Control Theoretical Modeling of Trust-Based Decision Making in Food-Energy-Water Management

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Abstract We propose a hybrid Human-Machine decision making to manage Food-Energy-Water resources. In our system trust among human actors during decision making is measured and managed. Furthermore, such trust is used to pressure human actors to chose among the solutions generated by algorithms that satisfy the community's preferred trade-offs among various objectives. We model the trust-based loops in decision making by using control theory. In this system, the feedback information is the trust pressure that actors receive from peers. Using control theory, we studied the dynamics of the trust of an actor. Then, we presented the modeling of the change of solution distances. In both scenarios, we also calculated the settling times and the stability using the transfer functions and their Z-transforms as the number of rounds to show whether and when the decision making is finalized.

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1 Introduction and Background

Decision making is a problem that can be faced in different time intervals, such as annually, daily, or every millisecond and could have varying impact areas and degrees. Several fields, such as economics, politics, agriculture, and warfare, are among the ones that can have crucial long-term impacts on millions of people's life. Food-Energy-Water (FEW) can be considered as one of the fields with severe effects, which can be difficult to recover in greater areas. Therefore, FEW sectors can benefit from an advanced Decision Support System (DSS) utilizing feedback evaluation and supported solution highlighting.

Optimization techniques have been used for problems in numerous fields, including Food-Energy-Water (FEW). Various methods and algorithms are developed and applied to reach efficient solutions. However, the accuracy of the results could benefit from the inputs from the users of the system and the people in the field with the consideration of different parameters and scenarios. As human input can be used to improve the algorithms, they can also be used as a control mechanism over the computerized optimization approaches.

In this paper, the trust management framework by Ruan et al. [31] is summarized, and then, decision making in FEW is explained by describing the solution proposal and rating mechanisms. Also, a distance metric is introduced to compare multiple solutions to a reference solution considering specific parameters. Then, we give a brief introduction to control theory and control systems and present the control theory approach for FEW decision makings. We model the change in trust and also the difference in solution distances. We provide the significant specifications of the control systems such as settling time and stability as the number of required rounds for the end of the decision making and whether it converges.

Kambiz [15] emphasizes that the global economic crisis in 2008 is one of the examples of such events that occurred after a series of decision makings which had a devastating impact on the significant part of the world. He also explains that the reason behind these complicated decisions by indicating the trend that the world is becoming a more interconnected and complex place. These decisions are required to be made by multiple stakeholders from different fields and from different backgrounds. As the decision making is inevitable and becoming more challenging, Dong et al. [10] propose an approach to minimize the modifications to the solutions in a decision making involving experts in the field.

In the field of decision making, the interaction between the stakeholders could play an essential role in reaching a consensus, and trust could facilitate the decision making process directly or indirectly [32, 33, 34]. However, measuring the interactions and trust could require a computerized approach for maintaining and considering historical measurements [14, 19, 26]. Ruan et al. [31] proposed a measurement theory-based trust management framework that can be used among the entities in a network environment. It also provides trust inference capability for disjoint nodes. Some of the applications of this framework include stock market analysis using Twitter data, trust management of Internet of Things, fake user detection, and crime predictions. [16, 27, 23, 28, 29, 30, 11, 40, 41, 8, 39, 7, 25, 24, 6, 17].

Trust also has a various area of usage in decision making such as decision of consumers in e-commerce [18], online transactions [13], water allocation problem of multiple stakeholders [1], and a generic consensus framework [2]. Also, we presented our work on decision support system for resource sharing [38], the influence of rating of ratings [35], a game theory approach [36], and the role of trust sensitivity [37].

Control theory has numerous applications on various fields from spacecraft stabilization [9] to production-inventory problems [22]. Levison and William [21] shows the ability of a control system to predict human decision making in pilot-vehicle systems. Carver and Scheier [5] explained an approach to human behavior using control theory. Brehmer [4] shows how the performance of decision making is affected by the feedback delays in the control system.

This paper is organized as follows. In Sect. 2, we introduce the trust management framework. In Sect. 3, decision making in FEW is explained. In Sect. 4, control theory approach for decision makings in FEW is presented. In Sect. 5, the results of the control theory approach are presented. Finally, we conclude the paper in Sect. 6.

2 Trust Management Framework

Ruan et al. [31] proposed a measurement theory-based trust management framework with a flexible and adaptable structure for online social communities. In FEW decision makings, ratings given to the proposed solutions are considered as the measurements for the trust since a rating could be a bold candidate for the expression of the trust of an actor in the given context.

Impression, m, and confidence, c, are the 2 main parameters of the trust framework which are considered as the degree of the trust and the degree of the certainty. Impression is calculated by averaging the measurements whereas the confidence is given as inversely related to the standard error of the mean as shown in Eq. 1 where $m^{A:B}$, $c^{A:B}$, and $r_i^{A:B}$ are the impression, confidence, and a measurement from A to B.

$$\begin{aligned} m^{A:B} &= \frac{\sum_{i=1}^{N} r_i^{A:B}}{N} \\ c^{A:B} &= 1 - 2\sqrt{\frac{\sum_{i=1}^{N}(m^{A:B} - r_i^{A:B})^2}{N(N-1)}} \end{aligned} \tag{1}$$

The interactions between two individuals are used by the trust management framework to measure the unidirectional trust between them. Furthermore, it can also anticipate the trust without the interactions using propagation methods, which are transitivity and aggregation. Selected methods for the transitivity and aggregation are shown in Eq. 2 from [31] where S, D, and T represent source, destination, and transition.

$$
\begin{aligned}
m^{ST} \otimes m^{TD} &= m^{ST} m^{TD} \\
e^{ST} \otimes e^{TD} &= \sqrt{(e^{ST})^2 (m^{TD})^2 + (e^{TD})^2 (m^{ST})^2} \\
m^{SD}_{T_1} \oplus m^{SD}_{T_2} &= \frac{m^{SD}_{T_1} + m^{SD}_{T_2}}{2} \\
e^{SD}_{T_1} \oplus e^{SD}_{T_2} &= \sqrt{\frac{1}{2^2}((e^{SD}_{T_1})^2 + (e^{SD}_{T_2})^2)}
\end{aligned}
\tag{2}
$$

3 Decision Making in Food-Energy-Water

In our scenarios, decision making consists of multiple rounds where actors propose a solution from a solution set and receive ratings from other actors for their solution. The solution set is generated using environmental models, and the solutions can be considered as partially optimized regarding different parameters such as profit, environmental protection value, or a combination of multiple parameters. Different actor profiles are included in the decision making such as more profit-oriented or more environment-friendly actors. An actor who has priority on her profit sorts the solutions based on the profit and starts proposing solutions in that order, whereas an actor who also cares about the environment could use a weighted average of profit and environmental values as sorting criteria.

In each solution, the area for each type of crop is determined for over 20 different crop types. Then, the amounts of water from various sources and different types of fertilizers are included. Finally, the profit from each crop is calculated, and the cost for the water and the fertilizers are subtracted to calculate the net profit. Furthermore, depending on the amount of water and fertilizers, environmental protection values are calculated. A sample of a sorted solution set is shown in Table 1, where several of the important parameters are included, such as water amount used, the environmental protection value, and the profit. The solution rank column shows the order of the solutions to be proposed where 0 means that the solution is not proposed, and a solution with rank n is proposed before the solution with rank $n+1$. The main reason behind skipping a solution is that although the actor loses profit, the environmental value is not improved compared to the previous solutions. Also, the actors do not propose solutions that give them less than 75% of the profit of their first proposals. In other words, they do not accept losing more than 25% of the highest possible profit.

The second phase of the decision making is where the actors rate each other's solutions. The ratings are based on the environmental protection values of the solutions. Each actor is assigned a ratio of their highest environmental protection value for their objective to reach at the end of the decision making. The highest rating is achieved when the actor proposes a solution that is at least as environmental as his objective.

Furthermore, we used a distance metric to measure the distance between proposed solutions to the reference or objective solutions. In our metric, we implement

Table 1 First several rows of a solution set of an actor including environmental protection value and her profit as well as the order in which she proposes solutions.

Solution ID	Iteration	Water Amount	Environmental Protection	Profit	Solution Rank
2628	4	396	0.745260	1.00000	1
2876	4	396	0.024715	0.98131	0
1884	3	375	0.762260	0.91892	2
3372	5	355	0.776400	0.87439	3
2132	3	375	0.014901	0.86310	0
3124	5	355	0.993470	0.85475	4
1636	3	375	0.995860	0.85414	5
7588	11	339	0.994820	0.85340	0

the Euclidean distance method by selecting significant parameters of the solutions such as environmental protection values as shown in Eq. 3 where e_s^i is the environmental protection value of i^{th} actor in his final proposal, e_t^i is the value of the same parameter in his reference solution, and n is the number of the actors. The distance metric can also be extended by including multiple parameters from one solution.

$$Dist(s,t) = \sqrt{\sum_{i=1}^{n} (e_s^i - e_t^i)^2} \tag{3}$$

4 Control Theory Approach for Decision Making

In addition to the game-theoretical approach [36], decision making among FEW actors can also be modeled using control theory. Control theory, as a field of applied mathematics, is used in control systems engineering to deal with particular processes and systems to manage or regulate the system using the control loops [20, 12].

Control systems receive input and emit an output where the controller, the target system, and the transducer can be included in essential elements of a control system. Controllers are designed such that the control signal aims the target system to emit the reference output signal. In some control systems, there is also a feedback path where the sensor measures the primary output signal and directs it to the controller [12].

Decision makings among FEW actors can be considered as a control system in multiple ways. When we examine the decision making from the actor's point of view, the actor becomes the controller as she proposes a solution. The process of rating proposed solutions is considered as the target system. The sensor represents our trust management framework, where the ratings are considered as the measurements for trust, which becomes the measured signal that is sent to the controller. Control system diagram of a FEW decision making from the actor's point of view is shown in Fig. 1.

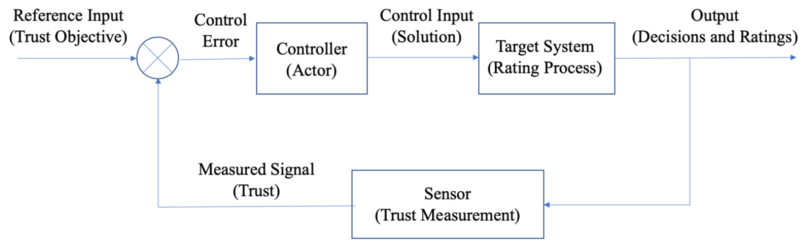

Fig. 1 The control system diagram is shown with essential elements which are input and output signals, controller, target system, and sensor and their meanings in FEW decision making.

Control systems can be divided into subgroups regarding several parameters such as the type of the signal, number of inputs and outputs, and the existence of the feedback path. When we consider the type of the signal, there can be continuous or discrete time control systems. Regarding the number of inputs and outputs, there are Single-Input-Single-Output (SISO) and Multiple-Input-Multiple-Output (MIMO) systems. Also, systems can be grouped into open-loop and closed-loop systems based on the presence of the feedback path [12].

Our scenario can be seen as a discrete time control system since the decisions are made, and the feedback is received during the same round, and the actors wait for the next decision until the next round. It can also be seen as SISO when we model the system based on the decision of one actor since she has one reference input, makes one decision and receives one output. The importance that actors give their trust is the basis for the feedback in the system. Then, the system is said to be a closed-loop system because of the existence of the feedback path. The type of feedback is negative since it balances the system by influencing the decision of the actors and finally causing the system to converge.

Using control theory, systems can be modeled and identified regarding various outcomes such as settling time and stability. Also, the functions in time-domain, which describe the signal as an ordered sequence, are translated into the frequency domain using Z-transformation to have a better ability in the manipulation of signals such as adding, subtracting, and shifting. A signal that is transformed into Z-domain can be used to encode the signals in such a way that the key specifications such as settling times and steady-state values can be derived easily [12].

Another important specification of a control system is the settling time, which is the time required for the system to achieve a specified error band from the time a step input is applied. In our scenarios, we can consider the time as the number of rounds required for the output to be within a specified boundary where the error rate of 2% is the default error rate in control theory [12].

Similar to the settling time, stability is also another significant specification of control systems in control theory. It is important to measure the stability of dynamic systems for the identification of the systems and the design of the controllers. Lyapunov stability criteria are usually used to determine the stability of dynamic systems. For linear systems, it is required that the output is bounded when the input is bounded, which is also called Bounded-Input-Bounded-Output (BIBO) stable systems. Also, for nonlinear systems, Input-to-State-Stability (ISS) is required, which can be considered as the combination of Lyapunov and another form of BIBO stability [3].

5 Results

In this section, we present the results of our control theory approach to decision makings in FEW, including transfer functions, Z-transforms, settling times, and stability for modeling the dynamics of trust and the distance.

5.1 Modeling the Dynamics of Trust

In [36], we presented the game theory approach for actors with the historical trust of 0.4 and objective trust of 0.8 and 0.65, respectively. They follow the strategy of decreasing the difference between their current and objective trusts at each round by 60% and 30%, respectively, based on their trust sensitivities. Trust equations of the actors and their Z-transforms are shown in Eq. 4 for Actor 1 and Eq. 5 for Actor 2 and the change in their trust in the first ten rounds of the decision making is shown in Fig. 2.

$$\begin{aligned} y_1(k) &= y_1(k-1) + 0.6(0.8 - y_1(k-1)) \\ Y_1(z) &= \frac{0.4z(5z+1)}{(z-1)(5z-2)} \end{aligned} \tag{4}$$

$$\begin{aligned} y_2(k) &= y_2(k-1) + 0.3(0.65 - y_2(k-1)) \\ Y_2(z) &= \frac{0.05z(80z-41)}{(z-1)(10z-7)} \end{aligned} \tag{5}$$

The settling times, k_s, of the actors 1 and 2 can be calculated as shown in Eqs. 6 and 7 where Actor 1 reaches her objective trust level within 2% error rate in round 4 whereas Actor 2 requires nine rounds to reach her trust objective within the same error rate.

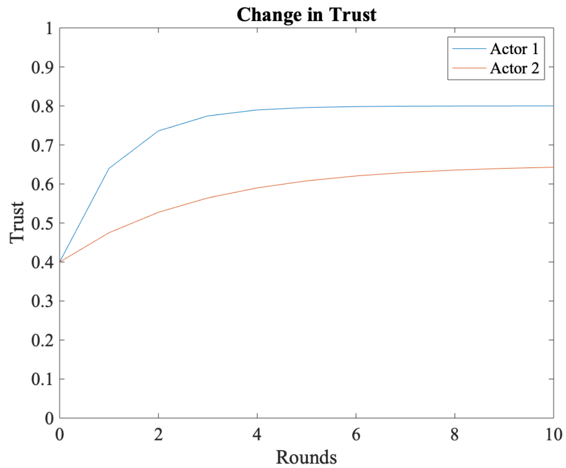

Fig. 2 The change in trust is shown for the actors with the same initial trust value of 0.4, trust objectives of 0.8 and 0.65, and different trust sensitivities.

$$\left|\frac{0.8-(-0.4(0.4^{k_s}-2))}{0.8}\right| < 0.02$$
$$k_s \approx 3.51294 \tag{6}$$
$$\left|\frac{0.65-(0.65-(1.4^{k_s}2^{-k_s-2}))}{0.65}\right| < 0.02$$
$$k_s \approx 8.28909 \tag{7}$$

The stability of the system can be shown by finding the poles of the transfer functions. The transfer functions for the Actor 1 and 2 can be calculated as shown in Eqs. 8 and 9 where the poles can be calculated as 0.4 and 0.7 which shows the asymptotic stability [3].

$$G_1(z) = \frac{0.4(5z+1))}{5z-2} \tag{8}$$
$$G_2(z) = \frac{0.05(80z-41))}{10z-7} \tag{9}$$

5.2 *Modeling the Dynamics of Distance*

Similarly, the distance between the proposed and the objective solutions can be modeled using Control Theory. In distance computation, the environmental protection value of the solutions is used as the distance parameter, as shown in Eq. 3.

We selected a group of actors with the same trust sensitivity where they tend to increase their trust and decrease the distance of their own solutions to their objective solution by proposing environmentally better solutions. Actors also have a threshold point, which prevents them from proposing solutions that make them lose more than a specified amount of profit, which finally results in a steady-state distance around 0.65.

When we calculate the settling time for the actors, their distance reaches the steady-state distance within a 2% error rate in 15 rounds, as shown in Eq. 10. In a real scenario, the actors achieved to propose solutions with distance 0.66 in round 10, which is within the 2% error rate of the steady-state distance of 0.65. However, they were expected to reach the steady-state condition in round 15 based on their strategy function. The difference arises from the discrete nature of the solutions. Since there is no solution to propose that gives an incremental increase in trust, it resulted in relatively drastic changes in both trust and distance in one round.

$$\begin{aligned} \left| \frac{(0.35(0.8)^{k_s} + 0.65) - 0.65}{0.65} \right| &< 0.02 \\ k_s &\approx 14.7572 \end{aligned} \tag{10}$$

To determine the transfer function of an unknown system, the system identification methods of MATLAB, which have an iterative approach, can be used. The output function is estimated based on the function given in Eq. 11 where the orders of the polynomials $B(q)$ and $F(q)$ need to be specified. Identifying the system with orders 1 and 2 resulted in the polynomials $B(z)$ and $F(z)$ as shown in Eqs. 12 and 13.

$$y(t) = \frac{B(q)}{F(q)} u(t - nk) + e(t) \tag{11}$$

$$B(z) = 0.1424z^{-1} \tag{12}$$

$$F(z) = 1 - 0.7747z^{-1} - 0.002261z^{-2} \tag{13}$$

The plot of the original data points from the simulations and the identified system function is shown in Fig. 3. Using the system identification tools, the settling time is found as 16 for the given orders of the polynomials, which is very close to the settling time found in Eq. 10. Also, the stability of the system can be shown by calculating the poles of the system by finding the roots of the denominator, which makes the system unstable, considering Eq. 13. Since the poles, 0.77691, are inside the unit circle, the system is said to be asymptotically stable.

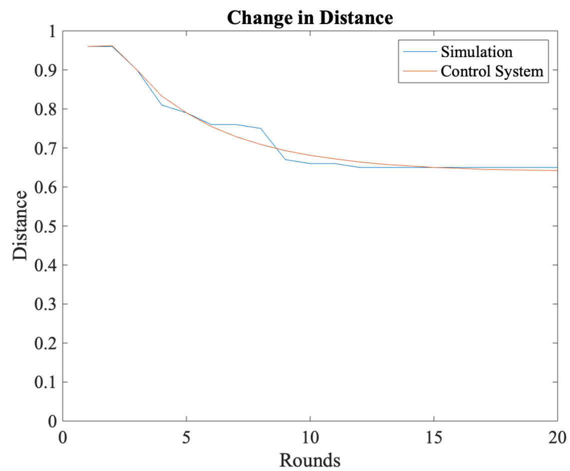

Fig. 3 The change in solution distances is presented for real data points from the simulation and the estimation using system identification of control theory approach.

6 Conclusion

In this paper, we studied a hybrid Human-Machine collective decision making to manage Food-Energy-Water resources. We modeled the decision-making process as a feedback closed-loop control system. The negative feedback information is the trust pressure an actor receives from the community or actors involved in decision-making. Using control theory, we studied the dynamics of the trust of an actor. Then, we presented the modeling of the change of solution distances. In both scenarios, we also calculated the settling times and the stability using the transfer functions and their Z-transforms as the number of rounds to show whether and when the decision making is finalized.

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