Modeling decision making in cognitive architectures

Heuristic-based, Utility-based and Hybrid Strategies

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Abstract

This study is a systematic literature review that was conducted to investigate and further explain how different decision making strategies are implemented through heuristics-based, utility-based approaches, or how different blends of these approaches are created to make hybrid decision making models that excel in their domain. Following the identification, screening and the analysis procedures of the systematic literature review, relevant literature works were found. After close analysis of the relevant works, it was evident that introducing a heuristic-based approach on top of a utility-based approach was beneficial for a robust decision making process, and vice versa. However, it was also identified that the trade off of hybridization comes with a cost of specialization for the niche domain the implementation is tasked to work in.

1 Introduction

Human decision making is performed by evaluating options based on experience, rules, or goals. [14] Cognitive architectures like ACT-R and SOAR have been used to simulate everything from air traffic control decisions to playing chess, mimicking human thought so precisely that they can even model the time it takes for a person to respond to a traffic light. As the technology develops, understanding human decision making processes and strategies on a deeper level gets more crucial in artificial intelligence and computational modeling. This applies to modeling decision strategies such as systems that aim to replicate realistic thinking and reasoning.

A cognitive architecture is a blueprint that outlines the fixed structures and interactions within cognitive systems, aiming to achieve functions of the mind by embodying knowledge that drives intelligent behavior. [2]. Within these architectures, decision-making strategies such as heuristics-based and utility-based reasoning are used to simulate how people simplify choices, follow structured guidelines, or evaluate outcomes based on evaluating advantages versus disadvantages. To this end, hybrid decision making strategies were also created. Each strategy represents a different side of the human mind, and their integration into cognitive architectures allows for more accurate and adaptive models of how humans behave.

Heuristics-based reasoning and utility-based reasoning, are modeled in various implementations that utilize cognitive architectures. This study was conducted to investigate and explain how different decision-making strategies are implemented through heuristics-based, utility-based, or hybrid approaches. The aim of this study is to answer the research question **"How do heuristic-based, utility-based, and hybrid decision making strategies modeled in implementations that utilize cognitive architectures affect the capabilities of decision making models?"** by closely studying relevant literature, using the methodology of systematic literature review. This research question entails the sub-questions as follows:

- How do heuristic-based and utility-based decision making strategies improve the capabilities of decision making models?
- How does the hybridization of the strategy improve the capabilities of decision making models?

This study is presented in a conventional fashion, where the next section introduces background information and necessary details on the methodology of this literature review. Section 3 presents the analysis of the relevant found works in the literature in accordance with the described methodology, with each strategy type is presented in a different subsection. Section 4 presents a discussion of the presented works, and aims to answer the research question by closely analyzing the relevant works in section 3. Section 5 presents the methods used to ensure the responsible research principles. Finally, Section 6 presents the conclusions, along with the suggestions of possible future work in this subject.

2 Background Information & Methodology

Decision making is a very important part in the implementations using cognitive architectures, acting as the mechanism by which systems select actions. These cognitive architectures aim to simulate the human cognition processes by integrating multiple strategies for decisions that require control and choice. [11] These strategies entail different categories of approaches to decision making systems, which can be described as following:

- Utility-based models calculate the expected value of different actions to support adaptive and goal-directed responses. These models can foresee the outcome of each individual action separately and is very effective in guessing outcomes, yet require heavy computation that entail to longer operation times.
- Heuristic-based strategies offer fast, experience-based judgments, often at the expense of optimality, while rule-based systems rely on predefined if-then structures to ensure consistent and interpretable behavior. In situations where exhaustive analysis of the current situation is not feasible, implementations of these approaches can pay off in terms of successful decisions.
- Hybrid strategies are also adopted, utilizing trade-offs between utility-based strategies and heuristic-based strategies. These approaches use both utility-based and heuristic-based decision making modeling, in order to create models that excel in decision making problems in their domain.

2.1 Systematic Literature Review Methodology

The methodology used for this study is systematic literature review. To ensure the transparency and reproducibility, PRISMA framework is used in collecting resources which entails Identification, Filtering (Inclusion/Exclusion) and Analysis of the relevant literature works studied. Figure 1 illustrates the workflow for this study, including details on how many records were used in each step.

The methodology adopted for this systematic literature review is outlined as follows:

Identification: To locate relevant academic works, the academic databases Scopus, IEEE Xplore, ACM Digital Library, and Google Scholar were used. An example of one of the exact search terms used is as following for the database **IEEE Xplore:**

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"cognitive AND architecture AND ( heuristic* OR utility-based OR
rule-based ) AND decision AND making"
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Consequently, the type of documents were filtered down to conferences and journals to increase credibility. Only the literature of last 10 years, starting from 2015 to 2025, were used to ensure only the works of highest relevance are studied. The search terms and filters were applied exactly as described with all of the keywords and filtering applied in all of the searches in the databases used.

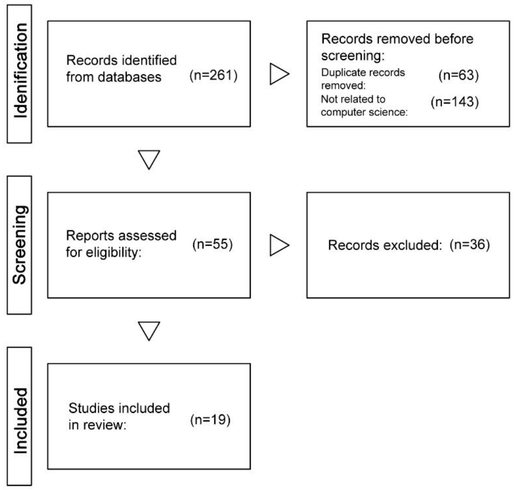

Figure 1: The PRISMA workflow used in the systematic literature review

Inclusion/Exclusion criteria: Studies were selected if they focused on decision making and cognitive architectures, or offered concrete examples of such strategies in practice. Studies were then selected with respect to their relevance Sources that were not peer-reviewed was excluded.

Analysis: The remaining literature was analyzed to extract meaningful insights. Key aspects were organized to collect details on decision-making approaches. How these decision-making approaches are implemented are explained in sufficient detail and implementations are analyzed consequently.

3 Analysis

This section presents studies that have found to be relevant as described in the previous section after a full text screening. The following subsections present three different kinds of strategy in decision making. The first subsection presents implementations that use utility-based approaches in their decision making, whereas the second subsection is about implementations that leverage heuristic-based approaches. The third subsection is based on implementations that utilize both approaches to some extent to create a hybrid model, in order to optimize decision making capabilities of the model.

3.1 Utility-Based Approaches

This subsection contains the literature that focus on utility-based approaches in their implementations mostly if not fully, or leverages utility-based approaches to optimize their decision-making.

Utility-based decision-making within cognitive architectures can be explained as optimal or nearly optimal decisions by quantitatively assessing outcomes to maximize overall system performance. Simply, it focuses on the best result and compares the options by using scores. Last implementations mention that it is effective to integrate utility based methodologies within cognitive systems, especially reinforcement learning approaches where systems learn by trial and error to improve decisions over time.

Zhou et al. (2025) examines a utility driven approach by offering hybrid lane changing strategy for autonomous vehicles, integrating the SOAR cognitive architecture with deep reinforcement learning (DRL). The utility driven approach can be seen in Figure 2, where the computation-based model is introduced alongside the cognitive architecture to optimize decision making. Article claims that employing DRL enhances the model's adaptability and making decision efficacy in dynamic environments since it improves training by taking into account the importance of data samples and states, "the ACPPO algorithm adopts different clipping strategies for SOAR samples and ACPPO samples during the training process, enabling the algorithm to more effectively utilize samples with different levels of importance" [16]. This adaptive mechanism significantly boosts learning efficiency, demonstrating a clear utility-based orientation toward optimizing lane-changing maneuvers, meaning deciding on the best possible time to change lanes for safety and efficiency. They conducted an experiment using CARLA simulator comparing the hybrid approach meaning utility based and traditional DRL method to an only DRL method, the hybrid algorithm visibly improved driving performance, particularly in different levels of traffic scenarios which is the most complex one, and showed advancements in interpretation and human like decision patterns compared to traditional DRL methods.

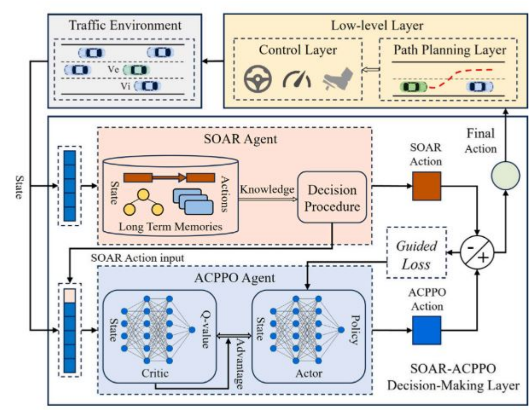

Figure 2: The architecture used in the implementation, introducing ACPPO Agent that is utility-driven alongside the SOAR architecture [16]

Similar to that, **Thome et al. (2015)** also integrate utility approach into hybrid path planning system that leverages the SOAR cognitive architecture to handle robust navigation tasks such as helping a robot or an agent to perform reliably. Cognitive architecture is benefited in decision process creating a "sufficiently populated decision space, from which the path planning solution is derived," so it optimizes paths from different scenarios across multiple complex metrics such as risk, smoothness, and path length [12]. Their approach utilizes a decision space that maximizes overall utility, considering multiple conflicting criteria simultaneously like different goals such as safety and speed. The method of this study involves refining decision space through cognitive utilities, enabling effective path selection meaning optimizing safety, speed and road length even under uncertain and dynamic environmental conditions, improving navigation robustness so making it reliable.

Another example is **Karagoz and Mavris (2019)** who reinforce utility-based strategies through a utility-driven, Rule Based System (RBS) tailored for conceptual aircraft design. RBS incorporates quantitative assessments of design variables, guiding engineers systematically toward the optimal configuration to evaluate design factors for the best setup. Instead of relying on intuition or heuristics, their model filters design alternatives based on whether they meet predefined aerodynamic and propulsion criteria such as thrust-to-weight ratio and wing loading. Authors claim that system efficiently navigates the "space of possible actions following a path from the current state to the desired state," optimizing aircraft performance within specified constraints [6]. This methodical, utility based assessment highlights how effective it is to use clear quantitative goals in complex design procedures. Their approach provides a structured methodology for decomposing complex design problems into manageable subproblems, each quantitatively assessed against performance requirements, ultimately facilitating an effective solution space determination. Though not explicitly ranking alternatives with a utility score, the architecture effectively models utility-based reasoning by constraining the solution space to quantitatively justifiable options.

Finally, all of these research show that utility based cognitive architectures have a lot to offer for the optimization, especially when combined with reinforcement learning techniques. For example, lane changing strategy for autonomous vehicles, path planning system. Utility based techniques' quantitative evaluation and adaptive nature guarantee better performance in challenging, dynamic tasks, underscoring their crucial role in improving cognitive decision-making in autonomous systems.

3.2 Heuristic-Based Approaches

This subsection presents literature that leverages heuristic-based approaches in their implementations mostly if not fully, or they utilize the heuristic-based approach for enhanced optimization. Heuristic techniques have taken center stage in the development of cognitive architectures in applications where quick, human-like decision making is crucial. Instead of using utility-based optimization strategies, these systems primarily rely on intuitive, rule-based procedures. It can also be said that these procedures are problem solution approaches that, rather than using comprehensive, exact solutions, quickly determine sufficient ones by using realistic shortcuts or reduced methodologies.

Mashkova et al. (2018) exhibit heuristic methodologies and applications in Plan Image which is their cognitive architecture and it is inspired from Test-Operate-Test-Exit (TOTE) cognitive model. This model presents a search algorithm with heuristic features in focus. Heuristic strategy taking place in Plan Image can be explained as "Plan corresponds to the algorithm that determines its behavior in the environment," enabling agents to carry out search tasks efficiently even when given insufficient or inaccurate information [8]. The reliability of heuristic approaches in position which require a certain choice when including partial information is tested. As a result, heuristic-based search algorithms enabled agents to quickly and effectively locate objects on a grid, proving its practicality as well as robustness in the experiment conducted in this study.

In addition, **Luo et al. (2022)** use heuristic techniques with the Soar-based cognitive architecture for mobile robot space exploration. The figure 3 illustrates how the SOAR cognitive architecture is used with a heuristics-based decision making strategy, making the decision making faster on the input from the surroundings. Luo et al. accents that heuristic algorithms notably accelerated the exploration speed by stating that "three space exploration heuristic algorithms (HAs) are further proposed based on the model to improve the exploration speed of the robot," which resulted in an exploration rate that was more than double of traditional methods [7]. This demonstrates the benefit of using heuristics to quickly adjust to changes in the environment without requiring a lot of computer power.

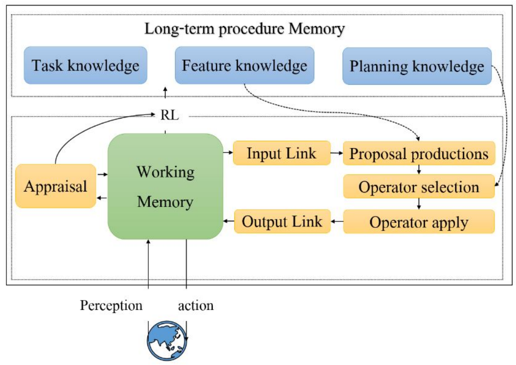

Figure 3: The SOAR based architecture of the decision making model, reactive to the heuristics detected from the environment [7]

Budaev et al. (2018) suggest Adapted Heuristics and Architecture (AHA), cognitive framework based on rules and strongly embedded in neurobiological processes. According to them, the core of this architecture is heuristic survival circuits, which combine various perceptual inputs into logical internal states and facilitate "adaptive decision making and naturalistic behavior in the model environment" [1]. This example also supports heuristic mechanisms by proving that AHA architecture exhibits high adaptability and efficiency in evolutionary cases by using simple and heuristic plausible mechanisms.

Another study that utilizes heuristic-based strategies is **Zamprogno et al. (2023)** using this kind of approach in their Cognitive Tangram Solver (CTS), which is anchored in the ACT-R cognitive architecture. In sequential problem-solving activities like Tangram puzzles, they specifically promote cognitive principles, which can be interpreted as "heuristics that guide human decisions," allowing for anticipation and adaptation [15]. As a result, it improves the efficiency and dependability of problem-solving in real-time by enabling dynamic alterations in decision-making processes.

As a last example, **Ivanov et al. (2015)** portray multi-agent recursive cognitive architecture (MuRCA), to point out the context in ambient systems of intelligence dynamically which means it must identify, understand and adapt even though the conditions are not stable. The usage of heuristic methods is simple, has practical rules and shortcuts visible lessen "the time of logical context formation of the situation due to the automatic synthesis of a series of heuristics" [3]. The automatic generation contributes to responsiveness and effectiveness of making decisions in distributed environments like the ones in assisted living applications (elderly or disabled individuals) because the system is able to give the required immediate response even though multiple systems or devices operate simultaneously.

To sum it up, the studies which are explained above underscore the advantages and how effective heuristic strategies are in cognitive architectures. It has efficient, intuitive, and adaptive characteristics and it ensures a broad applicability in dynamic environments such as assisted living, tangram puzzles, survival circuits, mobile robot space exploration and Plan Image. That is why it reinforces a vital role in enhancing cognitive system capabilities.

3.3 Hybrid Approaches

Recent developments in implementations utilizing cognitive architectures have blended different decision-making strategies, using heuristic-based methods as well as utility-based methods to advance in adaptability, robustness, and effectiveness in dynamic environments. These studies have presented implementations with decision making strategies that are a mix of rule-based heuristics with utility-based, computationally heavy mechanisms, aiming to master their tasks at hand by using mixed approaches in their cognitive architectures.

Vilchis-Medina et al. (2021) also create a hybrid strategy by integrating heuristic-based Non-Monotonic Reasoning (NMR) with utility driven planning in autonomous marine robots. The designed system aims to complete uncertain information by heuristic defaults thus contributing to robust decision making process in ambiguous situations: "default logic allows defining a default behavior, specialized by specific rules depending on encountered situations" [13]. Figure 4 briefly illustrates how the heuristic layer works with the utility layer, and how the hybrid strategy works with the functional layer. When combined with automated, utility-based planning procedures, this explicitly heuristic reasoning handles challenging real-world applications.

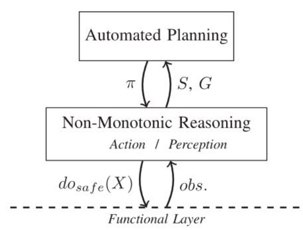

Figure 4: Illustration of the hybrid strategy used by the implementation [5]

Likewise, **Jafari et al. (2023)** put forward a hybrid approach in their Cognitive Hybrid Autonomous Motion Planner (CHAMP), particularly designed for autonomous vehicles. CHAMP combines a hierarchical rule-based system with Reinforcement Learning (RL) to address certain calculated driving scenarios, most especially unprotected left turns at intersections under troubled traffic conditions. It is argued that "the RL agents are integrated into a logical planner using a cognitive architecture to address challenging unprotected left turn maneuvers at T and 4-way intersections under congested and chaotic traffic conditions" [4]. This approach points out the complication effectively compared to purely heuristic or purely computationally based methods.

Aligned with this idea, **Panilov and Tsibizova (2025)** stress the significance of merging swarm intelligence which is inherently heuristic with cognitive models that include RL to further improve the performance on decision-making. They design a Cognitive Swarm-Based Control System (CSBCS), indicating it "integrates cognitive models that simulate human-like thinking, enabling individual agents within the swarm to operate autonomously, collaborate effectively, and adapt to changing conditions without centralized oversight" [9]. This method proves the importance of mixed strategies by improving the performance as well as the adaptability in decentralized scenarios.

Papaioannou et al. (2024) promote a cognitive controller designed to overcome possible disaster scenarios which is inspired from Dual Process Theory. As can be seen in Figure 5 It emphasizes "synergistic integration" of rapid heuristic responses (System 1) and analytical optimization (System 2), claiming that the framework is arranged to optimize dynamic shifts to react in uncertain or rapidly evolving situations [10]. This architecture depicts how cognitive systems are able to stabilize swift intuitive actions with precise computational decision-making.

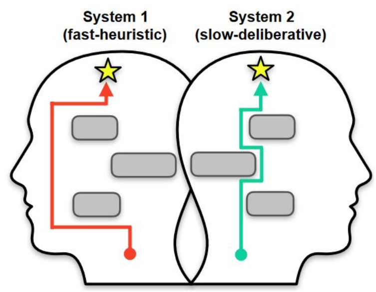

Figure 5: The two systems working together in human-like cognition [10]

Furthermore, **K et al. (2024)** state that "Agentic AI," which merges RL and cognitive frameworks like ACT-R and Soar, allowing off on point reasoning and proactive behaviour As stated in the study, blending together cognitive architectures and RL results in "adaptive systems can adjust their strategies based on changing environmental conditions," [5] which is why the implementation in the study is providing robust solutions for multilayered real world problems, including autonomous driving and financial markets. The capacity of executing heuristic-based reasoning combined with utility-based learning from previous experiences makes the Agentic AI competent towards its given tasks.

4 Discussion

This section entails the discussion of the studies presented in the previous section, and provides further evaluation, on how utility-based and heuristic-based decision making strategies impact decision making capabilities of the models implemented in the studies.

In the study of **Zhou et al. (2025)**, it is evident that introducing the utility-based approach to an already existing cognitive architecture is beneficial when optimized correctly. In this study, it is presented that the perspective of a utility-based approach is beneficial for the optimization of the capabilities of the decision making in the model. This, along with the other studies presented clearly shows that utility-based approach is a very prominent approach in decision making modeling.

As for the heuristic-based strategies in decision making models, the study of **Luo et al. (2022)** underlines the importance of focusing on the heuristic-based strategy for the decision making in their implementation, stating that it has improved the performance of their model drastically. Likewise, **Zamprogno et al. (2023)** solidify the fact that introducing heuristic-based decision making strategies in their model has increased the performance of their model, and also gained robustness in terms of mimicking human thinking, as stated by their study. [15] Consequently, these presented studies evidently present that heuristic-based strategies are useful for the decision making process, when optimized correctly.

The hybridization of the decision making strategy is evident to be successful in the relevant literature works presented. In the works of **Jafari et al (2023)**, a hybrid approach of utility-based reinforcement learning and a heuristic-based rule system was implemented successfully. In this study, it is evident that the implementation is highly successful as it boasts the strengths of both utility and heuistics-based approaches. However, it can also be observed that the domain that this implementation excels is very narrow, namely only T and 4-way intersections with no stop signs. In the works of **Vilchis-Medina et al. (2021)**, the hybrid approach can again be observed clearly, with the approach of adding "heuristic defaults" to normal utility-based decision making. [13] This approach has again increased the robustness of the decision making process in the implementation, but, it is also evident that the domain that the model excels in is very narrow, namely autonomous marine robotics.

In the light of these insights, it is evident that even though the hybridization of the decision making strategy is clearly increasing the robustness and accuracy of the decision making process, such an hybridization often require extreme specialization to niche domains. This demonstrates that hybridization in the decision making strategy is often coming with a trade off of decreased generalization. Consequently, the introduction of a heuristic-based strategy on an already existing utility-based strategy, or vice versa, is evidently increasing robustness for the specified domain. Clearly, the trade off that the generalization of the implementation decreases is not of the highest concern in these studies as the goal is to optimize the performance, so it is observed that the decision making models are benefiting from the blending of different approaches.

5 Responsible Research

Responsible research principles were obligated while surveying the literature on this research. Such as avoiding plagiarism, reliability of sources, sharing the methods openly and using robust methods. All studies and information which inspired the paper are cited and referenced according to the BibTex scheme which can be found at the end of the paper. The included literature consists of credible sources such as articles and conference papers. To respect authorship, credits were given to the authors. To show robust methods and ensure transparency, reviews of literature were made systematically in accordance with the PRISMA workflow framework. Details of methodology in reviewing literature is found in Section 2.1, where the workflow is explained thoroughly.

6 Conclusion

This section presents the conclusions drawn from the found literary works, along with suggestions and insights for future work. This systematic literature review was conducted to investigate and explain how different decision-making strategies are implemented through heuristics-based, utility-based approaches, or how different blends of these approaches can be created to make hybrid models that maximize the performance. After analyzing the relevant found literature, it was concluded that even though utility-based and heuristic-based approaches have their own strengths, implementations that leverage a hybrid approach are more capable in decision making. However, this comes with a trade-off of the model being limited to its own niche domain that it is tuned for, such as the CHAMP model that excels in decision making in "unprotected left turn maneuvers intersections" [4], meaning these models become less general the more hybridized the decision making strategy is. Keeping this trade-off in mind, it is evident that hybridized approaches are creating more effective and robust solutions to decision making situations, and boosts decision making capabilities.

6.1 Future Work

It is evident that there is currently not a better solution to creating a hybridized decision making strategy other than creating niche models that excel in their own domain. However, with the recent developments in technology and computation, utility-based models that require heavy computation to ensure constraints can be developed to execute faster. This can be leveraged to further optimize decision making strategies in future implementations. This was also stated by **Papaioannou et al. (2024)** which supports that there are two aspects of decision making, where the utility-based decision making is described as "slow, deliberative." [10] With developments in computation technology and faster computing speeds reached every day, the utility-based implementations can be expected to be more prominent as a decision making strategy.

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