistancy\ Index\,(CI) = \left[\frac{6.616-6}{5}\right] = 0.123 \tag{4.5}$$

In this context, the Random Index (R.I) values are presented in Table 2. R.I. from the table inferred as 1.24 for 6 number of criteria. The process of calculating the consistency ratio value proceeds as follows:

$$Consistancy\ Ratio\,(CR) = \left[\frac{0.123}{1.24}\right] = 0.099 \tag{4.6}$$

The obtained consistency ratio is 0.099 < 0.10. Thus, the estimated consistency ratio indicates a satisfactory degree of consistency, making the criterion suitable.

4.6 Formation of Pairwise matrix weight calculation for cost criteria

The pairwise matrix for the cost criteria for three different robots, such as Cartesian-type robot, cylindrical-type robot, and SCARA robot, with the total value, is given in Table 8. This analysis aims to quantitatively evaluate the cost criteria of Cartesian, SCARA, and cylindrical robots. Experts' Saaty scale response values help identify the most cost-effective robot type. The matrix reflects the relative preferences or performance of the three robot alternatives in the specified criteria, where values less than 1 indicate a lower preference or performance, values equal to 1 indicate equality, and values greater than 1 indicate a higher preference or performance.

Table 9 illustrates the pairwise matrix containing the priority I value for each alternative based on criterion I. The values for this matrix were derived by dividing each value by the individual total sum values, and the priority – I value was obtained by adding all the row values. Table 9 shows that, according to experts' judgments, the Cartesian robot is perceived as more cost-effective than both the SCARA and Cylindrical robots. SCARA and Cylindrical robots are considered to have comparable costs.

Table 8. Pairwise matrix for Criterion 1 with Total Sum Value (Cost)

	Cartesian robot	Cylindrical	SCARA
Cartesian robot	1	7	5
Cylindrical	0.143	1	7
SCARA	0.2	0.143	1
Total	1.343	8.143	13

Table 9. Pairwise matrix for Criterion 1(Cost) with Priority

	Cartesian robot	Cylindrical	SCARA	Priority - 1
Cartesian robot	0.745	0.86	0.385	0.663
Cylindrical	0.106	0.123	0.538	0.256
SCARA	0.149	0.018	0.077	0.081

Table 10. Pairwise matrix for Criterion 2 with Total Sum Value (Dimensional Accuracy)

	Cartesian robot	Cylindrical	SCARA
Cartesian robot	1	3	0.8
Cylindrical	0.333	1	0.333
SCARA	1.25	3.003	1
Total	2.583	7.003	2.133

According to the findings of the survey, it has been determined that dimensional correctness has significant relevance. Table 10 represents the pair-wise matrix for dimensional accuracy and indicates that the SCARA robot is more precise than the other two alternatives. The pairwise matrix with priority was obtained by following the same procedure mentioned above and presented in Table 11.

Table 11. Pairwise Matrix for Criterion 2 with Priority

	Cartesian robot	Cylindrical	SCARA	Priority - 2
Cartesian robot	0.387	0.428	0.375	0.397
Cylindrical	0.129	0.143	0.156	0.143
SCARA	0.484	0.429	0.469	0.461

Table 12. Pairwise matrix for criterion 3 with Total Sum Value (Surface finish)

	Cartesian robot	Cylindrical	SCARA
Cartesian robot	1	5	0.333
Cylindrical	0.2	1	0.8
SCARA	3.003	1.25	1
Total	4.203	7.25	2.133

Similar to the dimensional accuracy, the surface finish of the product obtained higher importance than other criteria. The obtained values from Questionnaire were used to construct a pairwise matrix, and afterward, the priority values were computed and shown in Tables 12 and 13, respectively. The expert's response suggests that the SCARA robot may have a slight advantage in achieving a desired surface finish compared to the Cartesian and Cylindrical robots.

Producing intricate profiled structures using a cartesian robot is challenging compared to using a cylinder or SCARA robot. Based on the respondents' data and the Saaty scale, this pair-wise matrix for complex profile criteria was developed and given in Table 14. Then the Pairwise matrix with priority values is presented in Table15 and it is found that SCARA robot is more important than the other 2 alternatives in terms of complex profile.

Table 13. Pairwise Matrix for Criterion 3 with Priority

	Cartesian robot	Cylindrical	SCARA	Priority - 3
Cartesian robot	0.238	0.69	0.156	0.361
Cylindrical	0.048	0.138	0.375	0.187
SCARA	0.714	0.172	0.469	0.452

Table 14. Pairwise matrix for Criterion 4 with Total Sum Value (Complex profile)

	Cartesian robot	Cylindrical	SCARA
Cartesian robot	1	0.2	0.111
Cylindrical	5	1	0.142
SCARA	9.009	7.042	1
Total	15.009	8.242	1.253

Table 15. Pairwise matrix for Criterion 4 with Priority

	Cartesian robot	Cylindrical	SCARA	Priority - 4
Cartesian robot	0.067	0.024	0.089	0.06
Cylindrical	0.333	0.121	0.113	0.189
SCARA	0.6	0.854	0.798	0.751

Table 16 presents a pair-wise matrix created using data collected from respondents of academic and industry experts. The priority values were derived using the same methodology as in Table 9. The obtained priority values are presented in Table 17. Based on this data, it's evident that the respondent favoured the Cartesian robot, indicating a greater work volume than the other two robot

Table 16. Pairwise matrix for Criterion 5 with Total Sum Value (Work volume)

	Cartesian robot	Cylindrical	SCARA
Cartesian robot	1	9	7
Cylindrical	0.111	1	5
SCARA	0.143	0.2	1
Total	1.254	10.2	13

Table 17. Pairwise Matrix for Criterion 5 with Priority

	Cartesian robot	Cylindrical	SCARA	Priority - 5
Cartesian robot	0.797	0.882	0.538	0.739
Cylindrical	0.089	0.098	0.385	0.191
SCARA	0.114	0.02	0.077	0.07

Table 18. Pairwise matrix for criterion 6 with Total Sum Value (Speed)

	Cartesian robot	Cylindrical	SCARA
Cartesian robot	1	7	5
Cylindrical	0.143	1	7
SCARA	0.2	0.143	1
Total	1.343	8.143	13

Table 18 and 19 provide the details of pair wise matrix for criteria 6 (speed) with total sum value and priority value respectively. This indicates that the cartesian robot having high priority than other robots. Table 19 indicates that the Cartesian robot is perceived as having a slight advantage in speed over the SCARA and Cylindrical robots. These tables serve as tools to systematically assess the criteria, alternatives, and priorities involved in the decision-making process, ultimately aiding in the selection of the optimal choice.

Table 19. pairwise matrix for criterion 6 with Priority

	Cartesian robot	Cylindrical	SCARA	Priority - 6
Cartesian robot	0.745	0.86	0.385	0.663
Cylindrical	0.106	0.123	0.538	0.256
SCARA	0.149	0.018	0.077	0.081

4.7 Formation of Decision Matrix and Rank Determination

The consolidated values of criteria weight and priority values of each criterion are given in Table 20. This value serves as the basis for ranking and comparing the alternatives to make an informed decision. By incorporating both the relative importance of criteria and the specific priorities assigned to each alternative, this method facilitates the identification of the most suitable option from the available alternatives.

Finally, Table 21 demonstrates the decision matrix with ranks determined by the priority values assigned to each alternative. The rankings of the available options show that the Cartesian Robot is the best option, followed by the SCARA robot and the cylindrical robot. In patent [19], Behrokh Koshnevis notes that the Gantry Robotic system is lightweight yet sufficiently rigid, ensuring efficient material delivery and functionality in CC for construction.

Table 20. Decision matrix with criteria weight

Criteria weight	0.174	2.71	1.472	0.555	0.293	0.799
	Priority 1	Priority 2	Priority 3	Priority 4	Priority 5	Priority 6
Cartesian robot	0.663	0.397	0.361	0.06	0.739	0.663
Cylindrical	0.256	0.143	0.187	0.189	0.191	0.256
SCARA	0.081	0.461	0.452	0.751	0.07	0.081

Table 21. Final decision matrix with rank

	Priority1 x Criteria weight	Priority 2 x Criteria weight	Priority 3 x Criteria weight	Priority 4 x Criteria weight	Priority 5 x Criteria weight	Priority 6 x Criteria weight	Total	Rank
Cartesian robot	0.115	1.076	0.531	0.033	0.217	0.53	2.502	1
Cylindrical	0.045	0.388	0.275	0.105	0.056	0.205	1.074	3
SCARA	0.014	1.249	0.665	0.417	0.021	0.065	2.431	2

5. DISCUSSION

The key goals of this study are (1) To help academics and the Architecture, Engineering, and Construction (AEC) sector choose the best CC machine by using the Analytical Hierarchy Process (AHP) and (2) To increase global use of this technology. The literature study indicates that Contour Crafting (CC) can yield benefits, including reduced production time, enhanced product quality, and environmental conservation.

The paper establishes six criteria for comparison in AHP: Cost, Dimension Accuracy, Surface finish, Complex profile, work volume, and speed. By gathering respondent’s answers, a pair-wise matrix is constructed, facilitating the determination of criteria weights. From the criterion weights ranking, its seen that Dimensional Accuracy is identified as the most critical criterion for the success of the CC process. Surface finish is the second most important factor, Speed is considered the least critical among the specified criteria. Moreover, the low consistency ratio, below 0.10, indicates the accuracy of the chosen criteria. Priority values for each criterion are determined based on respondents' input, utilizing a pairwise matrix and focusing on comparing the criteria across the three robots: Cartesian, Cylindrical, and SCARA. Although this study encompasses six criteria for CC robot selection, AHP is adaptable to accommodate any number of criteria and alternatives.

After successfully ascertaining the priority values for each criterion, further ranking is executed according to these values in the decision matrix. It has been determined that the Cartesian Robot is the best machine for CC using the AHP approach. The proposed strategy not only holds value but also offers guidance for future researchers who must choose the most appropriate machine from a multitude of options.

6. CONCLUSIONS

CC (CC) has emerged as a transformative automated methodology for building an industry, that is experiencing significant global growth. Selection of a suitable robot for the CC application is indispensable for the construction of buildings with less manpower and less cost with high accuracy and surface finish. Nevertheless, the process of selecting a robot is an intricate task due to the presence of several parameters associated with CC. This study aimed to use the Analytic Hierarchy Process (AHP) approach to identify the most appropriate robot for CC applications.

In this article, an in-depth analysis of three prominent types of robots: Cartesian, Cylindrical, and SCARA was conducted. These robots have been ranked based on selection criteria such as Cost, Dimensional Accuracy, Surface finish, Complex profile, Work volume, and speed. From the literature review, it becomes evident that the Analytic Hierarchy Process (AHP) stands out as one of the most effective Multiple Criteria Decision Making (MCDM) methods for the selection of suitable robots. Furthermore, it was found that the Cartesian robot is the most suitable robot for constructing a building structure. Next to the Cartesian robot, the SCARA robot attained the second rank followed by the cylindrical robot. In conclusion, CC's expansion has been quite noteworthy. The potential for this technology to revolutionize building practices on Earth and beyond is fascinating because of the benefits it offers in terms of speed, sophisticated design, and cost.

7. LIMITATIONS AND DIRECTIONS FOR FUTURE STUDY

The most appropriate robot for CC application has been identified by using the AHP method. Though it provides expected results, there are some limitations in this study. The list of limitations is as follows

1. Still more parameters that affect the performance of the robot. Future researchers should include more criteria and alternatives.
2. The criterion weight and alternative rank may be determined using a variety of MCDM methods, including TOPSIS, VIKOR, ANP, etc.
3. The same method can be employed further with some sub-criteria.

AHP heavily relies on expert judgments, introducing subjectivity. Different experts might assign different weights to criteria, impacting the final decision.

ABBREVIATIONS

STL	:	Standard Triangle Language
MCDM	:	Multi Criteria Decision Making
MADM	:	Multi Attribute Decision Making
MODM	:	Multi Objective Decision Making
AHP	:	Analytic Hierarchy Process
ANP	:	Analytic Network Process
TOPSIS	:	Technique for Order Performance by Similarity to Ideal Solution
VIKOR	:	Kriterijumska Optimizacija Kompromisno Resenje
CI	:	Consistency Index
CR	:	Consistency Ratio

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APPENDIX

Questionnaire for contour crafting robot selection

1. Importance of cost over dimensional accuracy for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equ:	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

2. Importance of cost over surface finish for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equ:	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

3. Importance of cost over complex profile handling for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equ:	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

4. Importance of cost over speed for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equ:	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

5. Importance of cost over work volume for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

6. Importance of dimensional accuracy over surface finish for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

7. Importance of dimensional accuracy over complex profile for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

8. Importance of dimensional accuracy over work volume for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

9. Importance of dimensional accuracy over speed for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

10. Importance of surface finish over complex profile handling for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

11. Importance of surface finish over work volume handling for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

12. Importance of surface finish over speed for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

13. Importance of complex profile handling over speed for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

14. Importance of complex profile handling over work volume for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

15. Importance of work volume over speed for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

16. Importance of cost for cartesian robot over cylindrical robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

17. Importance of cost for cartesian robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	○	○	○	○	○	○	○	○	○	Extremely Important

18. Importance of cost for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	○	○	○	○	○	○	○	○	○	Extremely Important

19. Importance of dimensional accuracy for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	○	○	○	○	○	○	○	○	○	Extremely Important

20. Importance of dimensional accuracy for cartesian robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	○	○	○	○	○	○	○	○	○	Extremely Important

21. Importance of dimensional accuracy for cartesian robot over cylindrical robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

22. Importance of surface finish for cartesian robot over cylindrical robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

23. Importance of surface finish for cartesian robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

24. Importance of surface finish for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

25. Importance of complex profile handling for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

26. Importance of complex profile handling for Cartesian robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

27. Importance of complex profile handling for Cartesian robot over cylindrical robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

28. Importance of work volume for Cartesian robot over cylindrical robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

29. Importance of work volume for Cartesian robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

30. Importance of work volume for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

31. Importance of speed for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

32. Importance of speed for Cartesian robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important

33. Importance of speed for cylindrical robot over SCARA robot for contour crafting

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equal importance	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important