Perspective of MAS in Power System via a Fuzzy Framework

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Abstract: Multi agent systems (MAS) are popularly used in practice, however; a few studies have looked at MAS capabilities from the power engineering perspective. This paper presents the results of an investigation concerning the compatibility of MAS capabilities in different power engineering categories. Five MAS capabilities and seven power system categories are established. A framework for applying MAS in power engineering is developed. A fuzzy inference system is adopted to evaluate the paper proposed framework. Two approaches, namely simulation and real, are considered for different power categories. The paper shows that MAS capabilities are generally compatible with both approaches, although compatibility of MAS with real approach is more significant. The paper concludes that in the near future MAS is anticipated to be a key important tool in the development of intelligent systems and smart grids in power system. This paper contributes to thinking on perspective of MAS in power System.

Keywords: multi agent systems; power system; fuzzy assessment

1. Introduction

Today multi agent systems, as a distributed artificial intelligence (DAI) method, are popularly used in power engineering disciplines, such as power system modeling and simulation [1], generation expansion planning [2], network management [3], smart grid operation [4], electricity market [5], substation automation [6], restoration [7], reconfiguration [8], load shedding [9], monitoring and diagnostic [10], power system control [11] and protection [12]. Despite this popularity, few studies have looked at MAS capabilities from the lens of power engineers. A number of researchers have discussed MAS in the power engineering literature. However, only limited in-depth analysis has been undertaken in order to provide practitioners with an appropriate use of MAS in power system. States of the art of MAS from the power engineering perspective coupled with an advanced taxonomy in power engineering were provided by the authors in [13]. The research of [14] argues key terminology and concepts associated with multi-agent systems. It also argues the MAS important contributions to power system. Some guidance and recommendations are given in [15] concerning MAS design and implementation in power system. In the same vein, [16] and [17] argue different concepts and approaches of multi-agent systems in power system. Also, some theoretical and practical benefits of multi-agent systems are discussed in [18].

Despite an extensive body of publications on MAS, few studies have examined issues, such as MAS compatibility with power system categories or the way of MAS design tailored to power system categories. No literature appears to have focused on the compatibility of MAS capabilities in power system. Addresses this gap in the knowledge the authors have reviewed MAS applications from the lens of power engineering in [13] and in continue, the results of an investigation concerning the compatibility of MAS capabilities in different power system categories are presented in this paper. For achieving this purpose, a framework for applying MAS in power engineering is developed in three steps: i) illustrating MAS capability compatibility with its operation phase, ii) establishing MAS operation phase compatibility with power system categorizes and iii) evaluating MAS compatibilities with different power system categories. A fuzzy inference system is adopted to evaluate the paper proposed framework.

The paper will be relevant to academics and practitioners interested in applying MAS to power system. It presents a guideline for design of MAS in power engineering categories which demonstrates for designer which capa-

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bilities of MAS are more important in each category of power system studies and therefore which challenges should be overcome at the MAS design process. It provides an understanding of the design of MAS within power system, broader than currently available.

The order of presentation in this paper is as follows. Firstly, background on multi agent systems is given. Then applications of MAS in power engineering are discussed. This is followed by developing a fuzzy inference system to evaluate MAS compatibility with different power system categories. Finally, discussion and results are provided.

2. Background on multi agent systems

In the following, some definitions, capabilities and operation of MAS are briefly outlined.

2. 1. Definition

In this paper, the term agent is defined in the sense of [19] as "a computer system that is situated in some environment, and is capable of autonomous action in this environment in order to meet its design objectives". A multi-agent system (MAS) refers to a collection of agents interacting and negotiating with each other within the same environment to solve an overall problem [18] and [20]. In a multi agent system, the overall goal is divided to some local goals for each agent [14] and the system data are decentralized so that agents have incomplete information and the agents are not able to solve the problem alone [21]. The term environment refers to what external to the agent. Environment, which might be physical and non-physical, should be partially or fully observed and altered by the agent. Physical environment (e.g. distribution networks) can be observed by sensors while non-physical environment, also referred to as computing environment, (e.g. data sources or computing resources) can be observed by system calls, program invocation, and messaging. Environment might be altered by agent actions, physically or non-physically, such as closing a normally-open point to reconfigure a network or storing diagnostic information in a database for other agents [14].

Typically, agents are distinguished from similar hardware or software systems based on their intelligence and flexibility [14]. Characteristics, such as reactivity, pro-activeness and social ability are central in intelligent agents in order to satisfy their design objectives [19], [22].

2. 2. MAS Capabilities

A number of capabilities for MAS have been discussed in the relevant studies [14], [18], [20] and [21]. Following such studies, five main capabilities for MAS are considered in [13], as shown in Figure 1. These capabilities are: dealing with large and complex problems, modularity and cooperation, intelligence and autonomy, handling distributed sources of data and expertise, and extendibility and flexibility.

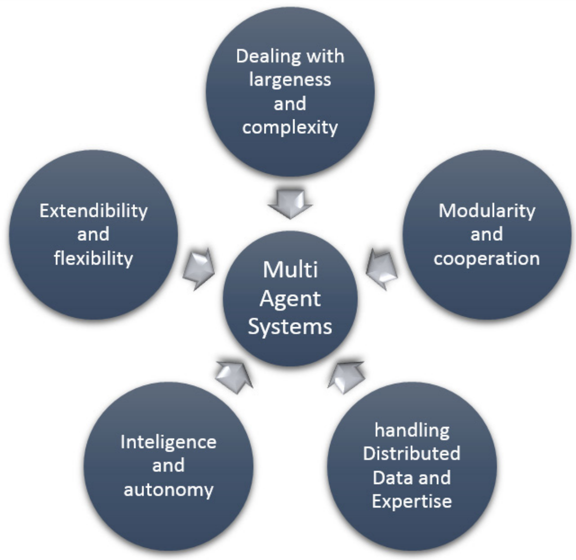

Fig. 1. Capabilities of multi agent systems

2. 3. MAS Operation

Operation of multi agent systems might be considered in three phases, namely: perception (or data acquisition), reasoning (or decision making), and action, as shown in Figure 2. In the perception phase, the required data is obtained, either by considering some assumptions (predicting future) or by monitoring real exercises (gathering real data), while in the reasoning phase, the decision making process is conducted, either offline or online. In the action phase, agents affect the environment physically (hardware actions) or non-physically (software actions).

3. Power engineering categories

Different categories might be attached to power engineering studies so that MAS can be applied. In this paper, seven categories are studied by focusing on the time frame

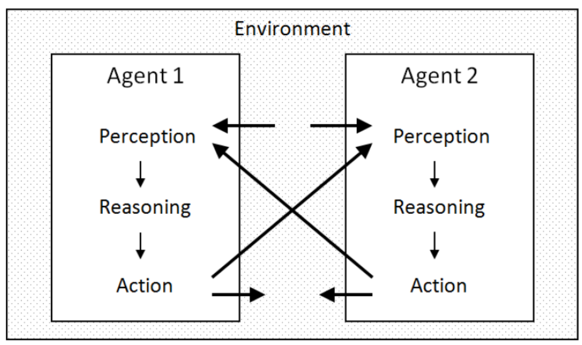

Fig. 2. Operation of MAS and interactions of agents [22]

of the power study problems and considering MAS applications [13] as discussed below.

Expansion planning: This refers to studies concerning the plan of power system expansion in medium or long time horizon.

Electricity market: This refers to studies dealing with simulation and prediction of electrical market actors' reaction from the financial and economy perspective.

Management: This refers to studies concerning the management of technical and economic conditions of the network in the near future, such as generation scheduling, optimization, unit commitment, and economic power dispatching.

Network operation: This refers to studies dealing with the improvement of network conditions (such as reliability, flexibility and providing a continuous service) in medium and short time operation (such as restoration, reconfiguration and load shedding).

Control: This refers to studies dealing with automatic and real-time actions to control the system condition and to keep the system electrical variables in permitted ranges.

Monitoring and diagnostics: This refers to studies coping with post-fault monitoring and defect diagnosing in the system.

Protection: This refers to studies dealing with fault detection to protect the system via fault clearing.

By considering the MAS operation phases, discussed earlier, the above categories might be further organized in two approaches, namely simulation and real [14]. In simulation, agents simulate the behavior of the system's components by focusing on far future which is typically treated off line. In comparison, in a real approach agents operate directly in a real environment which is typically treated online. With a simulation approach the action offered by MAS, in the action phase, is implemented through the aid of software agents or unreal simulated agents. The action of MAS in a real approach is applied by the help of real agents or hardware. The categories of each approach and their common characteristics are summarized in Table 1 and are discussed in the following.

3. 1. Simulation approach

In a simulation approach, agents play the role of system components to predict the component actions in advance. This in turn provides a way for testing the complexity of power system behavior in the real world [14]. Simulation approaches focus on long time studies. Expansion planning, electricity market and network management are three major categories using a simulation approach. These three categories adopt predicted data for the estimation of far future in the perception phase while they gather real data for the estimation of current conditions. Also in these three categories, offline reasoning is employed for making decision associated with non-physical actions.

3. 2. Real approach

In real approaches, agents typically behave in real world rather than in simulated environment. Real approaches find favor in categories, such as network operation, control, monitoring and protection of power engineering as these categories focus on short time horizon. These categories use real data of current conditions, make decision in real time and influence the environment by physical actions.

4. Research question

Based on the paper discussion the research question is proposed as,

How compatible is MAS in handling different categories of power system?

To address the research question following methodology is developed.

Table 1. Characteristics of power system approaches verses MAS operation

Approach	Category	Time horizon	MAS operation phase		
			Perception	Reasoning	Action
Simulation	Planning	Long term	Predicting future	Offline	Non-physical
	Market				
	Management				
Real	Operation	Short term	Gathering real data	Online	Physical
	Monitoring				
	Control				
	Protection				

5. Methodology

The paper methodology comprises three steps: illustrating the level of compatibility of MAS capabilities with MAS operation; determining how MAS operation are compatible with power system; and demonstrating how power system is compatible with MAS capabilities.

Step 1: Compatibility of MAS capabilities with MAS operation

The level of compatibility of MAS capabilities with different MAS operation phases depends on the number of factors which are affected by the problem nature, such as planning, market, management, operation, control, monitoring and protection. Five capabilities were considered, earlier in this paper, for MAS. The compatibility of each of the five MAS capabilities with the MAS operation phases depends on characteristics of the given case study. For example, in the perception phase, among different capabilities of MAS, the capability of dealing with large and complex systems is of particular significance when real data acquisition is required; however, in the case of unreal data this capability is not of interest. Also capabilities of being modular and cooperative as well as being extendible are more significant for the case of gathering real data rather than the case of assuming unreal data. This is because modularity and cooperation capabilities help in data gathering process particularly where such data is spread over the system. In comparison, extendibility aids in providing new sources of data. Moreover, in the reasoning phase, the ability of cooperation and modularity of MAS is central in online decision making processes as such ability enhances the speed of reasoning at real time using parallel processing. However, in the case of offline decision making the speed of the reasoning phase is not of interest. Moreover, the capability of being intelligent and flexible stands out as a dominate capability either in online or offline decision making. Being intelligent aids the system to decide autonomously while being flexible helps in dealing with fault tolerance of decisions. Furthermore, in the action phase, cooperation and autonomy capabilities are essential for both physically or non-physically actions as such capabilities make the actions of agents aligned; this in turn assists in meeting the system objective. To provide a rigorous framework for the above discussion Table 2 is presented. This table is an attempt to provide compatibility of MAS capabilities with the MAS operation phase in linguistic terms. The table is derived from the relevant literature by the authors, though it is acknowledged that assessing such compatibility level subjectively is not easy.

Step 2: MAS operation phase compatibility with power system

To assess the MAS operation phase compatibility with different power system categories a comprehensive literature review was conducted. The results are summarized in Table 3. This table, for example, shows that in the electricity market category, perception highly relies on real data acquisition, though, assuming unreal data is not of significance. Reasoning, in this category, is offline most of the time while MAS action is applied non-physically. Moreover, protection relies highly on: real data in the perception phase, making decisions online in the reasoning

Table 2. Compatibility of MAS capabilities with operation phase

Operation phase		MAS capability				
		Largeness and complexity	Modularity and cooperation	Distributed data and expertise	Intelligence and autonomy	Extendibility and flexibility
Perception	Real data acquisition	VH	H	H	M	VH
	Unreal data assuming	M	L	VL	L	VH
Reasoning	Online decision making	VH	VH	L	VH	M
	Offline decision making	M	M	VL	VH	VH
Action	Physically action	VH	H	VL	H	L
	Non-physically action	M	VL	VL	H	H

(VL: very low, L: low, M: medium, H: high, VH: very high)

Table 3. Compatibility of MAS operation phase with different power system categorizes

Approach	Operation	Perception		Reasoning		Action	
	Category	Real data acquisition	Unreal data assuming	Online decision making	Offline decision making	Physically action	Non-physically action
Simulation	Expansion planning	M	M	VL	VH	VL	VH
	Electricity market	H	L	L	H	L	H
	Network management	H	L	L	H	M	M
Real	Network operation	VH	VL	H	L	H	L
	Monitoring and diagnostics	VH	VL	H	L	M	M
	Control	VH	VL	VH	VL	H	L
	Protection	VH	VL	VH	VL	VH	VL

phase, and behaving physical in the action phase.

Step 3: Compatibility of MAS with power system

To assess the compatibility of MAS with different power system categories a fuzzy inference system is developed. The development is based on the Mamdani inference. Mamdani defines the characteristics of the fuzzy system so that minimum is used for AND operator, maximum for OR operator, minimum for implication, maximum for aggregation and centroid for de-fuzzification. In the proposed fuzzy system, inputs are the MAS operation phases and outputs are the levels of compatibility of MAS capabilities with power system categories. The relations of Mamdani inference system are presented in appendix.

Eight rules based on if-then statements are considered, as shown in Table 4. For example, Rule1 is presented by the term: if perception is unreal, reasoning is offline and action is non-physical then the compatibility level of capabilities for dealing with largeness and complexity are VL, for modularity and cooperation are VL, for handling distributed data and expertise are VL, for intelligence and autonomy are M, and for extendibility and flexibility are VL.

Membership functions of the fuzzy system inputs and outputs are defined by triangular sets; two examples are illustrated in Figure 3.

Table 4. Rules of fuzzy interface

Rules	Inputs (If …)			Outputs (then …)				
	Perception	Reasoning	Action	Dealing with largeness and complexity	Modularity and cooperation	Handling distributed data and expertise	Intelligence and autonomy	Extendibility and flexibility
Rule 1	Unreal	Offline	Non physical	VL	L	VL	M	M
Rule 2	Unreal	Offline	Physical	VL	M	VL	H	H
Rule 3	Unreal	Online	Non physical	H	H	M	H	M
Rule 4	Unreal	Online	Physical	H	VH	M	VH	H
Rule 5	Real	Offline	Non physical	M	M	H	H	H
Rule 6	Real	Offline	Physical	M	H	H	H	VH
Rule 7	Real	Online	Non physical	VH	H	H	H	H
Rule 8	Real	Online	Physical	VH	VH	VH	VH	VH

(VL: very low, L: low, M: medium, H: high, VH: very high)

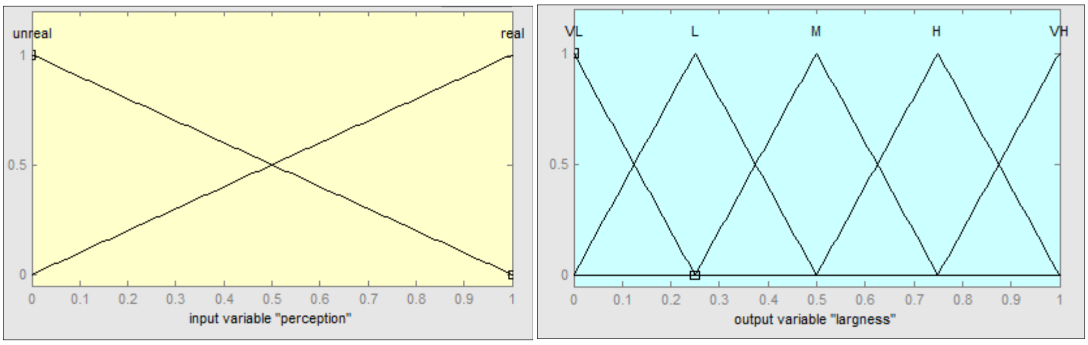

Fig. 3. Examples of input and output membership functions

Table 5. Inputs of fuzzy system

Power category	MAS operation phase		
	Perception	Reasoning	Action
Expansion planning	0.5	0	0
Electricity market	0.75	0.25	0.25
Network management	0.75	0.25	0.5
Network operation	1	0.75	0.75
Monitoring and diagnostics	1	0.75	0.5
Control	1	1	0.75
Protection	1	1	1

Inputs of the system are crisp sets (0, 0.25, 0.5, 0.75 and 1), shown in Table 5, defined by allocating numbers to the linguistic terms (VL, L, M, H and VH) of Table 3.

6. Results and discussion

The results of the proposed fuzzy inference system are summarized in Table 6. This table gives the compatibility level of MAS capabilities with power system categories. The results demonstrate that in categories using simulation, the MAS compatibility is low and MAS capabilities are not of particular significance. This might be largely due to the fact that such categories use unreal data in perception, off line decision making in reasoning and non-physical actions. However, the results demonstrate that in categories using real approaches, the MAS compatibility is high and MAS capabilities are of usefulness. This is because such categories use real data in perception, on line decision making in reasoning and physical actions. In ad-

Table 6. Compatibility of MAS capabilities with power system categories

Approach	Category	Capability				
		Largeness and complexity	Modularity and cooperation	Distributed data and expertise	Intelligence and autonomy	Extendibility and flexibility
Simulation	Expansion planning	0.362	0.375	0.528	0.625	0.625
	Electricity market	0.511	0.512	0.597	0.687	0.687
	Network management	0.512	0.557	0.574	0.675	0.700
Real	Network operation	0.718	0.720	0.827	0.827	0.827
	Monitoring and diagnostics	0.690	0.700	0.782	0.782	0.782
	Control	0.915	0.827	0.827	0.827	0.827
	Protection	0.920	0.920	0.920	0.920	0.920

dition, the results show that being intelligent and extendible is more compatible with power system categories. Accordingly, it is anticipated in the near future MAS becomes a key important tool in the development of intelligent tools and smart grids in power system.

- Multi agent technology challenges and power engineering requirements

There are some key technical challenges in the case of effective implementation of multi-agent systems within the power engineering applications, such as: "selection of platform" to ensure long-term compatibility and the required robustness for online applications, "selection of toolkit" which allow the reuse of existing agent behaviors and capabilities, "intelligent agent design" for different power engineering applications, "agent communication languages and ontologies" to define how agents exchange information, communicate, and negotiate, "standards of data", "security of messaging" due to the peer-to-peer nature of agent systems and "mobility" completely (source code and data) [14].

Although these challenges are discussed in literature but all these challenges are not a problem in every applications. Table 6 is a guideline for design of MAS in power engineering categories which demonstrates for designer which capabilities are more important in each category and according to these requirements which challenges should be overcome. In the other words, the more compatible a MAS capability with a power system category is the more consideration of this capability in the design of that category is required. For example, in the case where the social ability of power system is required the communication interfaces and the messaging standards are of very importance for inter-agent communication [14]. Such social ability is relevant to two capabilities: modularity and cooperation, and handling distributed sources of data and expertise. Table 6 shows that in real approaches, good communication is required because of a high level of compatibility and importance of these two capabilities of MAS.

Also in the case where interoperability with other systems is required the improvement of flexibility and extendibility capabilities is desire. Such improvement can be achieved via developing standards for MAS architecture, agent communication language, and content language [15]. For this purpose, a set of standards for an open architecture (agents can easily be added and removed) was established by Foundation for Intelligent Physical Agents (FIPA) to introduce standards for creating, locating, removing, and communicating with agents [14]. Table 6 illustrates that the compatibility of all power system categories (simulation and real) with the MAS capability of being flexible and extendable is relatively high. This implies that the establishment of such standards is anticipated to find favor in the power system arena in the near future particularly for microgrids and smart grids as extendibility and flexibilities are vital for these two sub-power systems.

7. Conclusion

Multi agent system is increasingly used in different categories of power system. Practitioners need to consider two steps in order to understand how MAS should be applied to the power system context. First, the problem nature should be analyzed to identify its requirements, then MAS should be adopted in such a way that the problem nature is addressed based on MAS capabilities. This paper developed a framework for applying MAS in power engineering via establishing five capabilities for MAS and seven categories for power system. The development was carried out based on finding the compatibility between such capabilities and categories. Three steps were considered in finding such compatibilities: illustrating the level of compatibility of MAS capabilities with MAS operation; determining how MAS operation are compatible with power system; and demonstrating how power system is compatible with MAS capabilities. The paper demonstrates that MAS capabilities are generally compatible with power system categories. In large and complex modern power systems with cooperating modules and subsystems where huge data intelligent processing is required the necessity of MAS capabilities for handling such modern power systems become evident. So MAS is suggested as an appropriate tool for modeling, analyzing and control of power systems.

The paper concludes that owing high adaptability of MAS capabilities with power system requirements, in the near future, MAS is anticipated to be a key important tool in the development of smart grids in power system.

Appendix: Mamdani fuzzy inference system

A fuzzy inference system comprises four principal component: a "fuzzification interface", a "knowledge base", a "decision making logic" and a "defuzzification logic" [23]. One of the most popular fuzzy reasoning methods is Mamdani inference system which uses a rule base for reasoning as follows [24]:

For simplicity, assume that we have two fuzzy rules as knowledge base, as follows:

R1: if x is A_1 and y is B_1 then z is C_1,

R2: if x is A_2, and y is B_2, then z is C_2.

where x, y, and z are linguistic variables representing the process state variables respectively; A_i, B_i, and C_i are linguistic values of the linguistic variables x, y, and z.

In the case of crisp inputs, the value of input may be treated as a fuzzy singleton. Then the firing strengths α_i of the rules may be expressed as:

$$\alpha_1 = \mu_{A_1}(x_0) \wedge \mu_{B_1}(y_0)$$
$$\alpha_2 = \mu_{A_2}(x_0) \wedge \mu_{B_2}(y_0)$$

where $\mu A_i(x_0)$ and $\mu B_i(y_0)$ play the role of the degrees of partial match between the user-supplied data and the data in the rule base, also the sign of "^" implies intersection of two parameters that computed as minimum of them.

$$x \wedge y = \min\{x, y\}$$

Fuzzy reasoning is associated with the use of Mamdani's minimum operation rule R, as a fuzzy implication function. In this mode of reasoning, the ith rule leads to the control decision

$$\mu_{C_i'}(w) = \alpha_i \wedge \mu_{C_i}(w)$$

which implies that the membership function μC of the inferred consequence C is pointwise given by

$$\mu_C(w) = \mu_{C_1'} \vee \mu_{C_2'} = \left[\alpha_1 \wedge \mu_{C_1}(w)\right] \vee \left[\alpha_2 \wedge \mu_{C_2}(w)\right].$$

The centroid Method are used for defuzzification of the result of mamdani inference system that generates the center of gravity of the possibility distribution of a control action.

In the case of a discrete universe, this method yields

$$z_0 = \frac{\sum_{j=1}^{n} \mu_z(w_j) \cdot w_j}{\sum_{j=1}^{n} \mu_z(w_j)}$$

where n is the number of quantization levels of the output. The fuzzy reasoning process is illustrated in Figure 4 [24].

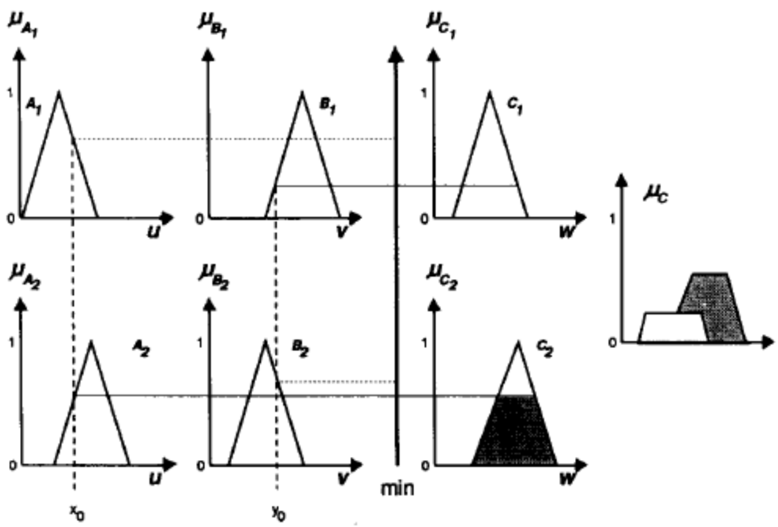

Fig. 4. Mamdani fuzzy inference process [24]

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