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A METHOD FOR SELECTING CAX TOOLS FOR ERGONOMIC DESIGN DURING THE ESTABLISHMENT OF A DESIGN PRACTICE

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Purpose: The purpose of this paper is to develop an algorithmic decision-support method for selecting CAx tools that support ergonomic design at the stage of establishing a design practice, under conditions of high decision uncertainty and organizational constraints.
Design/methodology/approach: A multi-stage decision-making algorithm is proposed, integrating the identification of criteria, their prioritization using the Fuzzy AHP method, the evaluation of functional fit of CAx tools, and a selection procedure based on the aggregation of indicators and priority analysis. The method is illustrated using a realistic implementation scenario of a newly established design office in the furniture industry.
Findings: The simulation results indicate that, in the analyzed scenario, none of the considered CAx tools fully satisfies all critical criteria, confirming the validity of a compromise-based and adaptive approach. However, the proposed algorithm enables the comparison of alternatives and supports informed decision-making even when essential ("must-have") conditions are not fully met.
Research limitations/implications: The study is limited by the use of a single implementation scenario and reliance on expert-based data. Future research may include extending the method to additional industries and conducting empirical validation in real-world implementations.
Practical implications: The method may serve as a decision-support tool for SMEs, reducing the risk of arbitrary tool selection and supporting the rational planning of CAx environment development.
Social implications: The application of the method contributes to improving the quality of ergonomic design and promotes the early integration of human–machine–environment interactions.
Originality/value: The originality of the paper lies in combining an algorithmic decision-making approach with FAHP and FCM methods in the context of ergonomic design and the establishment of a design practice.
Keywords: CAx, ergonomic design, decision support, Fuzzy AHP, SMEs.
Category of the paper: Research paper.

1. Introduction

1.1. Justification for the Study

The establishment of a design office under conditions of digital transformation involves making technical, organizational, and strategic decisions that significantly shape the functioning of the organization (Balas et al., 2024; Abuamria et al., 2024; Mittal, 2025). One of the key areas of these decisions is the selection of computer-aided design tools (CAx), which determine the execution of design processes, the scope of engineering and ergonomic analyses, as well as the modes of team collaboration and project information management (Sacks et al., 2020; Balas et al., 2024). These decisions are often made under conditions of limited information, time pressure, and budget constraints, which increases the risk of arbitrary or suboptimal choices.

The importance of tool-related decisions stems from their long-term impact on the functioning and development of the design office. The CAx environment selected at the stage of establishing the organization affects the scalability of design processes, the possibility of integration with other information systems, and the ability to carry out projects of higher complexity, including those involving ergonomic considerations (Sacks et al., 2020). In design practice, a tendency can be observed to retain previously adopted tool solutions even when organizational needs evolve, which may lead to increasing costs of reorganizing the design environment and limit further development potential (Mandinach, Schildkamp, 2021).

A particular challenge is the selection of CAx tools from the perspective of ergonomic design (ED). Despite the growing availability of tools enabling advanced geometric modeling, biomechanical simulations, etc., engineering practice still lacks coherent, algorithmic methods supporting decision-making in tool selection in relation to the objectives of the design office (Rojek et al., 2021). Such decisions are often made intuitively, based on limited functional comparisons or licensing availability, without a systematic reference to ergonomic requirements, design stages, and the nature of the tasks being performed (Mandinach, Schildkamp, 2021).

Decisions regarding the selection of CAx tools are inherently multi-dimensional: they encompass not only technical and ergonomic aspects, but also organizational conditions such as implementation costs, availability of team competencies, system interoperability, and the possibility of further development of the digital environment (Balas et al., 2024). In particular, at the stage of establishing a design practice, under conditions of high uncertainty and immature organizational structures, the lack of systematic decision support may lead to limitations in the anticipated functional capabilities of the design office.

In this context, it becomes justified to develop a method supporting the selection of CAx tools that structures the decision-making process, integrates diverse technical, ergonomic, and organizational criteria, and enables rational decision-making even under conditions of limited information and high decision uncertainty.

1.2. Research Problem and Research Questions

Based on the analysis of the identified conditions, it can be concluded that a key challenge for contemporary design offices, particularly at the stage of establishing a design practice, is the lack of a structured approach to decision-making regarding the selection of CAx tools supporting ED.

The identified problem has both a cognitive and an application-oriented nature. On the one hand, it concerns the lack of coherent decision models integrating knowledge from ergonomics, engineering graphics, and project management. On the other hand, it relates to the practical difficulties faced by newly established organizations.

The research problem addressed in this paper can be formulated as follows: the lack of an algorithmic method supporting decision-making in the selection of CAx tools in ergonomic design, adapted to the specificity of establishing a design practice and conditions of high decision uncertainty.

In order to operationalize the research problem, the following research questions were formulated:

RQ1: What decision-making conditions and selection criteria for CAx tools are critical at the stage of establishing a design office oriented toward ergonomic design?

RQ2: How can the process of selecting CAx tools be structured in the form of a decision-making algorithm that takes into account different organizational objectives and relationships between decision variables?

RQ3: Which decision-support methods can be integrated within a single algorithm to improve the accuracy and transparency of tool selection decisions?

The formulated research questions serve an organizing and guiding function for the analysis and constitute a reference point for illustrating the application potential of the proposed approach.

1.3. Aim and Scope of the Paper

With reference to the identified research problem and the formulated research questions, the aim of this paper is to develop an algorithmic method for supporting decision-making in the selection of CAx tools for ergonomic design at the stage of establishing a design practice. The method is designed as a structured, multi-stage decision-making algorithm that takes into account diverse organizational objectives.

The paper presents the characteristics of a newly established design office and its decision-making context, as well as the assumptions of the method, the decision model, and the logic of successive stages of the algorithm leading to the evaluation and selection of CAx tools from the perspective of ED. The scope of the study particularly includes the stage of evaluating the functional fit of CAx tools to decision criteria and the stage of selecting the optimal solution. The logic of the algorithm is illustrated using a hypothetical yet realistic decision-making scenario, demonstrating the application potential of the method under conditions of high decision uncertainty, based on the example of a design office in the furniture industry.

2. Application of the Method in the Implementation of a Small Design Office

2.1. Characteristics of the Organization and Decision-Making Context

The analyzed case concerns a small design office (SME) specializing in the design of residential and office furniture, including built-in solutions, short production series, and product variation tailored to individual orders. The identification of requirements is based on defining typical and critical design tasks, as well as the nature of the analyzed human–machine–environment (H–M–E) interactions.

The organizational assumptions include a design team of 3-7 members, a workflow of approximately 8-12 projects per month, and the predominance of solution adaptation, product variation, and rapid design modifications. Cooperation with the manufacturing facility is carried out in a CNC subcontracting model with in-house assembly, which requires stable data formats, repeatable data exports, and unambiguous technical documentation. Tools with moderate costs and relatively low learning barriers are preferred.

The scenario distinguishes between typical tasks, characterized by high frequency of occurrence, and critical tasks, associated with an increased risk of cost or ergonomic errors. Key tasks include concept modeling and product variation, design of dimensions and usable space, design of joints and assembly details, preparation of documentation and data for CNC manufacturing, and evaluation of ergonomics in use, assembly, and maintenance.

Within the design office, ergonomics is primarily anthropometric and spatial in nature, and to a limited extent biomechanical, without the need for advanced CAE simulations.

2.2. Decision-Making Algorithm Procedure

2.2.1. Identification of Decision Criteria in the Furniture Industry

The identification of decision criteria for the implemented small design office in the furniture industry was carried out using informal analysis, complemented by selected elements of formal analysis. The starting point was the analysis of typical and critical design tasks, as well as the nature of H–M–E interactions, in particular relationships of the type human–product, human–space, and human–information technology, which determine the required scope of engineering and ergonomic functions.

In parallel, an analysis of the objectives of the design office was conducted, including both strategic and operational goals. Although these goals were not hierarchically weighted at this stage, they enabled the definition of the general decision-making profile of the organization and served as a filtering mechanism limiting the inclusion of criteria irrelevant to the planned scope of activities.

The process of identifying decision criteria was supported by typical requirements engineering techniques, in particular use case analysis and preliminary benchmarking of CAx tools. This made it possible to verify the availability of the required engineering and ergonomic functions in the analyzed solutions and their consistency with the specifics of projects carried out in the furniture industry, while simultaneously taking into account the organizational conditions of the design office.

2.2.2. Selection and Classification of Evaluation Sub-Criteria in the Furniture Industry

Based on the results of the previous stage of the algorithm, the method proceeds with the selection and classification of evaluation sub-criteria, which constitute the operational basis for the subsequent decision-making process. This stage corresponds to the transformation of variables describing the design activity into decision variables.

The starting point for the selection of criteria was the developed set of decision variables consisting of 44 sub-criteria and 13 strategic and operational objectives.

The outcome of this stage of the method is a matrix of decision criteria and CAx tool functionalities (Table 1).

Table 1.
Decision sub-criteria and CAx tool functionality matrix for the selection of CAx tools for a newly established design office

Category	Symbol	Subcategory	Assigned CAx Tool Functionality (based on the developed classification)
Organizational function variables in design (K1)	Z01	Industry	F8
	Z02	Typical H–M–E system	F28
	Z03	Role in the structure of the design system	F21
	Z04	Level of standardization of the ED process	F4

Cont. table 1.

Variables related to the core characteristics of the designed H–M–E system (K2)	Z09	Type of H–M–E system interaction	F21
	Z11	Level of ergonomics of the designed system	F22; F23
Operational variables (K3)	Z12	Cost of CAx tool license and implementation	F28
	Z13	Hardware requirements	F28
	Z14	Availability of technical support and updates	F28
Interoperability variables in production planning (K4)	Z15	Compatibility with PLM system	F17; F7
Implementation variables (K5)	Z20	Efficiency of H–M–E system implementation	F4; F17
	Z21	Design team experience in implementation and use of CAx tools	F4
	Z22	Level of ergonomics of the CAx tool interface	F4
Engineering functionality variables (K6)	Z23	Geometric modeling (solid, surface, etc.)	F8
	Z27	Technical visualization (rendering, 3D animation)	F12; F21
	Z30	Production cost analysis	F15
	Z31	Libraries of predefined design solutions	F16
	Z32	API	F17
	Z33	Interoperability with other CAx tools (data import/export)	F7
Ergonomic functionality variables (K7)	Z34	Anatomical modeling	F18
	Z37	Static and dynamic visualization (CAD, animation, VR/AR)	F21
	Z38	Ergonomic simulations (REBA, RULA, OWAS, spatial accessibility)	F22; F24; F25
	Z40	Ergonomic analysis (working postures, biomechanics, ergonomic risk)	F19; F22; F24; F25; F26
	Z41	Availability of ergonomic assessment methods and scales	F19; F22; F24; F25

Legend: F4 – CAx tool interface ergonomics; F7 – Interoperability with other CAx tools (import/export of DHM models); F8 – Geometric modeling (solid modeling, etc.); F12 – Technical visualization; F15 – Production cost analysis; F16 – Libraries of predefined design solutions; F17 – Automated generation of design documentation (API); F18 – Anatomical modeling (anthropometric models); F19 – Functional modeling (biomechanics, motion analysis, load analysis); F21 – Static and dynamic visualization; F22 – Ergonomic simulations; F23 – Input data modeling; F24 – Ergonomic analysis (working postures, biomechanics); F25 – Availability of ergonomic assessment methods and scales; F26 – Capability to predict health effects; F28 – Scalability of the CAx tool.

Source: Own elaboration.

To define the scope of criteria, an adaptive selection path was adopted, in which informal analysis played a dominant role, complemented by elements of requirements structuring. In order to organize the variables and assign them a decision-making structure, the sub-criteria were classified into categories and subcategories according to their nature and area of influence.

The process of selecting and classifying sub-criteria was further supported by requirements structuring techniques, in particular the MoSCoW method. This made it possible to preliminarily assign sub-criteria to the following categories: critical (Must), important (Should), and desirable (Could).

2.2.3. Ranking of Criteria and Sub-Criteria in the Furniture Industry

The ranking of criteria and sub-criteria was carried out using the Fuzzy AHP method. The results of the criteria ranking are presented in Table 2.

Table 2.
Ranking of Decision Criteria and Sub-Criteria for a Design Office in the Furniture Industry

Criterion symbol (Table 1)	Criterion weight	Sub-criterion symbol (Table 1)	Sub-criterion weight
K1	0.11	Z01	0.30
		Z02	0.25
		Z03	0.25
		Z04	0.20
K2	0.08	Z09	0.55
		Z11	0.45
K3	0.19	Z12	0.45
		Z13	0.30
		Z14	0.25
K4	0.06	Z15	1.00
K5	0.22	Z20	0.35
		Z21	0.25
		Z22	0.40
K6	0.18	Z23	0.28
		Z27	0.16
		Z30	0.14
		Z31	0.16
		Z32	0.16
		Z33	0.10
K7	0.16	Z34	0.20
		Z37	0.15
		Z38	0.25
		Z40	0.22
		Z41	0.18

Source: Own elaboration.

These results constitute a direct basis for the subsequent stage of the method, namely the evaluation of the fit of CAx tools to the decision criteria.

2.2.4. Evaluation of the Fit of CAx Tools to the Activities of the Established Design Office

The evaluation of the fit of CAx tools to the defined decision criteria and sub-criteria constitutes a key stage of the method. It has a tabular form and includes a comparison of criteria, their weights (determined using the FAHP method), the corresponding sub-criteria, and the functionality assessments of the analyzed CAx tools. In this way, a complete profile of the fulfillment of decision requirements is obtained for each tool.

The calculations are based on normalized weights of criteria and sub-criteria satisfying the following conditions:

$$\sum_{i=1}^{m} w_i = 1, \tag{1}$$

$$\sum_{j=1}^{n_i} w_{ij} = 1. \tag{2}$$

They constitute the input data for further calculations.

For each sub-criterion c_{ij} the functionality assessments assigned to the set of variables Z_{ijk}, where $k = 1, \ldots, K_{ij}$, are aggregated. This yields a representative value:

$$\bar{s}_{ij}(t) = \frac{1}{k_{ij}} \sum_{r=1}^{k_{ij}} s_{ij}^{(r)}(t). \tag{3}$$

In the case where a sub-criterion is associated with a single functionality of a CAx tool ($k_{ij} = 1$), the aggregation reduces to a single value.

Next, the normalized evaluation of the CAx tool functionality is calculated with respect to the evaluation scale:

$$\hat{s}_{ij}(t) = \bar{s}_{ij}(t)/s_{max}, \tag{4}$$

where $s_{max} = 4$ for the adopted four-level scale.

The partial evaluation with respect to a sub-criterion is defined as:

$$f_{ij}(t) = W_i \cdot wij \cdot \hat{s}_{ij}(t). \tag{5}$$

All partial values are then aggregated using the following equation:

$$F(t) = \sum_{i=1}^{m} \sum_{j=1}^{n_i} W_i \cdot w_{ij} \cdot \hat{s}_{ij}(t) \tag{6}$$

The evaluation takes values in the interval [0,1] and constitutes a synthetic indicator of fit. This value allows for the comparison and classification of tools—for example, values close to 1 indicate a very good fit, whereas values close to 0 indicate a poor fit.

However, this aggregated indicator may obscure significant discrepancies in the fulfillment of priority criteria. Therefore, several additional measures were introduced, including the Priority Satisfaction Index (PSI), defined as:

$$PSI(t) = \frac{\sum_{(ij)\in p} w_1 w_{ij} \hat{S}_{ij}(t)}{\sum_{(jj)\in P} w_1 w_{ij}} \tag{7}$$

where P denotes the set of priority sub-criteria (e.g., the top 30% in terms of weights). Values close to 1 indicate a high level of priority fulfillment.

Another measure is Must-Have Compliance (MHC), which verifies whether all sub-criteria marked as essential achieve values greater than or equal to the acceptance threshold γ. Formally, it is expressed as:

$$MHC(t) = \Pi_{\{ij\}\in M} 1\{\hat{S}_{ij}(t) \geq \gamma\}. \tag{8}$$

A value of 1 indicates that all conditions are satisfied, while 0 indicates non-compliance in at least one criterion.

A related measure is the Priority Gap (PG), expressed as the average deficit in meeting threshold values for priority criteria:

$$PG(t) = \frac{\Sigma_{(ij)\in P} W_i w_{ij}\, max\{0, \gamma - \hat{s}_{ij}(t)\}}{\Sigma_{[ij]\in P} W_j w_{ij}} \tag{9}$$

This is complemented by the analysis of partial contributions:

$$c_{ii}(t) = W_i w_{ij} \hat{s}_{ij}(t) \tag{10}$$

which allows for assessing the concentration of the result. By calculating the share of the largest components (e.g., Top-5), it is possible to determine whether a tool achieves a high score due to a balanced fulfillment of multiple criteria or due to very strong performance in a limited set of functionalities.

For a complete assessment, the minimum realization within priority criteria is also analyzed:

$$\left(MinP(t) = min_{(ij)\in p} \hat{S}_{ii}(t)\right) \tag{11}$$

in order to identify the weakest element within the most important areas.

The application of the set of indicators F(t), PSI(t), MHC(t), PG(t), MinP(t), and B(t) enables the evaluation of both the overall quality of CAx tools and their compliance with strategic and priority requirements, reducing the risk of favoring solutions that meet only a narrow range of functionalities.

Table 3.
Evaluation of the Functional Fit of CAx Tools to the Adopted Criteria and Sub-Criteria

	N4	**N14**	**N8**	**N9**	**N5**	**N16**	**N7**	**N15**	**N2**
F(t)	0.39	0.20	0.37	0.37	0.39	0.20	0.38	0.20	0.46
PSI(t)	0.17	0.08	0.17	0.17	0.17	0.08	0.17	0.08	0.20
MHC(t)	0	0	0	0	0	0	0	0	0
PG(t)	0.52	0.60	0.52	0.52	0.52	0.60	0.52	0.60	0.52
MinP(t)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B(*t*)=1−*Top5%*(*t*)	0.37	0.17	0.33	0.33	0.37	0.17	0.36	0.17	0.32
	N12	**N1**	**N11**	**N3**	**N13**	**N6**	**N18**	**N17**	**N10**
F(t)	0.30	0.46	0.30	0.45	0.23	0.39	0.19	0.20	0.34
PSI(t)	0.11	0.20	0.11	0.20	0.08	0.17	0.08	0.08	0.14
MHC(t)	0	0	0	0	0	0	0	0	0
PG(t)	0.57	0.52	0.57	0.52	0.60	0.52	0.60	0.60	0.54
MinP(t)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B(*t*)=1−*Top5%*(*t*)	0.35	0.32	0.35	0.32	0.22	0.37	0.12	0.17	0.41

Source: Own elaboration.

For the analyzed design office in the furniture industry, the acceptance threshold was set to $\gamma = 0{,}65$, the set of critical criteria was defined as M = {Z12, Z14, Z20, Z22, Z23, Z32, Z33}, and the set of priority sub-criteria as P = {Z11, Z13, Z15, Z21, Z27, Z30, Z31, Z34, Z37, Z38, Z40, Z41}. The results of the functional fit evaluation of CAx tools are presented in Table 3.

2.2.5. Selection of the Best Tool

To avoid a situation in which the decision-maker is required to interpret several separate numerical values, a complementary selection procedure was proposed, incorporating both elimination mechanisms and the aggregation of indicators into a single meta-evaluation.

In the first stage of the procedure, simple rejection rules are applied. If a tool does not meet the must-have requirements, i.e., $MHC(t) = 0$, it is eliminated from further analysis.

In the second stage, the indicators are divided into two groups. Group A includes decisive measures, namely $PSI(t)$, $MinP(t)$, and $1-PG(t)$, i.e., those directly related to priority requirements. Group B includes supporting indicators: $F(t)$, $B(t)$, reflecting the overall quality and functional balance.

Within each group, a partial score is calculated as a weighted average of its components:

$$U_{A(t)} = \alpha_1 PSI(t) + \alpha_2 MinP(t) + \alpha_3[1-PG(t)], \sum \alpha_k = 1, \quad (12)$$

$$U_{B(t)} = \beta_1 F(t) + \beta_2 B(t), \sum \beta_k = 1. \quad (13)$$

Next, both groups are combined into a single final evaluation using the parameter $\lambda \in [0,1]$, which reflects the relative importance assigned to priorities:

$$U(t) = \lambda U_A(t) + (1-\lambda) U_B(t). \quad (14)$$

For greater flexibility, the evaluation may be further modified by penalty functions for not meeting threshold values, for example:

$$U^{\star}(t) = U(t) \cdot min\left(1, \frac{Psi(t)}{\tau_P si}\right) \cdot min\left[1, \frac{n_1 n_^{P(t)}}{\tau x}\right] \quad (15)$$

The resulting final value $U^{\star}(t)$ enables the creation of a ranking of alternative tools or tool sets, taking into account both overall performance and the fulfillment of key criteria. This approach reduces the risk of the "average trap", as elimination and penalty mechanisms prevent results from being artificially inflated by less important aspects.

To select the best CAx tool, it is also necessary to define the algorithm parameters. In this case, the following input data were adopted:

1. thresholds: 1) $MHC(t) = 0$, elimination of the CAx tool; 2) $\tau PSI = 0.65$ (i.e. $PSI(t) \geq 0.65$); 3) $\tau min = 0.25$ (i.e. $MinP(t) \geq 0.25$),
2. weights within groups: 1) group A: $U_A(t) = 0.4 \cdot PSI(t) + 0.3 \cdot MinP(t) + 0.3 \cdot [1 - PG(t)]$; 2) group B: $U_B(t) = 0.6 \cdot F(t) + 0.4 \cdot B(t)$,
3. aggregation parameter: $\lambda = 0.65$: $U(t) = 0.65 \cdot UA(t) + 0.35 \cdot UB(t)$,
4. penalty function: $U\backslash^*(t) = U(t) \cdot \min(1, PSI/\tau PSI) \cdot \min(1, MinP/\tau min)$.

Table 4 presents the results and ranking of the CAx tools.

The analyzed case represents a relatively specific situation, as the decision-maker defined a large set of must-have and should-have requirements, resulting in three alternative solutions. Consequently, none of the CAx tools achieved $MHC(t) = 1$ and $U^*(t) > 0$. In such a case, to enable the selection of the best solution, it is recommended to base the ranking on the values of $U(t)$.

Table 4.
Ranking of CAx Tools for Selection in a Design Office in the Furniture Industry

Ranking [U(t)]	Tool (symbol from Table 3)	UA(t)	UB(t)	U(t)
1	ErgoReality (VR CAE) **(N1)**	0,23	0,40	0,29
2	Siemens Tecnomatix Jack **(N2)**	0,23	0,40	0,29
3	DELMIA **(N3)**	0,23	0,40	0,29
4	SolidWorks + HumanCAD-MQSW **(N4)**	0,21	0,38	0,27
5	Siemens NX / Tecnomatix (Process Simulate X Human) **(N5)**	0,21	0,38	0,27
6	Navisworks + TechViz **(N6)**	0,21	0,38	0,27
7	CATIA **(N7)**	0,21	0,37	0,27
8	SolidWorks + BodyWorks 2000 **(N8)**	0,21	0,35	0,26
9	PTC Creo + Human Factors Extension / Analysis Extension **(N9)**	0,21	0,35	0,26
10	Immersive VR design reviews (VR+Navisworks) **(N10)**	0,20	0,37	0,25
11	Parametric biomechanical CAD simulation **(N11)**	0,17	0,32	0,22
12	Ansys + Humanetics RAMSIS **(N12)**	0,17	0,32	0,22
13	Revit **(N13)**	0,15	0,22	0,18
14	SolidWorks + Zygote Human Factors **(N14)**	0,15	0,19	0,17
15	Ansys LS-DYNA + Hans HBM **(N15)**	0,15	0,19	0,17
16	SketchUp **(N16)**	0,15	0,19	0,17
17	IrisVR / The Wild (with BIM support) **(N17)**	0,15	0,19	0,17
18	BCF / Revit Families / RD Studio **(N18)**	0,15	0,16	0,16

Source: Own elaboration.

2.2.6. Prediction of Problems Using FCM

At this stage, potential problems related to the implementation and use of the selected CAx tool or tool set are identified using decision scenarios, a database of variables and relationships, and simulation techniques. Problem prediction complements the evaluation and selection procedure, enabling the analysis of solution behavior under conditions of uncertainty and variability in the design environment.

The analysis is based on an FCM model, in which nodes represent decision variables and edges represent cause–effect relationships with defined strength and direction. The model reflects the logic of the decision system and allows the effects of changes in its elements to be examined through simulation.

This enables the identification of critical points, the evaluation of alternative scenarios, the prediction of side effects of decisions, and the analysis of trade-offs and synergies between strategic and operational criteria.

The integration of FCM into the method supports decision-makers under conditions of uncertainty by indicating areas of increased risk and possible directions for adapting the tool environment.

2.2.7. Development of a Plan for Further Evaluation and Updating

In the final stage of the method, the implementation of KPI-based evaluation is assumed, referring to strategic and operational objectives and enabling systematic monitoring of the effectiveness of the applied CAx tools in practice.

The plan for further evaluation and updating performs both control and adaptive functions, allowing results to be compared with organizational goals, critical points to be identified, and the design environment to be adjusted to changing technological and market conditions.

The process is cyclical and includes the collection of empirical data, evaluation of goal achievement based on KPIs, updating of decision criteria and weights, and re-evaluation of tool fit. On this basis, it becomes possible to introduce adjustments, including the modification or replacement of CAx tools and the expansion of the design environment.

The implementation of this plan ensures that the method is iterative and remains consistent with the long-term development strategy of the organization, providing continuity of the decision-making process and flexibility under dynamic conditions.

3. Conclusions

The aim of this paper was to develop an algorithmic method for supporting the selection of CAx tools for ergonomic design at the stage of establishing a design practice. This objective was achieved by proposing a multi-stage decision-making algorithm integrating the identification and ranking of criteria (Fuzzy AHP), the evaluation of the functional fit of CAx tools, and a selection procedure based on the aggregation of indicators. The method was illustrated using a realistic implementation scenario of a small design office in the furniture industry.

The simulation results indicate that under conditions of high decision uncertainty and organizational constraints typical of newly established design offices, none of the analyzed CAx tools fully satisfies all critical criteria. This confirms the usefulness of the proposed method, which enables the identification of compromise solutions and supports informed decision-making even when must-have conditions are not fully met. The ranking based on the U(t) indicator identified VR and CAE environments, including ErgoReality, Siemens Tecnomatix Jack, and DELMIA, as relatively best suited to the analyzed decision context.

The obtained results are consistent with literature and industry sources indicating increasing interest in VR and CAE tools in furniture design, particularly in the SME sector, due to their potential for early ergonomic evaluation, reduction of prototyping costs, and support of design communication (Wolfartsberger, 2019; Vlah, Čok, Urbas, 2021; Kačerová et al., 2022; Praj et al., 2023). At the same time, studies emphasize that VR tools are currently used primarily as a complement to traditional CAD and CAE systems rather than as their full replacement (Berg, Vance, 2017; Horvat et al., 2019; Wolfartsberger, 2019).

From a practical perspective, the proposed method may support decision-makers in SMEs by reducing the risk of arbitrary tool selection and supporting the rational planning of CAx environment development. The originality of the paper lies in combining an algorithmic

approach with decision-support methods (FAHP, FCM) and ergonomic design in the context of establishing a design practice.

The obtained results also allow for a direct reference to the research questions formulated in the paper. The analysis demonstrates that the selection of CAx tools in a newly established design office requires consideration of both organizational conditions and the scope of engineering and ergonomic functionalities supporting the design of human–machine–environment systems. The proposed decision-making algorithm integrating Fuzzy AHP and relational analysis elements enables the structuring of the decision-making process and increases its transparency under conditions of high uncertainty.

However, several limitations of the study should also be noted. The presented application of the method is based on a single implementation scenario and on expert-based evaluations of CAx tool functionality. Therefore, further research should include empirical validation of the method in real design organizations, extension of the analysis to other industries, and further development of the decision variable relationship model, including the use of FCM-based simulations.

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