MULTI-STAKEHOLDER CONSENSUS DECISION-MAKING FRAMEWORK BASED ON TRUST AND RISK

A Dissertation

Submitted to the Faculty

of

Purdue University

by

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In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

May 2019

Purdue University

Indianapolis, Indiana

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To my father, Abdulaziz, who supported me

To my mother, Munirah, who prayed for me

To my siblings: Layla, Omar, Mohammed, Ahmed, Nouf, Lubna and Fahad

Thanks for always being there for me.

ACKNOWLEDGMENTS

I am grateful to all of those with whom I have had the pleasure to work during this journey. Each of the members of my Dissertation Committee has provided me professional guidance and taught me a great deal about scientific research.

I would especially like to thank my mentor and advisor, Dr. Arjan Durresi for his encouragement and guidance during my studies. He has shown me, by his example, what a good scientist should be. I want to acknowledge thesis committee members Dr. Mohammad Al Hasan, Dr. Snehasis Mukhopadhyay, and Dr. Mihran Tuceryan for reviewing and providing feedback on my thesis.

Nobody has been more important to me in the pursuit of this journey than the members of my family. I am grateful to my parent and siblings, who have provided me through moral and emotional support in my life. They are the ultimate role models. I am also grateful to friends who have supported me along the way and to my labmates, Yefeng Ruan and Murat Karakus for their kind supports and scientific advice.

Extraordinary gratitude goes out to my special friend, Dr. Abdullah Alzeer for his valuable guides, his moral support and his endless inspiration during my research work.

Thanks for all your encouragement!

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SYMBOLS

c Confidence

m Impression

R Rating

S Stakeholder

T Trust

W Weight

ABBREVIATIONS

MCDM	Multi-Criteria Decision-Making
MSCDM	Multi-Stakeholder Consensus Decision-Making
RMS	Root Mean Square
RWA	Rating Weighted Average
SM	Similarity Measure
WESM	Weighted Exponent Similarity Measure
WP	Weighted Product
WPSM	Weighted Product Similarity Measure
WS	Weighted Sum

ABSTRACT

Alfantoukh, Lina Abdulaziz Ph.D., Purdue University, May 2019. Multi-Stakeholder Consensus Decision-Making Framework Based on Trust and Risk. Major Professor: Arjan Durresi.

This thesis combines human and machine intelligence for consensus decision-making, and it contains four interrelated research areas. Before presenting the four research areas, this thesis presents a literature review on decision-making using two criteria: trust and risk. The analysis involves studying the individual and the multi-stakeholder decision-making. Also, it explores the relationship between trust and risk to provide insight on how to apply them when making any decision. This thesis presents a grouping procedure of the existing trust-based multi-stakeholder decision-making schemes by considering the group decision-making process and models.

In the first research area, this thesis presents the foundation of building multi-stakeholder consensus decision-making (MSCDM). This thesis describes trust-based multi-stakeholder decision-making for water allocation to help the participants select a solution that comes from the best model. Several criteria are involved when deciding on a solution such as trust, damage, and benefit. This thesis considers Jain's fairness index as an indicator of reaching balance or equality for the stakeholder's needs. The preferred scenario is when having a high trust, low damages and high benefits. The worst scenario involves having low trust, high damage, and low benefit. The model is dynamic by adapting to the changes over time. The decision to select is the solution that is fair for almost everyone.

In the second research area, this thesis presents a MSCDM, which is a generic framework that coordinates the decision-making rounds among stakeholders based on their influence toward each other, as represented by the trust relationship among

them. This thesis describes the MSCDM framework that helps to find a decision the stakeholders can agree upon. Reaching a consensus decision might require several rounds where stakeholders negotiate by rating each other. This thesis presents the results of implementing MSCDM and evaluates the effect of trust on the consensus achievement and the reduction in the number of rounds needed to reach the final decision. This thesis presents Rating Convergence in the implemented MSCDM framework, and such convergence is a result of changes in the stakeholders' rating behavior in each round. This thesis evaluates the effect of trust on the rating changes by measuring the distance of the choices made by the stakeholders. Trust is useful in decreasing the distances.

In the third research area, this thesis presents Rating Convergence in the implemented MSCDM framework, and such convergence is a result of changes in stakeholders' rating behavior in each round. This thesis evaluates the effect of trust on the rating changes by measuring the perturbation in the rating matrix. Trust is useful in increasing the rating matrix perturbation. Such perturbation helps to decrease the number of rounds. Therefore, trust helps to increase the speed of agreeing upon the same decision through the influence.

In the fourth research area, this thesis presents Rating Aggregation operators in the implemented MSCDM framework. This thesis addresses the need for aggregating the stakeholders' ratings while they negotiate on the round of decisions to compute the consensus achievement. This thesis presents four aggregation operators: weighted sum (WS), weighted product (WP), weighted product similarity measure (WPSM), and weighted exponent similarity measure (WESM). This thesis studies the performance of those aggregation operators in terms of consensus achievement and the number of rounds needed. The consensus threshold controls the performance of these operators.

The contribution of this thesis lays the foundation for developing a framework for MSCDM that facilitates reaching the consensus decision by accounting for the stakeholders' influences toward one another. Trust represents the influence.

1. INTRODUCTION

"A consensus means that everyone agrees to say collectively what no one believes individually." Abba Eban

1.1 Overview of Problem

In real-world problems where complexity exists, there is no single correct answer that solves a given one [1]. Multi-stakeholder decision-making is considered a complex problem because there could be various correct answers to select from. It requires the involvement of humans to discuss the possibility of forming a solution based on their discussions. The humans participating in the decision have a partial view of the problem domain because of the diversity of their mindsets, the experiences they have gained over the years, and their current experiences in various contexts. Therefore, combining those partial views in the decision-making produces a whole view of the problem. The challenge is to find a proper mechanism for combining those partial views during the negotiations about finding the solution or the answer to the problem.

In situations where collective decisions have to be made by a group rather than an individual, it is essential to find a procedure that facilitates reaching a group agreement. Without reaching an agreement, then the problem will face a dead end. A real example is the Challenger explosion [2] when the spacecraft exploded in 1986, 73 seconds after takeoff. Various people participated in the decision to take off: NASA management, NASA executives, and engineers. The engineers warned against the launch due to the seal problems. The executives made the decision to take off instead of listening to the engineers. NASA management made a decision to silence the engineers warnings. As a result, there was no consensus, and the decision outcome caused a disaster.

In general, when considering the consensus process in decision-making, the participants gather to propose a solution and then negotiate accordingly. The process ends when they agree on a solution in consensus. Every solution has an associated interest for the stakeholders. The conflicting interests of the stakeholders lead to complicating their negotiation process. The reason for such complications is that humans have a tendency to rationally propose solutions that serve their best interests under the assumption of rational choice theory [3].Therefore, it is challenging to adopt or design a mechanism that causes the stakeholders to be influenced by the others and at the same time maintains the expected interests.

Computers or machines are solutions to help stakeholders when seeking the best solution. However, relying on machines alone will lead to systematic decision-making that generates many solutions and using an algorithmic approach to compute the best one [4]. Although machines are useful, eliminating humans is not practical because humans add more information to the decision-making process based on their knowledge, experience, and historical data. In addition, an infinite number of solutions could be proposed by humans, but a machine would not be able to allocate them all because computers produce results based on what the humans feed them or based on what the computers learn from peoples behaviors in the past. Therefore, with computers, the solution selection algorithm works on a finite set of solutions. This is not practical in the consensus decision-making process because solution modification is important during the negotiations.

1.2 Motivation

"For good ideas and true innovation, you need human interaction, conflict, argument, debate". Margaret Heffernan

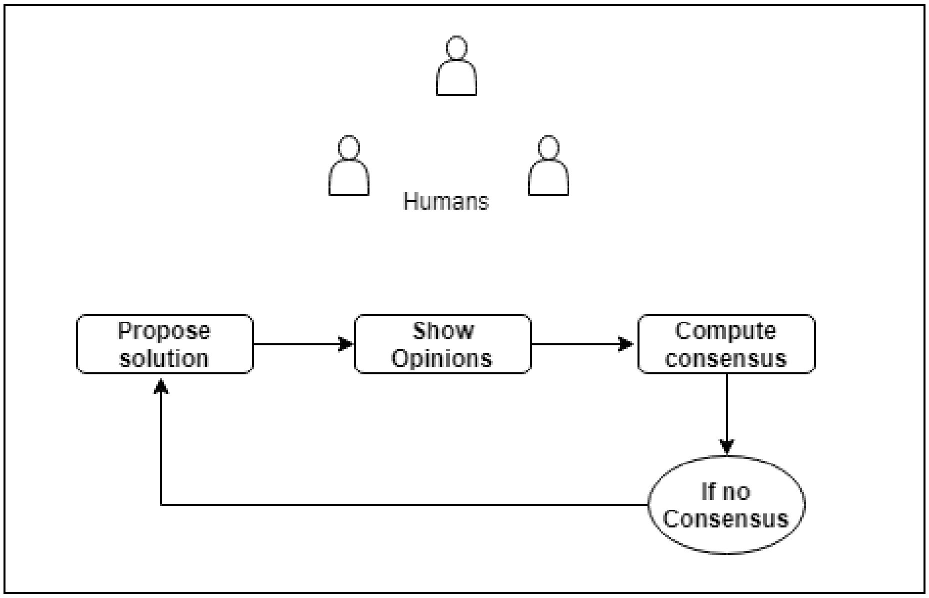

Fig. 1.1. The phases required for the consensus decision-making process. The stakeholders start by proposing solutions based on the interests the solutions serve; then, they express their opinions to each other. After that, they check the group consensus. Finally, if none of the solutions has achieved consensus, the stakeholders start the process again. This process might not end if the stakeholders have extremely conflicting interests.

Example: Groundwater allocation applications. There exist different stakeholders such as water suppliers, water users, and environmental policymakers.

The decision outcome is the amount of water to supply to the users under the environmental policy. However, if each one of the stakeholders has an interest that is different from the others, then reaching an agreement will be difficult or impossible. Therefore, a proper procedure is to influence each other while bargaining about the best solution that benefits everyone.

There are several challenges when dealing with multi-stakeholder decision-making due to humans involvement:

- The stakeholders might come from different backgrounds, which leads to a variety of expertise and, in turn, various proposals in the decision-making process.
- There might be extremely conflicting interests among the stakeholders, which leads to not agreeing on one decision.
- The stakeholders might have a partial view of the problem domain, which leads to not knowing the others decision preferences and expectations.
- The stakeholders might not be honest. There could be cases in which one or more stakeholders manipulate the decision-making process.

It is essential to add a new step or component to the consensus decision-making process illustrated in Fig.1.1 in order to solve the above challenges. This component should help in adding extra information, and, in turn, more knowledge of any stakeholder regarding the others. Also, this component contributes to combining the partial views of the decision problem domain corresponding to the stakeholders, which leads to obtaining a bigger picture of the decision problem. Moreover, this component can detect the honesty of the stakeholders. Finally, this component could work as an influential factor when making a decision, which leads to resolving the issue with the conflicting interests. Moreover, the advancement of technology and the existence of smart machines make it preferable to combine their capabilities with humans to achieve group decisions. Therefore, humans add extra information to the decision problem, and the machines moderate and facilitate the decision-making process to provide guides to the stakeholders while they negotiate about the correct solution to a given problem.

1.3 Proposed Solution

"Risk and trust are two facets of decision-making through which we view the world and choose to act." Alcalde et al

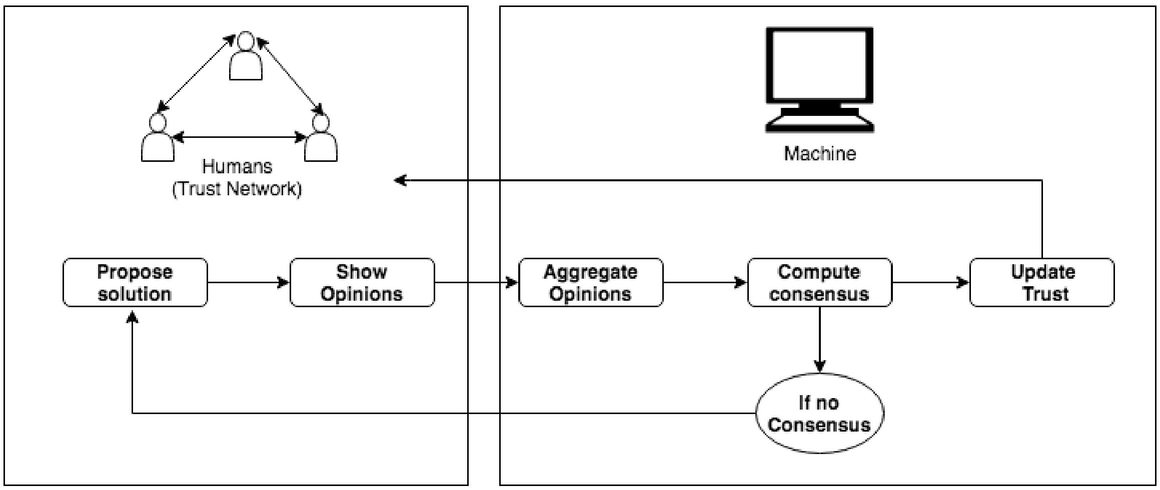

Fig. 1.2. The phases of the proposed multi-stakeholder consensus decision-making. It involves humans and a machine. The stakeholders start by proposing solutions, then express their opinions to each other. Next, the machine aggregates the opinions about each solution to compute the stakeholders consensus for each solution. After that, the machine updates the trust for each stakeholder. Finally, if none of the solutions have achieved consensus, the stakeholders start the process again.

Multi-stakeholder consensus decision-making involves participants who gather, propose solutions or decisions, and provide their opinions regarding the other solutions. Obtaining others views is used to gain some insight into the others needs and, in turn, modify the proposed solution accordingly. The opinions can result from the stakeholders perceived risk from each decision. Expressing an opinion is translated into trust.

In this thesis, trust is an essential part of developing a multi-stakeholder consensus decision-making framework to produce a decision outcome agreed on by all the stakeholders involved in the decision-making process.

The proposed decision-making framework (MSCDM) can be described as:

- Collaborative: The framework supports having several stakeholders who interact with each other during negotiation by proposing decisions and expressing opinions about the others decisions.
- Iterative: The framework supports several rounds of negotiation.
- Collective: The framework aggregates the stakeholders opinions to find a decision agreed on by all of them.hers to find the decision agreed by all of them.
- Flexible: The framework allows the stakeholders to adjust their proposals. There is no fixed set of decision outcomes.
- Trust-based: The framework supports involving humans in the negotiation, who have different knowledge and expertise.
- Risk-based: The framework supports having the stakeholders perceived risk with each decision represented by interest.
- Dynamic: The framework supports updating the trust values after each round while negotiating.
- Consensus: The framework produces one decision outcome agreed on by all the participants.
- Computer-based: The framework uses machines to guide the decision-making process.

The use of trust among stakeholders adds extra information to help them to understand the preferences and expectations of the others. Trust helps to represent and maintain the stakeholders honesty. Therefore, the framework considers trust to have an influence on the others, which could lead to changing the proposed solution to one offered by a highly trusted stakeholder.

1.4 Research Goals

> *"Recent advances in computer science offer a better way to support multi-issue, multi-stakeholder negotiation processes, especially by significantly reducing the time required for negotiation". Susetyo and et al*

The research goal of this thesis is to develop a consensus decision-making framework for multiple stakeholders based on trust and perceived risk to facilitate finding a decision agreed on by all of them. This thesis proposes a framework for consensus decision-making that uses the influence of stakeholders toward each other as its core. Such influence is translated to trust. The proposed framework takes into account the interests associated with each decision, where the interests include the perceived risks by the stakeholders. The main research question of this thesis can be summarized as:

> What is the trust-based consensus decision-making framework needed when the stakeholders have conflicting interests?

As this thesis explored the main research question, other fundamental questions associated with the research question arose.

- How should trust and perceived risk be applied in the decision-making framework being built?
  - Does the perceived risk affect trust?
  - Can the framework use the trust of the stakeholders to weigh their opinions?
- Does the interest corresponding to decisions for each stakeholder follow a specific distribution?

- What mathematical model and aggregation operators are required?
  - What is the possible mathematical model for stakeholders interactions during the decision-making process?
  - What aggregation operators should be used when aggregating stakeholders interactions?
- Would the trusted stakeholder influence the others in changing their interests associated with the decisions?
- How does trust help in detecting malicious stakeholders in the proposed decision-making framework?

These fundamental questions help motivate the development of a consensus decision-making framework that produces the final decision agreed on by all the participants by considering the trust relationships among them.

1.5 Assumptions and Limitations

This experimental thesis research involves building a simulator for the proposed framework. The framework assumes that the stakeholders propose decisions and interact according to the assumptions of rational choice theory and social influence theory. This thesis work does not include building a mathematical model for risk computation, rather than assuming that the risk infers the interests of the stakeholders, and such calculations depend on the context.

1.6 Expected Outcome

This thesis involves developing a framework for multi-stakeholder consensus decision-making based on trust. This thesis expects to develop an algorithm of the proposed framework and then build a simulator. This simulator operates by being fed with the potential decision-making scenarios. This thesis intends to focus on capturing the interactions among stakeholders during negotiations and translate those interactions into trust relationships. This thesis research combines decision-making, trust, software engineering, and database design to develop a framework that produces consensus decisions.

1.7 Scope

This thesis focuses on developing a framework that supports selecting a consensus decision in a multi-stakeholder decision-making field using trust and risk as the main components. This thesis identifies the framework elements and presents a novel algorithm for integrating them to produce the preferred decision for all the stakeholders. This thesis shows human and machine involvement in the decision-making, where the machine coordinates the decision process, and the humans make the choices. The machine does not produce a feasible solution because there could be more than one feasible solution from which to select. Instead, it gives the humans guides during negotiations. The proposed framework involves expressing the trust relationship through stakeholders interactions while negotiating. Justifying why one stakeholder would trust another is outside the scope of this thesis because there could be countless reasons for trusting someone.

1.8 Contributions

This thesis adopts measurement theory-based trust regarding the consensus decision-making framework. In the following subsections, we present the principal contributions of this thesis work.

1.8.1 Trust-based decision-making

Our first contribution in this thesis is to study the effect of trust on the consensus process in terms of the number of rounds, consensus degree convergence and consensus achievement. Our result showed that trust was effective in decreasing the number of rounds by approximately 4 and increasing the consensus achievement by 77%. Moreover, trust affects the rating matrix perturbation by 82% increment, 2% no change and 16% decrements, whereas it is 100% no change if there is no trust taken into consideration. Moreover, there is a moderate negative correlation of -0.45 between perturbation and the number of rounds. Therefore, increasing the matrix perturbation can be useful in decreasing the number of rounds.

1.8.2 The distribution of stakeholders' preferences

Our second contribution is to study the effect of the stakeholders preference distribution on consensus achievement and the speed of the consensus process. Our result showed that the assumption of normal distribution performed better than the random distribution, as the number of projects that achieved the consensus increased by 1.3% with normal distribution, and the consensus speed decreased by 3 rounds with normal distribution.

1.8.3 The aggregation operators selection

Our third contribution is to study the performance of the aggregation operators on the proposed framework. The aggregation operators are the weighted sum (WS), the weighted product (WP), the weighted product similarity measure (WPSM) and the weighted exponent similarity measure (WESM). Different performance measurements were considered such as degree of consensus, correlation between starting consensus and speed of convergence, correlation between ratings matrix perturbation and the number of rounds and changing the consensus threshold selection

Degree of consensus

Projects with WPSM and WPEM produce high consensus under the assumption of trust. The same was true with WA and WP but with lower performance.

Correlation between Starting consensus and speed of convergence

We studied the starting consensus degree of each operator to determine if it has an effect on the number of rounds. WS and WP had lower starting consensus compared with WPSM and WESM. WS and WP started with values between 0.4 and 0.8, whereas WPSM and WESM started with values between 0.8 and 0.95. However, our results showed that having a larger starting consensus degree did not necessarily decrease the number of rounds. For example, the average number of rounds for WS and WP was 6, which is faster than WPSM by 4 rounds, but at the same time, WESM had a larger starting consensus than them.

Correlation between Ratings matrix perturbation and number of rounds

We studies the rating matrix perturbation of each operator to determine if such perturbation would have an effect on the number of rounds. Our result showed that WS has a negative moderate correlation, 0.54 and WP has a negative moderate correlation, -0.6, while WPSM has no correlation, 0, and WPEM has a moderate positive correlation. This means the WS and WP operators were sensitive to the changes of the ratings more than the other operators.

Different consensus threshold selection

The selection of the consensus threshold has an effect on the number of rounds needed and the consensus achievement. In terms of the number of rounds, WPSM has the worst performance when the threshold is 1 and its number of rounds is larger by 4. However, when decreasing the consensus threshold to 0.90, WPSM became faster by reducing the number of rounds by 1, 2 and 3 compared to WESM, WS and WP, respectively. Similar to the consensus achievement, with WPSM, the achievement is lower by 78% and is higher than WESM, WS and WP by 1%, 4% and 6%, respectively.

1.9 Dissertation Structure

- Chapter 2 Survey of Multi-stakeholder Decision-Making based on Trust and Risk. Chapter 2 presents the existing schemes of using trust and risk in decision-making, whether it is individual or multi-stakeholder. It shows the group decision-making process, model, and application for each scheme and addresses the limitations that can be solved by the framework proposed in this thesis.

- Chapter 3 Trust-Based Multi-stakeholder Decision Making in Water Allocation System. Chapter 3 builds a multi-stakeholder Decision-Making Model having these characteristics: trust, damages, and benefits as criteria, trust is associated with the involvement of the human. The model is dynamic by adapting to the changes over time. The decision to select is the solution that is fair with almost everyone. This model is the basis for building the generic framework in chapter 4.

- Chapter 4 Multi-stakeholder Consensus Decision-Making based on Trust: A Generic Framework. Chapter 4 presents the design of the proposed framework by showing the components involved. It describes the simulator built for implementing the framework design and then evaluates the effect of trust on the decision-making performance in terms of reaching an agreement and reducing the time required to achieve the agreement.

- Chapter 5 Rating Matrix Perturbation in the Multi-stakeholder Decision-Making Framework. Chapter 5 presents the changes in the rating matrix during stakeholders negotiations throughout the rounds being held. It measures the changes by considering the concept of matrix perturbation, where such a change can lead to the convergence of the consensus threshold.

- Chapter 6 Rating Aggregation in the Multi-stakeholder Decision-Making Framework. Chapter 6 studies the potential operators for rating aggregations and compares their performance using the simulator built for the framework.

- Chapter 7 Conclusions. Chapter 7 summarizes the thesis study, highlights thesis contributions, and uses the thesis results to recommend future research directions.

2. SURVEY IN MULTI-STAKEHOLDER DECISION-MAKING BASED ON TRUST

2.1 Abstract

Decision-making is expected to be encountered in many aspects of peoples lives and is involved in fields such as economy, business, health care, and education. There are also different methods of making a decision as well as various factors that affect making such decisions. Decision-making, therefore, depends on the context. It can be individual or group level. Group decisions are more challenging than individual decisions because of the existence of conflicting objectives among the participants or stakeholders. Group decisions may require negotiation, which involve the stakeholders influences on each other. Such influences could be acquired from the trust among them. Therefore, trust is used as a criterion for making group decisions. Usually, the decisions come with consequences even if it is short term or long term; therefore, it is important to put those consequences into consideration before making any selections. Such consequences can be addressed by perceived risk. The main contribution of this chapter is that it applies trust and risk in the study of multistakeholder decision-making by considering the use these factors as decision criteria. Additionally, we study multistakeholder decision-making processes and models based on our analysis of existing works.

2.2 Introduction

In real life, people encounter different situations, ranging from critical to noncritical, that entail making a selection among several options. Therefore, there have to be some techniques or methods that help people with the selection process. Trust and risk are criteria used for decision-making because of the uncertainty of consequences involved in these situations. One study [5] stated that ”Risk and trust are two tools for making decisions in an uncertain environment.”

In multistakeholder decision-making, a group of people proposes an action or solution. From a psychological perspective, each individual in the group builds an impression toward others based on his or her selection or experience. As a result, we can imagine a network of participants who represent nodes and the links between them are the feelings they build for each other. This impression can be translated to trust. In this situation, each person proposes a solution that is feasible to him- or herself regardless of the effect it may have on others. Therefore, the multistakeholder decision-making model should help reach a solution that benefits everyone and prevents damage to the network of participants.

Numerous works on decision-making use different factors depending on the field and even the applications within the fields. Those factors can be used to model trust. Several studies [5–12] showed that trust influences decision-making. Moreover, every decision comes with consequences and, as a result, makes risk another important criterion in decision-making. The use and application of trust and risk as the two criteria in decision-making are beneficial.

Trust can be a result of the decision makers expertise or experiences as well as the interaction between the decision maker and other entities (e.g., humans and machines). Several studies [13–23] model these interactions and translate it to trust. Risk can be the result of estimating the potential damage or loss that may occur following the outcome of the decision [5, 6, 8–13, 15, 17–20].Furthermore, when two entities interact with each other, such interactions, which can influence decision-making, can be risky [14, 16, 21–23].

It is necessary to survey multistakeholder decision-making schemes to determine how to use trust value and risk value when making decisions. Various trust systems have been proposed, such as [24–34], including our framework [35–45]. This system has three phases, one of which is decision-making [35]. The outcome of the trust management step is a trust value, which is then used in the decision-making phase subsequently. (Figure 2.1).

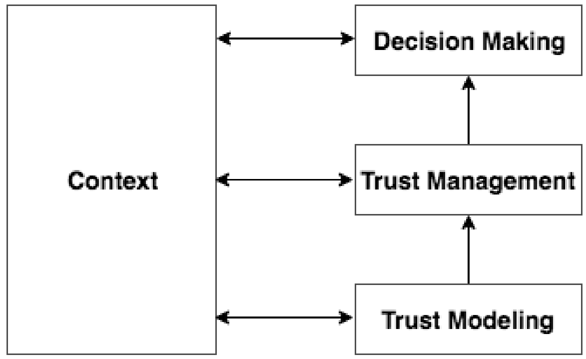

Fig. 2.1. Trust Framework which has three phases, each phase depends on the previous one.

This trust framework is based on measurement theory. To use the trust value for decision making, we need to acquire knowledge about what others have done regarding it. This trust management framework has been represented by [36], and it has been stated that trust modeling and decision making phases are dependent on context. The main contributions in this chapter are:

- Study the relationship between trust and risk.
- Study multistakeholder decision-making process and models.
- Survey individual decision-making schemes based on trust and risk.
- Survey multistakeholder decision-making schemes based on trust and risk.
- Analyze the challenges of existing multistakeholder decision-making schemes.

There are several challenges associated with multistakeholder decision-making. For example, the participants may come from various backgrounds and have different expertise. Also, the participants may have partial views about the problem domain as well as have conflicting objectives. Regarding the use of trust and risk in a decision, several challenges, such as risk quantification and, more specifically, rare events or those that have never occurred, arise as well. Another challenge can emerge from knowing how to apply trust and risk as decision criteria.

To the best of our knowledge, this is the first survey of multistakeholder decision-making using trust and risk. The outcomes of this survey include classifying the processes of multistakeholder decision-making and knowing the trust and risk models that were used for making decisions.

This chapter is organized as follows: In Section 2.3, we investigate different definitions of trust and risk, then we introduce the possible relationships between them by analyzing existing related works. Next, in Section 2.4, we discuss trust and risk in multistakeholder decision-making by presenting decision-making theories and existing multistakeholder decision-making schemes. In Section 2.5, we conclude the chapter.

2.3 Trust and Risk

In this section, we discuss trust and risk concepts by listing some definitions and possible classifications.

2.3.1 Trust

The definition and evaluation of trust can be challenging because trust depends on the context. For each context, several factors model the trust. One study [46] pointed out, "There is a consensus that trust depends on a variety of trust dimensions. However, there is no fixed set of such dimensions." According to another study [47], "Manifestations of trust are easy to recognize because we experience and rely on it every day, but at the same time trust is quite challenging to define because it manifests itself in many different forms." When trust comes into the picture, uncertainty follows. A study [48] stated that "trust relationships can be expressed as subjective opinions with degrees of uncertainty."

There is no exact universal definition for it according to one study [49], Another [50] indicated that many researchers use the definition of trust in a very specific form relating to topics, such as authentication, or the ability to pay for purchases. Some authors defined trust with risk [51, 52] . One study [53] defined trust as the level of reliance placed on an entity based on experience of a particular context. One study [18] viewed the trust concept as the degree of confidence given to an entity. Another [54] considered trust as an assurance among participants while engaging in online auctions. Many researchers defined trust as a subjective probability that leads an individual to believe that another person will behave as expected [19] and as a particular level of subjective probability in which an agent assesses one or more agents to perform a specific action [47, 55–57].

Many researchers see trust as an expectation [15, 58, 59]. For instance, one study [58] stated that trust is "psychological expectations or subjective belief that people think the trusted party will fulfill his obligations as their expectations." Trust has also been defined as "the extent to which one party is willing to depend on somebody, or something, in a given situation with a feeling of relative security, even though negative consequences are possible" [5, 47, 60]. Trust has been defined with vulnerability; one study [17] stated that "trust definition is mainly based on the vulnerability that the trusting party is exposed to by this trust relation, and both positive and negative actions taken against this vulnerability by the trusted party." Some authors view trust as "users thoughts, feelings, emotions, or behaviors that occur when they feel that an agent can be relied upon to act in their best interest when they give up direct control" [22].

Trust can be classified into several types. For example, one study [51] classified trust as communication, information, social, and cognitive. Another study [61] classified trust to be either generalized or specific. Yet another [62] classified it as relational or calculative. Relational depends on the relations between the parties while calculative depends on past behavior. One study [47] divided trust into reliability trust (probability of transaction success) and decision trust (risk attitude defined by the decision surface). It also sorted trust as being subjective (sources point of view) or objective (trustworthiness of the object).

2.3.2 Risk

Similar to trust, risk depends on the context as well. However, several works interpret risk as the probability of a negative event occurring. When taking risk into consideration, it is important to identify then evaluate it. The evaluation can be qualitative or quantitative. One study [60] defined risk as finding the balance between the likely cost and the possible reward. The cost is based on the likelihood of harm and its magnitude, which can be hard to asses. Another study [59] defined risk perception as the "trustors belief about likelihoods of gains and losses." Yet another study [63] defined risk as the probability of exploitation of vulnerabilities in terms of software. One study [64] mentioned the ISO/IEC TR 133351 definition of risk, which is related to the likelihood of exploiting vulnerabilities. Risk was also defined as the likelihood of an unwanted event and its consequence according to some studies [19, 53].

According to one study [54], perceived risk is defined as customers uncertainty of outcomes while performing an action. One study [65] stated that risk corresponds to uncertainty in outcome when making any decision. Another study [23] said that risk applies to situations when one is uncertain about the outcome. Another study [21] described risk as the consumers belief about potential adverse outcomes in uncertain situations. In one study [66], they described risk as the probability of making a loss. Another study [67] defined it as "the likelihood of violation of a basic security property enforced by the system. Basic properties include confidentiality, integrity, authenticity and non-repudiation."

From the above definitions, risk seems to depend on the possibility of a negative event occurring and the consequent amount of loss. Thus, risk evaluation is associated with probabilistic analysis. According to one study [68], risk is classified as subjective and objective or systematic and nonsystematic. Risk can also be categorized in the way it is evaluated and analyzed, such as through quantitative analysis or qualitative analysis.

2.3.3 Relationship Between Trust and Risk

It is necessary to understand the relationship between trust and risk to know how to use them for decision-making. According to our analysis of previous works, there are many types of relationships. The following subsections show those types of relationships with the corresponding existing works.

Risk influences trust

In this relationship, risk may influence trust calculation, trust definition and trust relationships. Many works have shown how risk can influence trust. Some studies [51, 69] have shown that risk affects trust relationships. Other studies [70, 71] have shown that perceived risk has a positive influence on trusting human decisions and consumer trust. However, trust is associated with lower perceived risk [50, 59, 72]. When calculating trust, the risk variable can be used [13, 73, 74]. Risk can be used to derive a definition of trust called decision trust [5]. One study [75] used a risk management model to develop trust policies. Another [54] viewed risk as a precursor of trust.

Trust influences risk

In this relationship, trust may influence risk calculation, risk assessment, risk mitigation, risk relationship, and risk management. In terms of risk calculation, some studies [11, 14, 76] used trust values from direct interactions for risk computation. One study [77] incorporated trust in risk assessments, and another [78] investigated how trust and control may mitigate risk. In terms of risk relationship, one study [79] illustrated that risk inversely depends on trust. If trust is high, then risk is small, and if trust is low, then risk is high. Another study [80] mentioned that parties who trust each other are more tolerant of risks. Another study [58] discussed the relationship between trust and perceived risk and mentioned that users trust in operators and application service providers would reduce the perceived risk of users. One study [81] showed that risk and trust are in an inverse relationship. For instance, riskier activities require a higher level of trust. Risk, in other words, is calculated based on trust. One study [21] stated that trust influences purchase intentions directly by influencing risk perceptions. Some studies [62, 82] showed the role of trust in risk management.

Complements to each other

Trust and risk can be viewed as complements to each other. One study [49] demonstrated that most systems consider trust and risk as complementary or ignore them. In our opinion, having such a relationship might lead to the use of one of them as a factor for decision-making because the other one is its complement. For example, if we say that one interaction has a trust value of 0.8, then the risk is 0.2. Therefore, we can use one of them to make the decision to proceed or not proceed.

No relationship

It is also possible that there is no connection between trust and risk. For example, trust can be considered as a property of principles but risk as a property of a process [49]. One study [21] showed that it is common to treat trust and risk as different concepts. In our opinion, this is practical if we deal with trust as a property of an entity that can make decisions and uses risk as a property of the decision itself. For example, someone is trying to decide whether to go on a picnic. He or she may ask two people whether it will rain. In this example, the individual needs to evaluate which of the two people is better at prediction; this can be translated into trust. He or she must then evaluate the consequences of each decision; this is evaluating risk. At the end, the person will make the decision based on trust and risk.

Other relationships

There are other relationships between trust and risk than the ones mentioned earlier. For example, trust can be part of risk or vice versa. One study [83] stated that trust management could be characterized as a special case of risk management, focusing on authentication of and cooperation with actors whose identities and intentions may be uncertain. According to one study [55] , researchers agree that trustworthiness is a more general issue than risk. Other studies [84–86] discussed the following risk-taking behaviors. For example, the truster would have more risk-taking behavior when the level of trust is high. As another example, the truster would need to accept some residual risks using trust assumption. Trust and risk should work together to avoid ambiguity according to one study [13]. Similarly, another [68] stated that risk is always associated with trust. Another study [87] mentioned that that if there is no risk involved, then trust does not need to exist. The relationship between trust and risk may be unclear because it is difficult to tell which one influences the other as shown by one study [54] .

2.4 Using Trust and Risk in Multi-stakeholder Decision-Making

2.4.1 Decision-Making Theory

Theories and concepts

Decision theory can be divided into two branches, normative and descriptive. The descriptive model aims to predict behavior while the normative model seeks to observe how ideal people might behave. One study [88] stated that "Emphasis has been placed on the normative aspects of human behavior, i.e., how a rational! A person or a group of rational persons ought to behave, as distinct from descriptive theories, which are to explain and predict actual human behavior." Therefore, decision-making models can relate to any of these branches. However, the central question is whether we can categorize each model to belong to a particular branch or not. According to one study [89], there is a little difficulty in categorizing some models as a clearly a descriptive or normative.

Expected utility theory is an important theory to address in terms of decision-making. Utility theory measures preferences related to decisions. One study [90] mentioned that economists and others have been developing mathematical theories regarding how people make choices among alternatives. "These theories center on the notion of the subjective value, or utility, of the alternatives among which the decider must choose" . People behave rationally when they have transitive preferences and that they make a selection that maximizes the expected utility. The basis of expected utility theory is the vN-M (Von Neumann-Morgenstern) theory. The vN-M utility theory is useful because it can be used for modeling risk by including it in an axiomatic foundation [91].

Decision-making can be done based on the preferences of actions. Savage presented some axioms for restricting preferences over a set of actions. The purpose of Savages theory is to relate uncertainty or partial belief to rational preferences [92]. He proves that rational preference can be represented in term of subjective probability and utility measure. The primitive elements in Savages theory are the set of states, set of acts, and the preference relations. Expected utility can represent rational preferences. The set of outcomes is also considered and can be represented by the set of states because outcome is a new state.

Multiple Criteria Decision Making

Multiple Criteria Decision Making (MCDM) makes a decision based on more than one criteria. One study [93] stated that "Multiple Criteria Decision Making is a discipline largely used to solve complex decision problems involving more than one criterion." Several challenges, such as the choice of criteria and the weight assignment for each criterion, arise with MCDM. Some studies [94, 95] proposed works to address a situation in which the weight is entirely unknown. Many MCDM techniques aim to solve selection and ranking or sorting problems. One study [96] listed the following common MCDM methods: weighted sum method, weighted product method, ELECTRE (Elimination and Choice Translating Reality), AHP (Analytic Hierarchy Process), and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution).

Another study [97] stated that the weighted sum method is the best known and simplest multicriteria decision-making method. If we assume that it is better to have a higher value of criteria, then the best alternative should have the maximum score among other alternatives. The score of each alternative can be calculated by multiplying each of the alternatives criterion values by the associated weight, then sum the result. The weighted product method is similar to the weighted sum method but uses the product instead of the sum. The ELECTRE technique selects the best alternative from a set of alternatives. However, according to one study [98], ELECTRE is not the best decision aid. In AHP [99–101], one study [102] stated that this technique is effective in situations where judgments are made subjectively from different people. The TOPSIS technique [96, 103–105] selects the option that is the closest to the most ideal solution and the furthest one to the negative ideal solution.

Trust and risk in individual decision-making

Some multistakeholder decision-making models involve individual decision makers who prefer to make individual decisions before sharing it with others. Therefore, we study the existing individual decision-making schemes with corresponding models to analyze the way individual decisions are made. Several decision-making models exist regardless of the criteria used. For example, some researchers [6, 8, 24, 106, 107] proposed that their algorithms take predefined criteria as an input to produce the result of decision-making as an output. Utility or expected utility is one of the other approaches. Expected utility takes into consideration peoples preferences about the available choices with uncertain outcomes. Some researchers [7, 23, 81, 108–113] used the expected utility value as a criterion for decision-making. In some cases, this utility value is related to risk. Some works [9, 10, 12–15, 17–21, 64, 73, 80, 114–122] used predefined policies or rules to make decisions. For example, one can put a threshold value for trust and another for risk then compare the computed trust and risk values to these threshold values. If the values meet the policy condition or rule, the next step is to perform a particular action associated with the decision outcomes. Some researchers [123, 124] used MCDM for producing decision outcomes. Some works [5, 11,16,22,53,68,79,83,125–127] mentioned the criteria used in decision-making without specifying how to use them for producing decision outcomes or without mentioning the decision-making approach. Table 2.1 shows a list of the existing individual decision-making schemes with the corresponding trust model, risk model, and decision-making models.

Table 2.1.: List of existing individual decision-making schemes with their trust, risk, and decision-making models

Schemes	**Trust**	**Risk**	**DM Model**
Alcalde & et al [6]	Function over reputation, recommendation, competence, and context	Information System Security Risk Management	Algorithm
Sen & et al [7]	Higher utility outcomes	Maximum Expected Utility	Expected Utility
Jiang & et al [109]	FluidTrust model	Number of successful interactions	Expected Utility
Ahmadi & et al [8]	Recommendation-based trust	Adaptive risk	Algorithm
Dimmock & et al [115]	SECURE Trust Model	Costs & likelihoods of possible outcomes	Policy
Dickson & et al [73]	Impression,reputation and risk attitude	Risk attitude of the customer	Policy
Wang & et al [79]	Transaction history, other peers' evaluation, old transaction amounts and the new transaction amount	Transaction trust value	N/A

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Table 2.1.: *continued*

Schemes	Trust	Risk	DM Model
Li & et al [13]	Game voting algorithm	Utility function	Policy
Li & et al [116]	Mapping from space (Subject, Operation)	Mapping from space (Operation, object)	Policy
Yao & et al [9]	Cumulative number of response correctly incorrectly	Cost and resources consumed	Policy
Hu & et al [10]	Normal distribution	Utility function	Policy
Zuo & et al [14]	p2p transaction	Based on trust values from the direct interactions	Policy
Ruizhong & et al [15]	Perceived Risk	Economic, time, functional, service social and privacy risk	Policy
Ye [16]	Feedback elements of online communication	Privacy, financial, functional, time , source, consignation, paying and mental riskS	N/A
Duan & et al [11]	Latest observation and the history trust data units	The centrality degree and average trust degree	N/A

continued on next page

Table 2.1.: *continued*

Schemes	**Trust**	**Risk**	**DM Model**
Cayirci [17]	Periodical data weighted using their freshness. Eliminate a security threat by recovering from a service outage	Periodical data weighted using their freshness. Security and service outage.	Policy
Pereira & et al [18]	Positive/negative feedback	Distance from the point of occurrence of pheromone deposition and the similarity of interest of each agent	Policy
Burnett & et al [19]	Subjective Logic model	Risk-aware authorization function	Policy
Liu & et al [64]	Three-Dimension Friendship Model	Probability of an object being illegally exposed or tempered and subsequent loss	Policy
Cho & et al [20]	Personality characteristics	Personality characteristics	Policy
Quercia & et al [81]	Agent cooperation	Computation of likelihoods Based on trust	Expected Utility
Sang & et al [5]	Reliability trust and decision trust	The decision surface which defines an agent's risk attitude	N/A

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Table 2.1.: *continued*

Schemes	**Trust**	**Risk**	**DM Model**
Grazioli & et al [12]	Grazioli, Jarvenpaa and the theory of deception by Johnson about trustworthy of the store	Grazioli, Jarvenpaa and the theory of deception by Johnson about the riskiness of the site	Policy
Patrick [22]	Ability to trust, experience, predictable performance, comprehensive information,shared values, communication and interface design	Based on uncertainty, personal details, alternatives and autonomy	N/A
Dimmock & et al [23]	SECURE Trust Model	SECURE risk model	Expected Utility

2.4.2 Changing preferences

Interactions among stakeholders when they make a collective decision is important since they negotiate while they are seeking for a solution to choose. In decision-making framework that uses machines for moderate the stakeholder negotiations, the interaction could be rating or even written comment to express the others opinion regarding the individuals choices and preferences [128–136]. Such notion of preferences occurs in decision-making field [137]. The individuals' preferences can be changed over the time due to the changes in the interests. Those interests change can be a result of the influence by the others [138], the choices made before or even other factors that are based on the individuals situation at the time of making selection. Several studies showed that the individual interest and preferences are changing [138–145] and these study are different in term of the causes that lead changing the preferences. In [141], they predicted the changes in preferences based on the feedback of the negotiation process. [142] presented the dominant theories of belief change that may be called input-assimilating models. They expressed how the subject's belief state is transformed upon assimilation of an input. In addition to the different factors that change the individuals' preferences, the choices proposed while making a decision may affect the preferences or in other word, it shapes them [145]. There is a study [138] explained the change the initial preference of an individual to match the others choices, either through coercion from others or selection by the individual team member. Preferences changes can be short term or long term [137,144,146,147]. Short term preferences affect the current choices while negotiating but the long term one affects the choices in the future. In social psychology field where they study the peoples' behavior, there are different theories that predict the preferences changes. For example, dissonance theory [139, 148, 149] motivates individuals to change their preferences to match their prior decision that can be a result of a selection they made in the past based on influence.

Multi-stakeholder decision-making

Decision-making is not limited only to an individuals decision. Some scenarios involve more than one person to make a decision. In these cases, it is called multi-stakeholders or GDM (group decision-making) [150–168]. One member involved in a group no longer makes the final decision without the involvement of other members. For example, when recruiting a new person in a company, several employees from administration will be involved in the decision. Each person will give his or her decisions, and the final decision will depend on all individuals opinions. In social settings, different approaches, such as taking the average of all the participant responses or taking the majority decision as final, have been proposed. For example, one study [24] proposed a GDM model that involves participants ranging from expert to novice. This approach employs the trust model to help in the decision process. If an individual cannot make his or her preference, then he or she seeks the advice of other member based on trust. Another study [111] used aggregated decision-making in urban planning. Each agent makes their evaluations of benefit, cost, and risk of the available alternatives. These assessments will then be aggregated to form a group decision. One study [169] combined the GDM method with AHP to evaluate the risk.

Arrows impossibility theorem is used in the field of GDM. According to one study [170], "When we consider the group decision-making problem (with more than two choices), it is clear that it would be nice to have a fair procedure that combined the individuals preferences about the alternatives (expressed as rankings) into a statement about the groups preferences about the alternatives while preserving the autonomy of each individual."

Multi-stakeholder decision-making process

The involvement of multiple participants when making a decision makes it essential to construct a process that takes each individual selection into consideration to reach a final decision. There are different types of multistakeholder decision-making processes. However, based on our analysis of the existing works, we found that the three common processes are consensus, ranking, and voting. Table5.1 shows the description of these methods and their corresponding challenges. An important point to mention is that there are some GDM scenarios that combine more than a GDM process.

Voting, for example, is considered a simple method because it involves making a decision based on the majority vote. However, its limitation comes from treating all participants equally even though they are different in terms of expertise. Also, the outcome of voting may be unsatisfactory for the members whose decisions received less votes [27]. Consensus, however, does have the advantage of reaching a solution that is agreed by everyone [26]. Thus, the decision makers need to negotiate several rounds, and in each round, they must modify their proposed solutions to be decided by other participants. However, this has its limitation as the participants cannot influence others, which could lead to an infinite number of rounds. The ranking process is used in several multistakeholder decision-making model by ranking the suggestions of each participant [28]. This has the advantage of knowing the degree of group convergence, which is useful in selecting the solution that receives the higher ranking. However, its limitation is the difficulty of ranking a large number of decisions. Also, it is possible that each participant will rank the solutions but will give his or her own the highest ranking.

In terms of using trust on those processes, it has been applied in a different way like obtaining the advices from the trusted individuals or weighting each alternative with the trust of the individual. One study [24] used trust for the consensus process and showed that the consensus decision is reached when decision makers adjust their preferences, such as the importance of the decision criteria, which can be obtained from the advice of other trusted participants. One study [25] selected the solution with the highest trust value to reach a consensus. This trust value is formulated using the decision-makers interactions when they propose suggestions. One study [26] proposed a GDM model that first creates a trust network that reflects the participants opinions toward others based on the proposed solutions. In other words, this trust value considers the participants weights when aggregating proposed decisions. For the voting process, one study [27] aggregated single votes to a single collective decision and used trust to weight the influences of the decision makers in decision-making. Another study [29] also used trust in voting to show the tendency of making a decision in favor of another participant.

One study [28] proposed a multistakeholder decision-making model to rank the preferences. However, in some cases, the decision makers may not have enough information about some alternatives to accurately rank them. Therefore, the decision makers opinion about such alternatives is influenced by other experts he or she trusts.

Table 2.2.
List of common Multi-stakeholder decision-making process with the associated challenges

Process	**Description**	**Challenges**
Voting	Take the majoritys opinion	The outcome is winning or not wining.Treat participants equally
Consensus	Consider the group decision instead of selecting one	The outcome is hard to reach if there is conflict
Ranking	Show the degree in which the group preferences converge	Difficulty to rank the large number of decisions

Multi-stakeholder Decision-Making Models

According to one study [171], there are five classes of GDM models. The first model, GDM1, assumes that the decision makers propose then aggregate their individual solutions, rank them based on their utilities, and finally select the highest ranked solution. In the second model, GDM2, the decision makers propose their individual solutions and use them as preferences when voting. In the third model, GDM3, there is a supra-decision maker that manages the decision-making process among the decision makers. The fourth model, GDM4, finds group utility to reach a consensus. In the fifth model, DGM5, the decision makers use the bargaining theory. There is no model better than the others because each model is useful in specific applications. For example, GDM1 is useful for applications that take individual preferences into account, GDM2 for applications that use voting as a decision-making process, GDM3 for applications where there is a hierarchy among participants, GDM4 for applications that take group preferences for the consensus process into account, and GDM5 for applications that deal with resource allocations.

2.4.3 Trust in Multi-stakeholder Decision-Making

Trust in multistakeholder decision-making is crucial [25] because it is a valuable group component and is essential in the collaboration process. It becomes, however, a further complicated or more dependent parameter when an expert may be uncertain, have incomplete information, or cannot access information. Experts have to use their domain expertise to arrive at a decision. An expert may give his or her subjective preferences, but they may not be agreed to by other team members. In such situations, experts have to collaborate, exchange information, and arrive at a consensus. One study [172] stated that "Trust can reflect the actual reputation between experts because it uses the history of an experts actions or behavior. Therefore, it should be taken into account as a reliable source to be used in deriving aggregation weights for individual experts." As a matter of a fact, trust can be used in the decision-making process to weight the influence of different decision makers [27].

Several schemes for multistakeholder decision-making vary in terms of the trust model as well as the GDM model and process. In addition, each of the schemes comes with limitations. For example, some schemes [24, 24, 25, 29, 31–33] do not allow the stakeholder to modify the decision outcome because there is a fixed set of decisions to select from. Such fixed outcomes limit the stakeholders ability to propose a new outcome. Some schemes [27, 28] apply preferences ordering. A large number of preferences is challenging to the stakeholder to order. In addition, each stakeholder might rank his or her own preference higher if he or she is the one proposing the decision outcome. Some schemes [26, 34] do not use historical interactions; they may lead to missing extra information that might help the stakeholder when proposing solutions and selecting the final decision. Some schemes [26, 30] limit trust to specific stakeholders, which leads to limited information in the problem domain. Figure 2.2 lists the limitations of existing multistakeholder decision-making schemes.

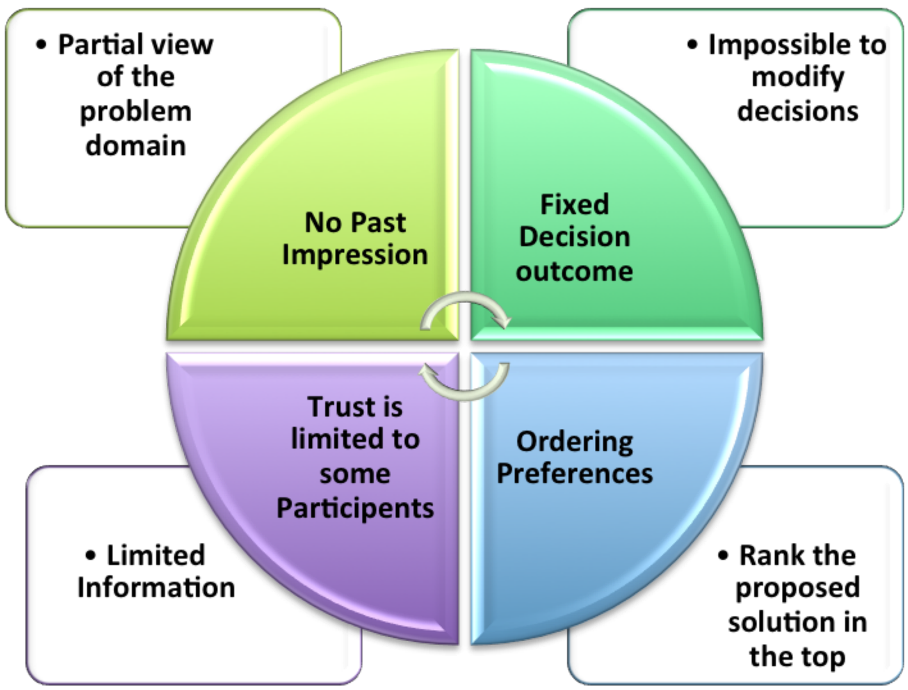

Fig. 2.2. Limitations of Existing Multistakeholder Decision-making Schemes

Table 2.3 shows the existing multistakeholder decision-making schemes with the corresponding trust model, GDM process and model, limitations, and applications.

Table 2.3.: Multistakeholder decision-making schemes with the corresponding trust model, group decision-making process, group decision-making model, the limitation and the application

Scheme	**Trust Model**	**GDM Process**	**GDM Model**	**Limitation**	**Application**
[24] Tundjungsari, Istiyanto et al	Direct interaction between participants	Consensus	GDM3	Fixed Decision outcomes	Urban planning
[25] Indiramma and Anandakumar	Direct experience/social interaction	Consensus	GDM1	Fixed Decision outcomes	Soil erosion
[26] Alonso, Perez et al	Opinions of all the experts involved in the process	Consensus	GDM2	No past impression and the trust is limited to some participants	Online and web systems
[27] Rodriguez	Similarity and expertise	Voting	GDM1 & 2	Ordering Preferences	Social decision support system

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Table 2.3.: *continued*

Scheme	**Trust Model**	**GDM Process**	**GDM Model**	**Limitation**	**Application**
[28] Capuano, Chiclana et al	The history of past actions and behavior	Ranking	GDM1	Ordering Preferences	Incomplete information
[29] Lau, Singh and Tan Scheme	Agent tendency of accepting other agent to join	Voting	GDM2	Fixed Decision outcomes	Multi-agents system
[30] Sanchez-Anguix, Julian et al	Full knowledge about the information	Voting	GDM3	Trust is limited to some participants	Bilateral alternating protocol in electronic systems
[31] Wu, Chiclana et al	Social Network Analysis with incomplete linguistic information.	Consensus	GDM1	Fixed Decision outcomes	Incomplete Linguistic Information Context

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Table 2.3.: *continued*

Scheme	**Trust Model**	**GDM Process**	**GDM Model**	**Limitation**	**Application**
[33] Wu, Chiclana et al	Social Network Analysis	Consensus	GDM1	Fixed Decision outcomes	Cloud service suppliers
[32] Liu, Liang et al	Opinions of the experts	Consensus	GDM1	Fixed Decision outcomes	Cloud services selection
[34] Park, Cho et al	Expertise for each criterion	Consensus	GDM1	Fixed Decision outcomes and no past impression	Supplier selection

Tundjungsari, Istiyanto et al

Tundjungsari, Istiyanto et al [24] proposed a multistakeholder decision-making model for urban planning in rural areas . In their scheme, they combined a trust model proposed by Abdul-rahman and Hailes [173] and the GDM3 model that assigns a supra-decision maker to manage the consensus process. Basically, the supra-decision maker adjusts other decision makers preferences of the possible alternatives and weights the criteria to reach a consensus. The trust model includes a trust level [1,4] that shows the role of the decision maker and a trust value [-1,4] that is the result of interaction between two decision makers. If a trustee has more than one route, then the average of the trust value is calculated. This scheme is useful for applications that require assigning different roles to decision makers based on trust. The trust value is not used directly in the decision-making outcome.

Indiramma and Anandakumar

The authors proposed a multistakeholder decision-making model for soil erosion applications [25]. In their scheme, they showed a multi-agent-based collaborative decision-making framework for distributed environments, where a group of agents collaborate on social issues. The proposed framework uses social parameters to reach a consensus in decision-making. Trust is strengthened by familiarity and similarity beliefs and evaluated during collaboration. The agents update their trust values dynamically when discussing decisions. The trust value is in the range of [0,1]. The proposed decision model starts by collecting the decision makers decisions and allows each agent to discuss any decisions, criteria, and conflicts. The trust values are then computed and aggregated, and each agent rates those trust values. The highest trusted decision is selected as the final decision. Therefore, the trust value is used directly to reach the decision-making outcome.

Alonso, Perez et al

The authors proposed a multistakeholder decision-making model for applications that involve large numbers of decision makers [26]. In their scheme, a group of experts will first be simplified into a smaller group via clustering, but it will still maintain the diversity of the groups opinions. Therefore, there are two groups: the selected expert and the nonselected expert groups. The nonselected expert group provides the utility toward the selected ones to establish the trust network. After, the consensus process, which has several rounds, begins. In each round, the selected experts show their preferences for the available options, then the consensus level is checked. The final step in this model involves the initiation of the selection process using aggregation of opinions and preferences, which is done via an IOWA (induced ordered weighted averaging)operator. A trust network is only established in a scenario that does not use previous trust information from other situations

Rodriguez

The author proposed a multistakeholder decision-making model for social decision support system applications [27]. In this scheme, the author proposed a process consisting of three serial stages. The first stage is individual solution ranking, where individuals review solutions to a problem and rank them based on their opinion. The second stage is collective solution ranking, which uses voting. The third stage is solution selection from collective solution ranking. Trust reflects the similarity and expertise of the individuals and is used to weight the influence of decision makers in the decision-making process. Conditional probability (i.e., the probability that B is a good individual given that A knows B) represents the degree of trust.

Capuano, Chiclana et al

The authors proposed a multistakeholder decision-making model for applications that have incomplete information [28]. In their scheme, they proposed a model that adopts fuzzy rankings to collect experts preferences on available alternatives and trust statements on other experts. Sometimes, experts cannot express an opinion on any of the available alternatives, leading to incomplete information. Therefore, to estimate the missing preferences, the Social Influence Network (SIN) addresses the experts influences. Then, the aggregation process is applied, followed by selection of the best alternative. Inclusion of elements captured from the opinions of trusted experts uses trust to evolve the opinions of each expert. Degree of trust is used to weight the FPR (fuzzy preference relation). Analysis of the data from social networks computes trust.

Lau, Singh and Tan Scheme

The authors proposed a multistakeholder decision-making model for coalition formation applications in multiagent system environments [29]. In their scheme, they proposed a weighted voting mechanism (WVM) that allows agents to join existing coalitions. There are two types of votes: agreement and disagreement. The trust element is the main criterion for deciding the weight in the voting session. The trust ration can be low, medium, or high.

Sanchez-Anguix, Julian et al

The authors proposed a multistakeholder decision-making model for a bilateral alternating protocol in electronic systems [30]. In their scheme, they proposed a mediated negotiation model for agent-based teams that negotiate with an opponent. This negotiation model defines the communication protocol with the opponent and the decisions of the negotiation team. Trust only applies to the group meditator because he manages the negotiation process and counts the votes from the team members. There is a maximum number of rounds assigned by the opponent.

Wu, Chiclana et al

The authors proposed a multistakeholder decision-making model for incomplete linguistic information contexts [31]. They proposed a trust propagation method to derive trust from incomplete connected trust networks. The decision-making model consists of computing trust degrees; estimating unknown preference values; determining the consensus index, consensus identification, recommendation, and feedback; and establishing a selection process. When the decision-making process starts, each alternative is presented with criteria. At times, the expert may not provide an assessment. As a result, trust is useful for getting a recommendation from trusted experts. Their decision-making model is useful for cases where preferences as well as the usage of linguistic value are missing. Similarly, they proposed a decision-making model [33] that is different from one [31] that employs dual trust (trust, distrust) and nonlinguistic assessments.

Liu, Liang et al

The authors proposed a multistakeholder decision-making model for cloud service suppliers [32]. The proposed decision-making model consists of four stages: "(1) Constructing the interval-valued trust decision making space; (2) Determining the consensus degree at three levels; (3) Visual consensus identification, trust induced recommendation and rationality analysis; and (4) Selection Process.". This model has the advantage of having a fewer number of rounds by using the harmony degree in addition to the consensus degree.

Park, Cho et al

The authors proposed a multistakeholder decision-making model for supplier selection [34]. The proposed scheme uses the stakeholder trustworthiness as an influencing factor on the final decision. The decision-making process uses weighted scoring system, where the trustworthiness are used for the weights. Moreover, decision alternatives ranking is applied in this decision-making scheme.

2.4.4 Risk in Multi-stakeholder Decision Making

Due to the consequences that might occur following the decision, using such consequences as decision criteria could be practical to decision makers. Table 2.4 summarizes the existing GDM model with the corresponding risk model.

Li, Kendall et al

In an environmentally conscious world [111] , they proposed a decision support approach that allows individual agents to make their own evaluations of benefit, cost, and risk over available alternatives. Then it aggregates individuals alternatives to form a group decision. They modeled the risk based on evidence supporting logic and expected utility theory.

Pham,Tran et al

The authors proposed a scheme for business settings [174]. The experiments show that applying the model for the quantification of expert sensibilities, together with common sense human reasoning, enhances the capability to best select alternatives that will achieve the greatest investment returns and reduces losses to be able to handle various domains in dynamic environments. In their approach, they aggregated expert preferences and sensibilities, quantified by a self-organizing map (SOM), in order to select appropriate alternatives.

Table 2.4.
Multi-stakeholder decision-making scheme with the associated Risk Model and the decision process

Scheme	**Description**	**Risk Model**	**GDM Process**
[111]	Group decision making process that allow agents to express their utilities or evaluations over different alternatives	Based on evidence support logic and expected utility theory	Voting
[174]	Dynamic group decision making which aggregates expert preferences and sensibilities, quantified by Self-Organizing Map (SOM) in order to select appropriate alternatives	Human Reasoning = fuzzy rules, quantitative knowledge and reasoning evidence	N/A
[175]	Risk-oriented group decision making for modeling the inherent risk in the multi-criteria group decision making process	Subjective assessments	Ranking

Wibowo and Deng

In the project selection problem [175] , the authors demonstrated the problem of evaluating and selecting a supply-chain management information-system project.

They proposed a GDM for modeling the inherent risk in the multicriteria GDM process. Subjective assessments model this risk.

2.5 Conclusion

Decision-making is deeply interwoven in peoples lives and is saturated in almost every field. It also incorporates various methods and factors that can affect the outcome of a decision. Thus, decision-making depends on the context. It can be individual or collaborative, which can be more challenging because of the existence of the conflicting objectives among stakeholders. Collaborative decisions may also require negotiation, which requires creating some level of trust among the participants. Usually, decisions come with consequences. Therefore, it is important to consider those consequences before making a decision. Decision makers use risk to assess possible consequences.

The main contribution of this chapter is analyzing the existing schemes of multistakeholder decision-making based on trust and risk. This chapter also explores the concepts of trust and risk and categorizes the relationship between them to investigate how to adopt them when designing a decision model. Moreover, we investigate some decision-making processes such as voting, consensus, ranking, and GDM models. For future work, we propose a generic multistakeholder decision-making framework that is applicable to every context and uses trust and risk for multiple stakeholders. The decision-making model will help to address several challenges, such as conflict in the interests of stakeholders, the partial view of the problem domain for each of them, and honesty when proposing a decision.

3. TRUST-BASED MULTI-STAKEHOLDER DECISION MAKING IN WATER ALLOCATION SYSTEM

3.1 Abstract

Water allocation domain requires collaboration among stakeholders when making any decision regarding the solution to use to get the maximum benefits with fewer damages. The challenging part of the water allocation system is the interactions among those entities with the existence of conflicts.Therefore, there has to be a decision-making model that takes the stakeholders into account when producing the best outcomes. Due to the involvement of people who make the decision, trust among them comes to the picture. Moreover, every solution is associated with a number of benefits and damages. Trust is used as primary criteria in decision-making model along with the damages and benefits associated with each solution. The main contribution of this chapter is to build a multi-stakeholder Decision-Making Model having these characteristics: trust, damages, and benefits as criteria, trust is associated with the involvement of the human. The model is dynamic by adapting to the changes over time. The decision to select is the solution that is fair with almost everyone.

3.2 Introduction

In this chapter, we propose decision-making model for Water Allocation system to help the participants to be able to select the solution comes from the best model. Several criteria involved when deciding on the model to choose such as Trust, Damage, and Benefit. The preferred scenario is when having a high trust, low damages, high benefits. The worst scenario is when having a low trust, high damage, and low benefit. Before discussing the computation of these criteria, it is important to introduce the entities and their attributes. The proposed model has many types of entities: organization, expert, model and the decision.

Our view about the problem domain involves a network of experts, and each one of them has an assigned trust value based on several factors such as interactions and the level of experiences. There are also a set of models with assigned trust value which is associated with the error of the model. Each proposed solution has benefits and damages. An important point to mention here is that the quantification of the trust is based on the management theory. We have proposed a trust model trust system [35–42]. This trust model has three stages: trust modeling, trust management, and decision making. The quantification of the trust has been taken care of in the trust modeling and management phases. The value comes out of the trust management phase will be applied in the decision stage (Figure 2.1)

When the project starts, each expert proposes a solution about the amounts of water to divide among everyone. The system will filter out the model according to the extreme damages. Therefore, the model with extreme damages will be excluded from the selection. The result is a subset of models. Then Each expert rates the proposed solutions as well as rates other experts to model the trust. Since each model is associated with damages, then such damages lead to a risky decision.

As it can be seen, this decision-making model can be described as collaborative and dynamic one. Collaborative because it is a group decision making, dynamic because it adapts to the changes over time.

In this chapter, we will list the existing works in section 3.3. Then, in section 3.4, we will address the trust and describe its meaning to the problem domain. In section 3.5, we list some possible ways of ratings and explain them by examples. In section 3.6, we present our proposed Multi-stakeholder Decision Making based on Trust. We apply the proposed model to a scenario in section 3.7. Finally, we conclude the chapter and show the future direction in section 3.8.

3.3 Related work

There are several works related to decision-making while using the trust as criteria. These works are different in term of trust model and decision-making technique. By analyzing the existing works, we may classify the decision-making techniques to algorithmic, policy, MCDM (Multicriteria Decision Making) approaches.

Trust as decision criteria has been applied to many existing works in different applications such as e-banking environment, [6] , online social networks [109], multi-agent system world [8,18], access control [11,19,64,115,116], economy [73], p2p (peer to peer) [10, 12–16, 21, 68, 79], mobile payment [22, 58] , voting [9] , cloud computing [17], cyberspace applications [20], spam detection application [23], mobile interaction applications [81] , general application [5]. In term of group decision making using trust, several works were proposed in different fields. [24–30, 172, 176–178]. In term of making the decision about Fragmentation-Free Land Allocation with multi-stakeholder, [179] proposed work and it has been stated that "We introduce three frameworks for land allocation planning, namely collaborative geodesign, spatial optimization and a hybrid model of the two, to help stakeholders resolve the dilemma between increasing food production capacity and improving water quality. ". [4] has proposed a multi-stakeholder framework for urban runoff quality management and showed results by using three methods of negotiations such as a non-cooperative game, Nash model and social choice procedures.

3.4 Trust

Trust is a result of meeting expectation and reaching a level of satisfaction toward other entities in particular context. Therefore, there is no universal definition of trust since it is context-dependent. In general, we formulate a trust toward other entity based on our interaction with them or the level of knowledge in the case of human and the reliability in case of a model. The factors which are corresponding to the interaction and model reliability depends on the context. Figure 3.1 shows the chain

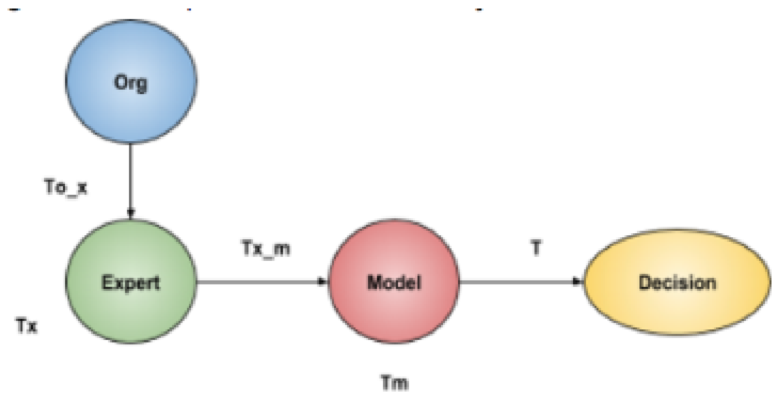


Fig. 3.1. Trust chain among entities in the Water Allocation system

of the trust assigned to the entities in our problem domain. In the chain, there is a trust between organization and expert, To_x,. There is a trust assigned to expert based on some criteria contributes to human trust, Tx. There is also a trust from the expert given to the model Tx_m. The model also has its trust. The result of the chain of the trust is a final trust value T which contributes to the decision-making criteria. Each expert is assigned a trust value based on others judgment toward him; we call it human trust.This kind of trust is between the humans in the human networks. It can be quantified by the Social communications between members, Experience, Background, Number of years of Experience, Profile similarity and Friendship. There is also a trust relationship between experts and models; we call it Human-to-Model Trust. This kind of the trust is the one given to the model by the human. It can be quantified by the frequency of using the model and model ratings. There is also trust related to the model, but without human judgment, we call it Model Trust. It is helpful because it contributes to the error of the model. Therefore, the factor that quantifies this value is the reliability of the model.

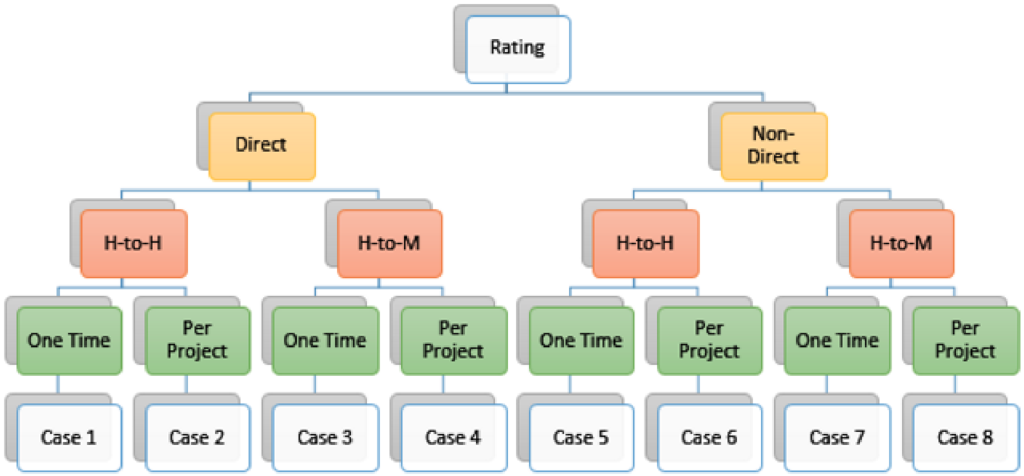


Fig. 3.2. Rating hierarchy structure which involves Direct and non-direct rating as well as Human to human and Model to Model ratings (H-to-H, H-to-M). Some ratings are given during the project and some are not (Per Project, One Time).

3.5 Possible cases of rating

The possible cases are shown in Figure 3.2. The rating has been first classified to Direct and Non-Direct. Next, each class is classified according to the rating target, Human or Model knowing that the source of the rating is always human. Then each class is further classified according to the relevancy to the project, One time or Per Project.

The following are the criteria to rate about human and model. Some of these criteria depend on the project (Per Project), and some are not (One Time):

- Human Criteria (One time): Years of Experience and Friendships.
- Human Criteria (Per project): Model Selections.
- Model Criteria (One time): Reliability.
- Model Criteria (Per project): Benefits, Damages, and Outcomes.

3.6 Multi-stakeholder Decision Making based on Trust

Knowing that there are different approaches to decision making is very helpful when building a decision-making model. In our view, the decision-making model is based on a particular algorithm we design (Algorithm 1). Additionally, the rules and policy approach will also be used in case of having group decision making to restrict the decision makers to the predefined policies like the maximum total amount of water to allocate. So, our decision-making model is a combination of these approaches we surveyed. The ultimate goal is to select a model with less damage and high benefit. This ultimate goal is easy to find for an individual stakeholder. However, with multi-stakeholder, it is challenging. Therefore each stakeholder computes the fairness of his solution to estimate his solution fairness to the others.

Algorithm 1 Solution Selection Algorithm based on Trust

$S = getStakeholders()$

$Soutions = selectSolutions()$

$Damages = ComputeDamages(Solutions)$

$Benefits = ComputeBenefits(Solutions)$

$Utilities = ComputeUtilities(Damages, Benefits)$

each Si rate solution Mj

$T = calculateTrust(S, M)$

$Fairness = Jain(Utilities, numberofstakeholders)$

$weightedFairness = WF(Fairness, T)$

Figure 3.3 shows the system workflow of this decision-making model. There are several steps. First, each stakeholder calculates the damages and benefits of the solution they choose to use those damages and benefits to compute the utilities. Then, the utilities are computed by subtracting the damages from the benefits corresponding to the stakeholders for each solution. Next, each stakeholder rates the others about their proposed solutions to show whether he agrees or not with the solution. As a

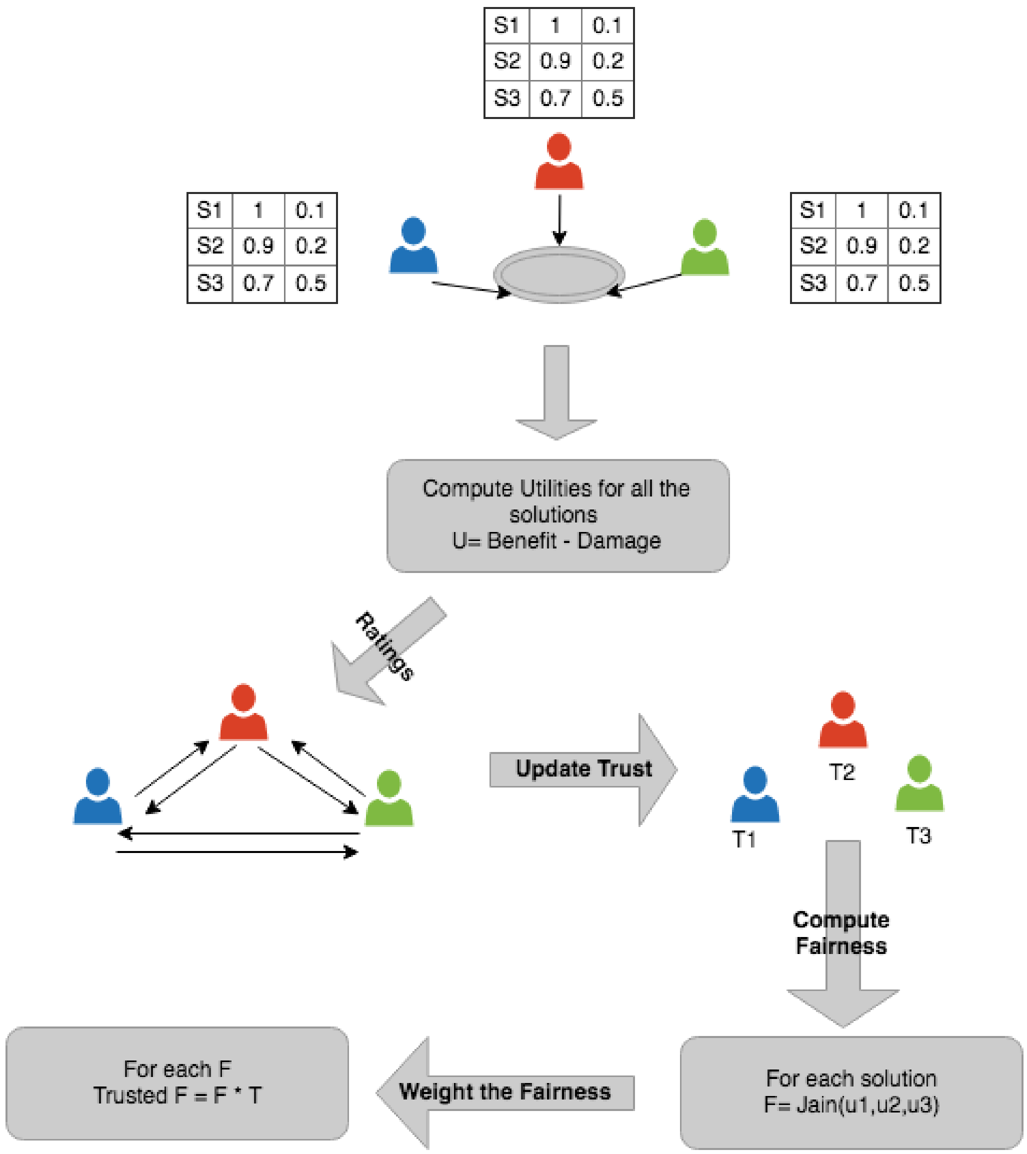


Fig. 3.3. System workflow which has several steps. It starts with proposing solution and the associated benefits and damages. Then, computing utilities, rating solutions, updating trust network and computing fairness for each solution

result, the trust value of each stakeholder is updated based on our existing trust trust system [35–42] . After that, each stakeholder computes the fairness to guarantee that is everyone happy with the amount to take. The fairness formula is proposed by Jain [180] (equation 4.1). Finally, Weigh the fairness calculated by the corresponding

Table 3.1.
Round 1, List of stakeholders and the corresponding trust values

Stakeholder	Trust Value
David	0.9
Steve	0.8
John	1

Trust value. If the stakeholders agree with a particular solution due to the best trusted-fairness then, this solution is selected. Otherwise, the stakeholder enters another round repeating the same steps but with new solutions.

$$Jain(x_1, x_2, ..x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n * \sum_{i=1}^{n} x_i^2} \quad (3.1)$$

3.7 Experiment and Result

In this section, we are going to apply the proposed solution to a water allocation by giving a scenario consists of two rounds.

3.7.1 Round 1

To simulate the water allocation scenario for the first round, we assume that three stakeholders have conflicts. These stakeholders have assigned trust value based on historical interaction and their profiles. Table 3.1 shows this kind of information. Then, each one of them proposes a solution which is an amount of water to share with other stakeholders. Table 3.2, table 3.3 and table 3.4 shows the solutions proposed by David, Steve and John respectively. After this step, the stakeholders start rating each other. Table 3.5 shows the rating details. The rating is a 5-star system, five is the best, and one is the worst. Based on the above ratings, the trust of each stakeholder is

Table 3.2.
Round 1, The solution proposed by David showing the percentage of water for each stakeholders and the corresponding benefit, damage and the calculated utility which is the damage subtracted from the benefit

Stakeholder	**Water percentage**	**Benefit**	**Damage**	**Utility**
David	50%	1	0.1	0.9
Steve	20%	0.9	0.2	0.7
John	30%	0.7	0.5	0.2

Table 3.3.
Round 1, The solution proposed by Steve showing the percentage of water for each stakeholders and the corresponding benefit, damage and the calculated utility which is the damage subtracted from the benefit

Stakeholder	**Water percentage**	**Benefit**	**Damage**	**Utility**
David	40%	0.9	0.1	0.8
Steve	30 %	1	0.1	0.9
John	30%	1	0.2	0.8

changed. So, it is going to be 0.8, 0.9 and 1 for David, Steve, and John.After updating the trust value, the fairness index is quantified using the utilities computed by each stakeholder. The fairness index is calculated according to Jain's fairness index using equation 4.2

$$F = \frac{(\sum_{i=1}^{n} u_i)^2}{n * \sum_{i=1}^{n} u_i^2} \tag{3.2}$$

Where U is the utility. Table 3.6 shows the computed fairness index for each proposed solution. Finally, the stakeholder decides on which solution to take by considering

Table 3.4.
Round 1, The solution proposed by John showing the percentage of water for each stakeholders and the corresponding benefit, damage and the calculated utility which is the damage subtracted from the benefit

Stakeholder	**Water percentage**	**Benefit**	**Damage**	**Utility**
David	40%	0.9	0.1	0.8
Steve	25%	1	0.2	0.8
John	35%	1	0.1	0.9

Table 3.5.
Round 1, Rating values from each stakeholders to others about the solutions proposed. This value contributes to updating the trust value for each participant

Stakeholder (from)	**Stakeholder (to)**	**Stars**
David	Steve	5
David	John	5
Steve	David	1
Steve	John	5
John	David	1
John	Steve	5

the maximum trusted-fairness index. If they do not agree then they repeat the above process until they decide on a solution.

Table 3.6.
Round 1, the fairness index values and the weighted fairness index values for all the solutions proposed by the stakeholders.

Stakeholder	Fairness	Trusted Fairness
David	0.805	0.64
Steve	0.818	0.73
John	0.996	0.996

Table 3.7.
Round 2, List of stakeholders and the corresponding trust values

Stakeholder	Trust Value
David	0.8
Steve	0.9
John	1

3.7.2 Round 2

Table 3.7 shows stakeholders and the assigned trust value. Then, each one of them proposes a solution which is an amount of water to share with other stakeholders. Table 3.8, table 3.9 and table 3.10 shows the solutions proposed by David, Steve and John respectively. After this step, the stakeholders start rating each other. Table 3.11 shows the rating details. The rating is a 5-star system, five is the best, and one is the Based on the above ratings, the trust of each stakeholder is changed. So, it is going to be 0.7, 0.9 and 1 for David, Steve and John . After updating the trust value, the fairness index is quantified using the utilities computed by each stakeholder. The fairness index is calculated according to Jain's fairness index . Table 3.12 shows the

Table 3.8.
Round 2, The solution proposed by David showing the percentage of water for each stakeholders and the corresponding benefit, damage and the calculated utility which is the damage subtracted from the benefit

Stakeholder	**Water percentage**	**Benefit**	**Damage**	**Utility**
David	40%	1	0.1	0.9
Steve	20%	0.9	0.2	0.7
John	20%	0.7	0.1	0.6

Table 3.9.
Round 2, The solution proposed by Steve showing the percentage of water for each stakeholders and the corresponding benefit, damage and the calculated utility which is the damage subtracted from the benefit

Stakeholder	**Water percentage**	**Benefit**	**Damage**	**Utility**
David	40%	0.9	0.1	0.8
Steve	25%	1	0.1	0.9
John	30%	1	0.2	0.8

computed fairness index for each proposed solution. Finally, the stakeholder decides on which solution to take by considering the maximum trusted-fairness index. If they do not agree, then they repeat the above process until they decide on a solution.

Table 3.10.
Round 2, The solution proposed by John showing the percentage of water for each stakeholders and the corresponding benefit, damage and the calculated utility which is the damage subtracted from the benefit

Stakeholder	Water percentage	Benefit	Damage	Utility
David	40%	0.9	0.1	0.8
Steve	25%	1	0.2	0.8
John	35%	1	0.1	0.9

Table 3.11.
Round 2, Rating values from each stakeholders to others about the solutions proposed. This value contributes to updating the trust value for each participant

Stakeholder (from)	Stakeholder (to)	Stars
David	Steve	3
David	John	5
Steve	David	1
Steve	John	5
John	David	1
John	Steve	3

3.8 Conclusion

In this work, we presented trust-based multi-stakeholder decision-making model for water allocation to help the participants to be able to select the solution comes from the best model. Several criteria involved when deciding on the solution to choose such as Trust, Damage, and Benefit. The preferred scenario is when having a high

Table 3.12.
Round 2, the fairness index values and the weighted fairness index values for all the solutions proposed by the stakeholders.

Stakeholder	**Fairness**	**Trusted Fairness**
David	0.971	0.679
Steve	0.996	0.996
John	0.996	0.996

trust, low damages, high benefits. The worst scenario is when having a low trust, high damage, and low benefit. However, in reality, where different stakeholders are involved, it is challenging to reach a solution that creates balance for their needs of the resources. Therefore, in the decision-making process, Jain's fairness index has been considered as an indicator of reaching the balance or the equality for the stakeholders needs. Other challenges occur is that when the stakeholder is not reliable in term of knowledge and expertise, and then propose a solution by claiming it is fair for everyone. For this reason, we considered the trust among stakeholders to avoid such cases. Having Trusted Fairness is useful for ensuring the stakeholder reliability, reducing the stakeholder tendency to request the full amount of resources and increasing the stakeholder's reputation. However, even though the designed model helped in reaching the consensus, it has some limitations. The first one is that the agreement means having equality in the fairness despite the low benefit associated with the agreed solution to all the stakeholders. In reality, no one will gain from the selected outcome. The second one, the model requires estimating the damage and benefit. In fact, those factors are context-depended, and it is more practical to create an external entity to attach these both factors to the decision model. Chapter 4 addresses these limitations.

4. MULTI-STAKEHOLDER CONSENSUS DECISION-MAKING BASED ON TRUST: A GENERIC FRAMEWORK

4.1 Abstract

The decision-making process is one we encounter in every aspect of our lives, ranging from critical decisions to noncritical ones. Decision making becomes more challenging when dealing with multi-stakeholder decisions due to the existence of conflicts among them and the diversity in their expertise. As a result, the influence among them which is represented by trust is considered a criteria when making a final decision. Such trust is a result of the interactions among those stakeholders. Rating is one of the methods in interactions for stakeholders to express their opinions of one another. It requires a decision that is agreed upon by everyone, which might take several rounds before reaching a final consensus decision. In this chapter, we build a consensus decision-making framework based on Trust. Then we study the rating convergences in those decision-making rounds and investigate their convergences with and without trust. Our result showed that trust is useful in the consensus-creating process, as it decreases the number of necessary rounds and even creates a consensus when there is an extreme conflict in preferences.

4.2 Introduction

In consensus multi-stakeholder decision-making models, there is a network of experts who might or might not influence one another. They gather, propose solutions and modify them in several rounds to reach a solution that suits everyone. During these rounds, the stakeholders interact with each other to declare their opinions regarding the proposed solutions. Stakeholders can express their opinions with ratings, which can later be translated to trust. As a result, due to the involvement of humans who interact during the negotiation, trust comes into the picture. Trust has many benefits. For example, it provides extra information through the impression the stakeholders develop of each other over time in a particular context. Also, trust indicates whether stakeholders have similar interests. Moreover, trust determines the stakeholders honesty during negotiations. Therefore, the stakeholders reputations can be created using trust. The more interactions, the better because they increase the amount of information available about the individuals. The longer the history, the better because it increases the chances of having more interactions.

There are several challenges associated with Multi-Stakeholder Decision-Making:

- The participants come from different backgrounds.
- The participants have different expertise.
- The participants have a partial view of the problem domain.
- The participants objectives conflict with each other.

In this light, we are going to explain the possible cases of conflicting interests among stakeholders and the possibility of achieving consensus decisions associated with each conflict case. Also, we will create consensus decision scenarios with stakeholders who want to reach a consensus decision. Due to the involvement of ratings, we are going to study under what condition ratings increase.

When the stakeholders propose solutions, their choices might be based on either interests or the influence from one another. Therefore, the stakeholders might follow the Rational Choice Theory [3] when choosing a solution with a maximum interest. However, if we use this theory as an assumption while selecting the decisions, then we might end up with no consensus decision especially when the preferences of each stakeholder are far away from others' preferences. To resolve such conflict, Kelman

[181] presented the theme of Social Influence Theory where the individuals attitudes and actions are influenced by others. Such an influence can be obtained from the Trust.

In this chapter, we aim to propose a decision-making framework that has the following characteristics:

- collaborative due to the participants cooperation.
- trust-based due to the involvement of the humans.
- interest-based due to the involvement of the stakeholders' perceived risk with each decision.
- dynamic due to the changes of trust value after each interaction.
- a consensus outcome to guarantee that all the participants agree on one decision.

The chapter is organized as follows. In section 4.3, we list the existing related works. Then we show the generic decision-making framework in section 4.4. After that, we introduce the trust concept in section 4.5. In section 4.6, we address rating convergence and aggregations After that, we explain the experimental setup and results in sections 4.7 and 4.8. Finally, in section 4.9, we conclude the chapter.

4.3 Related Work

There are numerous works related to multi-stakeholder decision making in different areas; however, few of them use trust as a factor. According to [172], trust can reflect the actual reputation between experts because it uses the history of an experts actions or behaviors. Therefore, it should be taken into account as a reliable source in deriving aggregation weights for individual experts. In urban planning in a rural area application, [24] combined a trust model proposed by Abdul-rahman and Hailes [173] and the group decision-making model that assigns a supra decision maker to manage the consensus process. In Soil erosion application, [25] proposed a decision model that collects decision makers decisions and allows each agent to discuss each decision. Then the trust values are computed and aggregated, and each agent rates those trust values. In applications that involve large numbers of decision makers, [26] proposed a model that involves establishing a trust network by considering the utility. Then several rounds are held for the consensus process in which the selected experts have to declare their preferences concerning the alternatives. In social decision support system applications, [27] proposed a model that involves individual and collective solution ranking by using voting and solution selection from collective solution ranking. The trust is used to weigh decision makers influence in the decision- making process. In incomplete information application, [28] proposed a model that considers fuzzy rankings to collect experts preferences in available alternatives and trust statements on other experts. In a multi-agent system environment, [29] proposed weighted voting mechanisms (WVM), allowing agents to join existing coalitions. The trust element is the main criteria for deciding the weight in the voting session. In an Incomplete Linguistic Information Context application, [31] proposed a scheme that uses trust to get a recommendation from the trusted experts for the decision-making process. In cloud service suppliers applications, [32] proposed a model that consists of four stages: constructing the interval-valued trust, identifying the consensus degree, identifying visual consensus and the selection process. Each stakeholder in the decision-making process has preferences about the choices, which are rational ones. In this regard, the stakeholders tend to follow the rational choice theory [3]. Therefore, the stakeholders rank their individual choices according to their associated interests. The ranking of such choices might follow a specific distribution. For example, [182–186] addressed the normal distributions about the individual preferences. In this chapter, we will use these assumptions and the assumptions of having no specific distribution (order the individual preferences randomly). In multi-stakeholder decision making, each stakeholder has a preferred decision. Those preferences can be evaluated by other stakeholders to form collective opinions about them. Therefore, those opinions might be aggregated somehow. In some applications that involve human and their interactions, the evaluations from one human about another in a specific context can be expressed in different ways, such as by a written review, likes or even ratings, [128] which are defined as intended interpretations of user satisfaction in terms of numerical values. For example, online purchase sites like Amazon give the buyer and the seller the opportunity to evaluate each other by sending feedback in a 5-star rating system. In Twitter and Facebook, there are like and reply options. Expressing opinions by rating, for example, is very useful when making decisions [129–136]. Several studies showed rating convergence between humans after several interactions. The ratings tend to converge toward positive or negative depending on specific conditions. For example, [129] showed that the ratings converged toward an overall positive rating using data from TripAdvisor. Another study on TripAdvisor [187] indicated that the rating behavior relies on the level of satisfaction. If the raters are highly satisfied, then they tend to think carefully about the ratings they give but if there is no satisfaction, then they will provide scores of 1-4 randomly.

4.4 Multi-stakeholder Decision-Making Framework Based on Trust

We have designed a generic framework for multi-stakeholder decision making based on trust that produces a decision agreed upon by the participants. The framework takes into consideration the interest of each decision, which includes the stakeholders' perceived risk. In this framework, the stakeholders negotiate with each other to declare their agreement regarding the other solutions. In this section, we give an overview of our multi-stakeholder decision-making framework. Fig.4.1 shows our multi-stakeholder decision-making framework based on trust. It has several entities, as follow:

- Trust Model: Our proposed trust model [35–43] that is based on measurement theory.
- A network of individuals: The individuals are the nodes, and the links are the trust between each pair. The value is computed by the trust model.

- Solutions: The decisions proposed by the individuals
- Utility function: Each solution has an associated interest, which is objective. The interest value is calculated by the utility function.
- GDM model: Group Decision Making Model. It takes the proposed decisions and the trust corresponding to each and produces the consensus value.

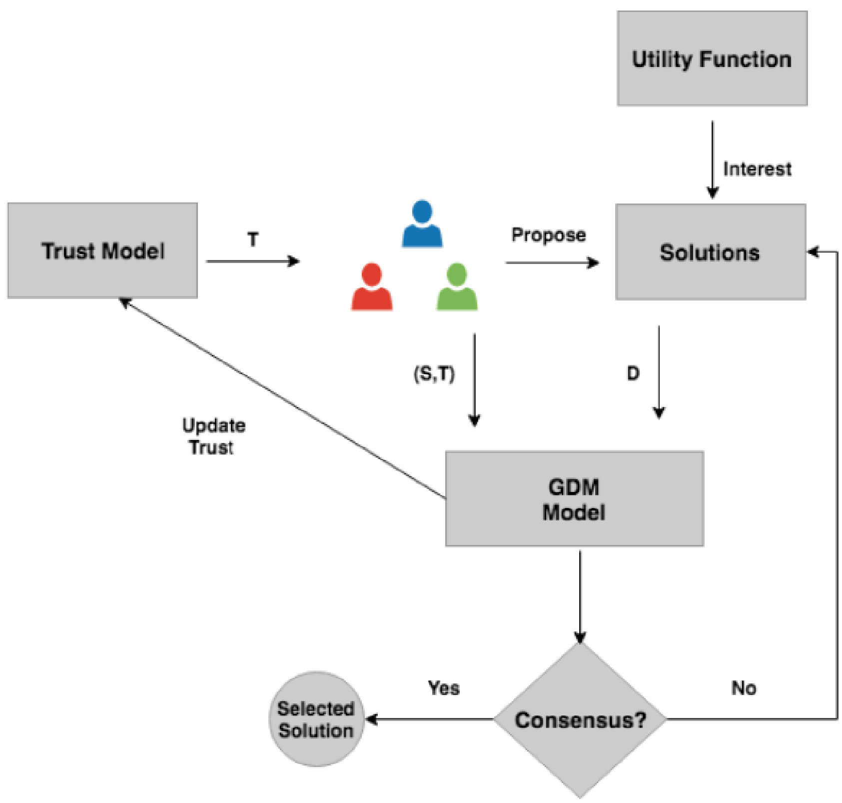


Fig. 4.1. Generic Framework of Multi-Stakeholder Decision Making.

An important point here is that there are two types of trust: local and global. The local trust is related to the ratings exchanged among stakeholders in every round. The global trust works as a reputation for the stakeholders by taking local trust and past local trust into account.

The process in this decision-making model starts with the stakeholders proposing their solutions. Each stakeholder has an assigned global trust value (Reputation). Each solution has an interest value that is obtained by the utility function. Then the stakeholders rate each other to declare their impressions of the proposed solutions. After that, the solutions are ranked descendingly based on the ratings. The consensus level is obtained by the rating that the solution received. Therefore, the top value should have a value equal or higher than a threshold value to indicate that consensus is achieved. Otherwise, a new round will start(Algorithm 2).

Algorithm 2 MSCDM Algorithm

```
for all P in Projects do
  while R < maxRound do
    S= getStakeholder();
    T= getTrust(S);
    D=proposeDecision();
    R=rate(D);
    G=Aggregate(R,D);
    Consensus=ComputeConsensus(G)
    if Consensus ≥ ConsensusThreshold then
      Go to the next project
    else
      Go to next round
    end if
  end while
end for
```

4.5 Trust

Trust is a result of meeting expectations and reaching a level of satisfaction with other entities in a particular context. Therefore, there is no universal definition of trust since it is context-dependent [49]. In general, an individual formulates trust in other entities based on his or her interaction with them or their levels of knowledge. We may define trust as the level of an individuals agreement with a proposed solution due to the interests or utility associated with it. We model trust by using the solution ratings during negotiation. We classify trust as local trust and global trust. Global trust is modeled by using all the historical interactions between any two individuals. This global trust creates the stakeholders reputations, which they use as power or weight to influence other decisions. Local trust consists of current negotiation interactions between any stakeholders. It is used later for updating the global trust.

We have proposed a trust system based on the measurement theory [35–43]. This trust system has three stages: trust modeling, trust management, and decision making (Fig.2.1). The quantification of trust has been taken care of in the trust modeling and management phases. The value that comes out of the trust management phase will be applied in the decision stage. The measurement theory, which is a branch of Applied Mathematics, is useful for quantification using a measurement. However, an error might occur corresponding to the value after measurement. As a result, finding and approximating such as an error is very important. This error can be treated as the measurements uncertainty. For instance, suppose someone wants to know how much he weighs. He will use a scale to find the weight. However, the weight might not give the exact value but only an approximation since different scales gives different measurements based on the scale brand.

In our trust system, we define two metrics, impression and confidence, as continuous values in [0, 1]. The impression m shows the stakeholders usefulness by evaluating his/her decision. Every two stakeholders have several interactions at different times, which lead to a distribution of their impressions of each other $M = \{m_1, m_2, \ldots, m_k\}$. The impression value is the mean of the distributions, m (4.1). The other metric, confidence c, shows the extent of certainty about the judgments. The confidence of the judgment is captured by knowing how far away from the real impression the stakeholder can be (4.2), where r is equivalent to the square root of the variance or standard error.

$$m = \frac{(\sum_{i=1}^{i=k} m_i)}{k} \tag{4.1}$$

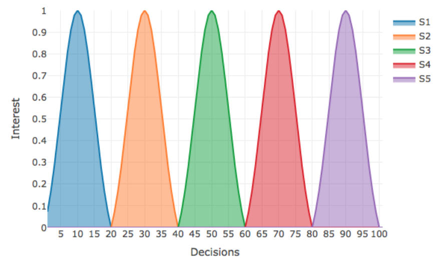
$$c = 1 - 2 * r \tag{4.2}$$

Two important operators in the proposed trust framework: transitivity and aggregation. Transitivity operator is useful in creating a trust link between any pair of stakeholder if there is no link between them. It helps to increase the density of the trust network which leads to gain more information about stakeholders interest. Aggregation operator is useful when there are more than one parallel paths between a pair of stakeholders. The global trust of any stakeholder could be computed as a weighted average of the impressions toward him or her and then using the confidence as a weight. For example, if shareholders j receives impressions and confidences pair (m_{ij},c_{ij}) from n stakeholders, then the trust value (T_j) of j is computed by (4.3) as:

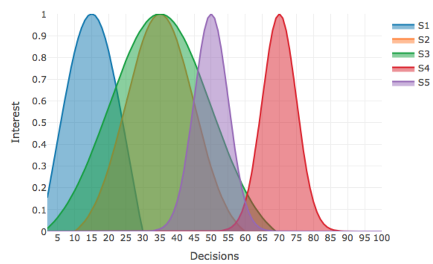
$$T_j = \frac{\sum_i^n m_{ij} * c_{ij}}{\sum_i^n c_{ij}} \tag{4.3}$$

4.6 Rating Convergence and Aggregation

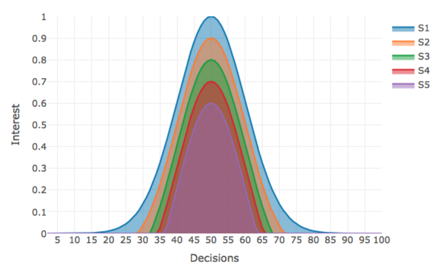
Conflicting interests among stakeholders might occur while they are making consensus decisions. There are three cases of conflict overlap; no overlap, semi-overlap and full overlap (Fig.4.2.(a), Fig.4.2.(b) and Fig.4.2.(c)). The difficulty of reaching consensus decisions depends on the stakeholders conflicting interests. Our interpretation is that trust offers extra information that guides the stakeholders and reduces the number of rounds required to reach final consensus decisions. Interactions among



(a) No overlap.



(b) Semi-overlap.



(c) Full overlap.

Fig. 4.2. The possible conflict of interest scenarios.

stakeholders are needed to formulate the consensus decision. In this light, the rating from each stakeholder of another regarding the proposed decisions can be used as a method of interaction. In each round, the ratings among stakeholders can be increased or decreased.

Let's assume that the rating system is 5-star rating and stakeholder a rates stakeholder b. If I_a represents the interest to a , D_a and D_b are the decisions proposed by a

and b respectively, then $I_a(D_a)$ is the a's interest from its own decision D_a and $I_a(D_b)$ is a's interest from the decision is proposed by b. If $I_a(D_b)$ is more than $I_a(D_a)$, then a gives b the maximum rating because b proposes a solution with good interest to a. Otherwise, we consider the difference between $I_a(D_a)$ and $I_a(D_b)$. The larger the difference the lower the rating and vice versa. Therefore, to find the star value associated with the difference, it requires to transform the difference value range to 5-star value range. The difference ($diff$) range is [0,1] and the start range is [0,5]. However, since the larger difference means lower rating, we need to find the transformation function, $f(diff)$, from [1,0] to [0,5], meaning to find value $rate$ in [0,5] associated with value $diff$ in [1,0]. If we assume the function to be linear, we may use the affine transformation function to find the rating from the differences.(4.4). Using the affine transformation function, we can calculate the rating using (4.5)

$$\text{function } f(diff) : [1, 0] \to [0, 5] \tag{4.4}$$

$$f(diff) = 5 * (1 - diff) \tag{4.5}$$

If b is highly trusted, $T_b high$, then the rating could be any number from the range between the output of (4.4) and the maximum start rating, 5. As a result, a rates b according to the following:

$$Rating_{ab} = \begin{cases} T_b high, & \text{rating= [f(diff),5]} \\ otherwise, & \text{rating=f(diff)} \end{cases}$$

The stakeholders rate each other during negotiation to show their impressions of the solution and their preferences. Those ratings have to be aggregated to compute the overall result of all ratings corresponding to each solution. The weighted average [188–194] is used as a method of aggregation. Suppose that there is a set of stakeholders, S, a set of decisions, D, and a set of corresponding trust values for each stakeholder. The stakeholders rate each other as represented in matrix R, where the element r_{ij} represents the rating from stakeholder i to stakeholder j regarding j's proposed solution. The associated trust for each stakeholder is represented in the vector T. The sum of the trust values is W. The rating weighted average is RWA and computed by using R, T and W (4.6), where T is used to weigh the ratings. The outcome is a vector of consensus degrees ($consensus_{di}$) corresponding to the proposed solutions. The $SelectedDecision$ is the decision with the maximum (max) consensus degree, which is later compared to $ConsensusThreshold$ to check the consensus achievement.

$$S = \{s_1, s_2, s_3\}$$
$$D = \{d_1, d_2, d_3\}$$
$$T = \begin{bmatrix} T_1 & T_2 & T_3 \end{bmatrix}$$
$$W = \sum_{n=1}^{3} T_n$$
$$R = \begin{bmatrix} 1 & r_{12} & r_{13} \\ r_{21} & 1 & r_{23} \\ r_{31} & r_{32} & 1 \end{bmatrix}$$

$$RWA = \frac{1}{W} * T * R \tag{4.6}$$

$$RWA = \begin{bmatrix} consensus_{d1} & consensus_{d2} & consensus_{d3} \end{bmatrix}$$
$$SelectedDecision = max(RWA)$$

$$Consensus = \begin{cases} Yes, & SelectedDecision = ConsensusThreshold \\ No, & \text{otherwise.} \end{cases}$$

4.7 Experiment setup

The aim of the experiment is to study the effect of trust on the consensus process among stakeholders. Such an effect can be examined through the number of required rounds, the consensus degree average in each round, and the consensus achievements. We have designed and implemented a simulation to generate decision-making scenarios. We used a Netbeans framework with java language to build the simulation software. To store the data, we created a database using derby and then linked it to the java program (Fig.4.3).

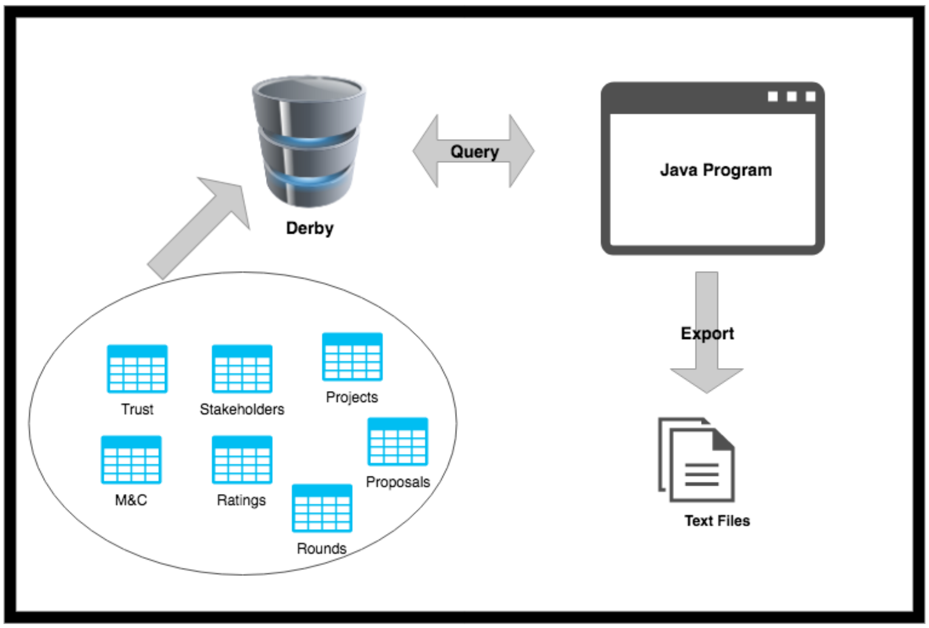


Fig. 4.3. Simulation Design

Table B.1 shows the parameter setup. The stakeholders have been divided into 3 groups based on the conflict of interest. Then we ran the simulations using these groups, one with trust and another without. We generated the interests of decisions for each stakeholder to facilitate the proposing and rating process by randomly generating a number between 0 and 1.0 for the decisions corresponding to every stakeholder. Also, we generated another set of interest of decisions by producing numbers that follow a normal distribution. The stakeholders start a round by proposing solutions of high interest to them. Then they rate each other. After that, the consensus is computed by aggregating those ratings. If the consensus degree is lower than the consensus threshold, a new round starts. The stakeholders have the option to mod-

Table 4.1.
List of the parameters used in the simulation with their corresponding values

Parameter	Description	Value
$NoSH$	Number of StakeHolders	1000
$numbStakehoder$	Number of StakeHolders per project	5
$globalNoD$	Total number of possible decisions to select when proposing	1000
$pCount$	Number of Projects generated	12000
$roundCount$	Maximum Number of rounds per project	10
T	Trust Value range	[0,1]
$Interest$	Interest Value range	[0,1]
$consThreshold$	Minimum Consensus Degree	1.0

ify their decisions by choosing the decision that has more interest to others than the previous rounds decision or keeping the same decision proposed in the previous round.

4.8 Results

The simulation has been executed under the above assumptions using two types of preference models: Random and Normal Distributions. For the random experiment, we assumed that the stakeholders preferences do not follow any distribution.

The assumption of the rational choice theory is associated with the "no trust" scenarios, meaning the selection depends on the solutions with the expected interests. The scenario tested with trust is also under the assumption of the rational choice theory but with taking the social influence theory into accounts, meaning the selection either depend on the solutions with the expected interests or the solution proposed

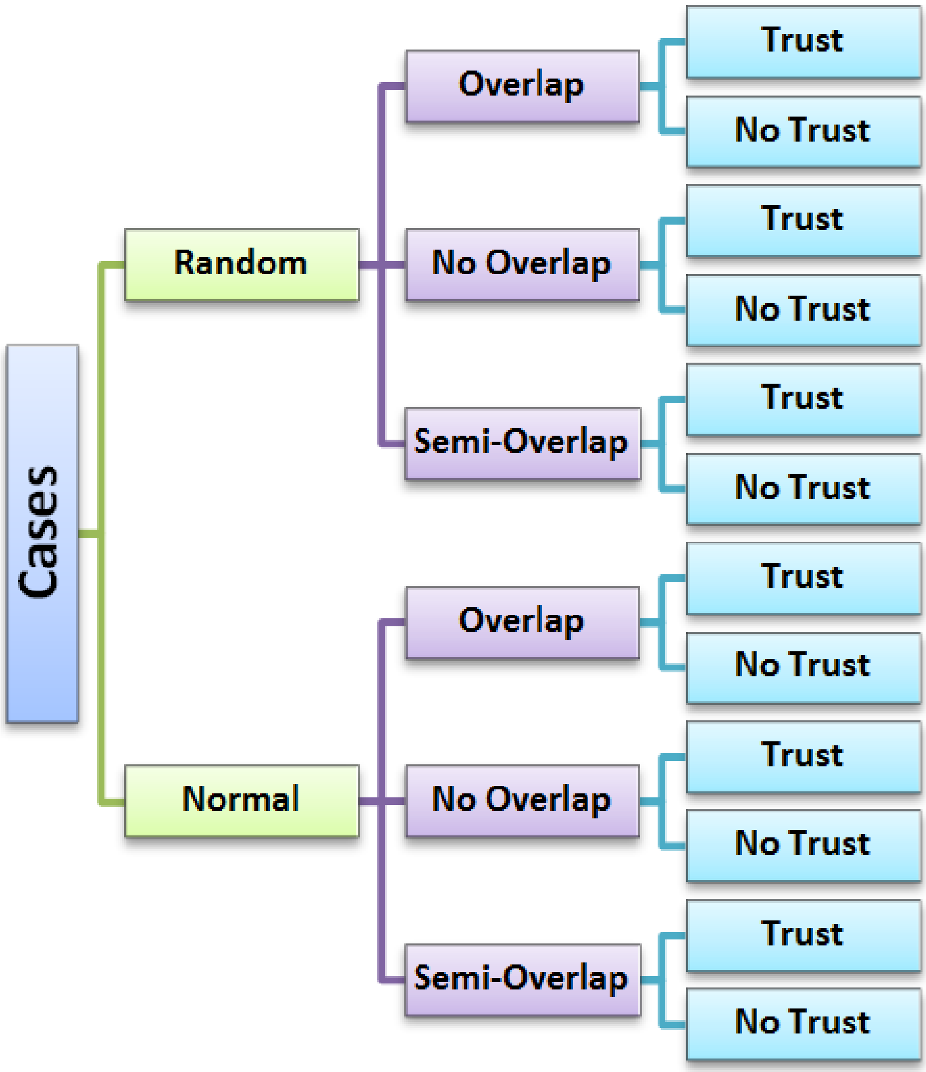
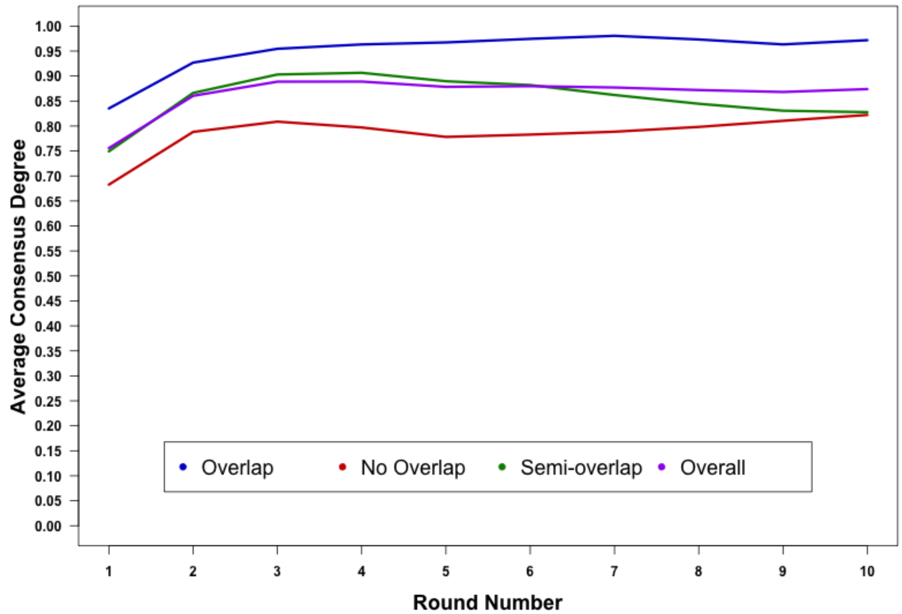
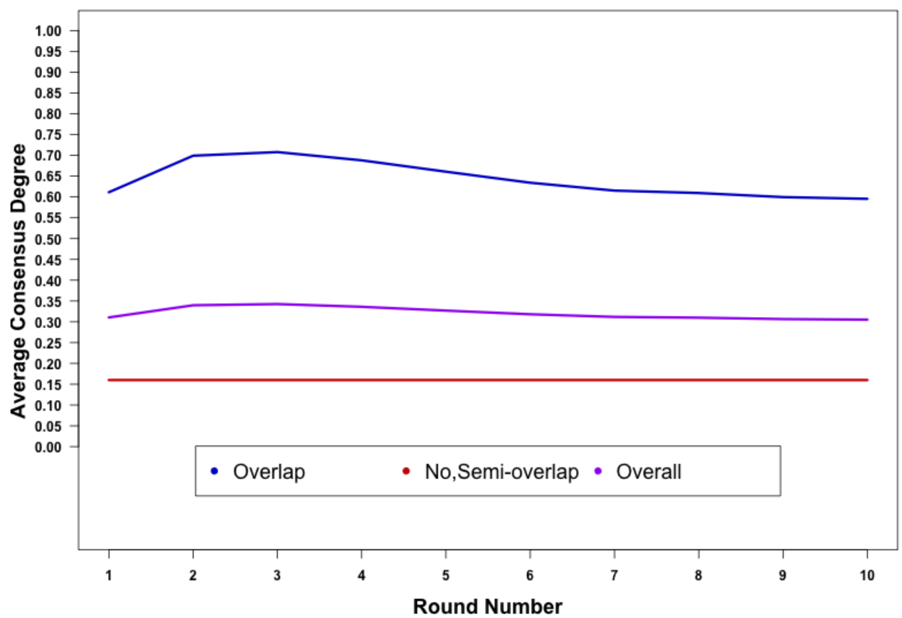


Fig. 4.4. The tree structure of the cases considered in the simulation

by the stakeholder with high influence on others. Fig.4.4 shows the cases that have been considered in the simulation.



(a) With Trust.



(b) Without Trust.

Fig. 4.5. Average Consensus Degree in each round for projects for Random preferences

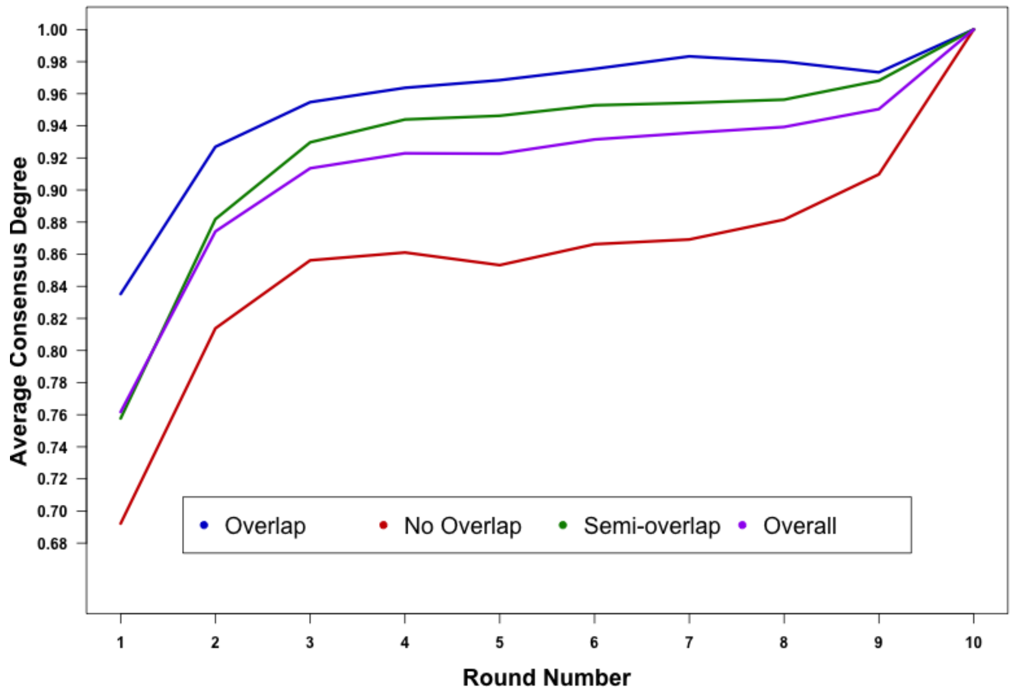


Fig. 4.6. Average Consensus Degree in each round for projects that reached the consensus with Trust for Random Preferences.

Fig.4.5 shows the average consensus degree associated with each round for all projects. Fig.4.5.(a) reflects the average consensus when taking trust into account, which indicates an increase in consensus value compared to Fig.4.5.(b), which does not consider trust.

For the projects that reached consensus after we applied trust, the experiment showed that the consensus degree tends to increase in subsequent rounds (Fig.4.6).

For the cases where the stakeholders have no overlap in interest, it is impossible to reach an agreement. However, when we applied trust, the experiment showed that an agreement was reachable (Fig.4.7).

For the normal distribution experiment, we assumed that the preferences follow the normal model. The results were similar to the random preferences case. However,

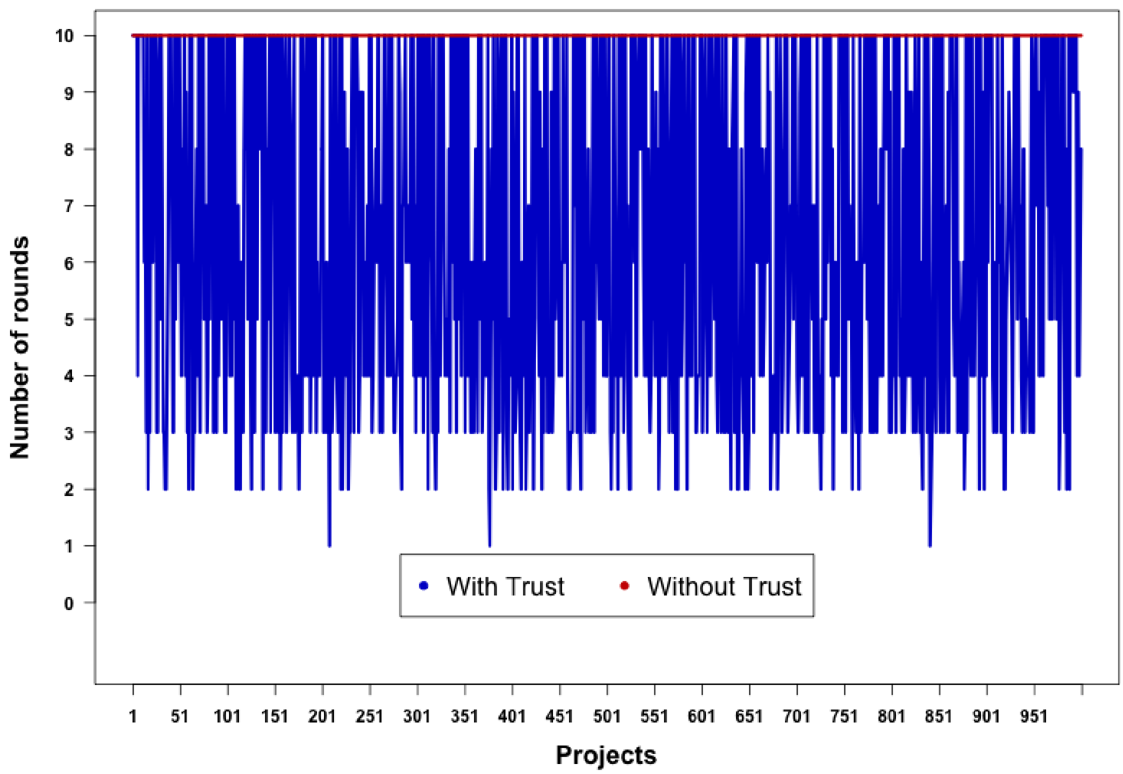


Fig. 4.7. Number of rounds with no overlap in interest with and without trust for Random Preferences.

the performance is better. For instance, if there is overlap in interest, the stakeholders reach agreement in the first round because they prefer the same decision at the beginning of the negotiation process.

The summary of the results is presented in Tables 4.2 , 4.3, 4.4 , and 4.5. Table 4.2 presents the average number of rounds for all three cases with and without trust for Random and Normal Distributions. We may notice that the number of rounds in the overlap case is lower than in the semi-overlap case, and the number of rounds in the semi-overlap case is less than in the case with no overlap. Also, with trust, the number of rounds is less than it is without trust for all cases. The normal distribution for all cases has less rounds compared to the random case.

Table 4.3 presents the percentage of projects that reached consensus for all three cases with and without trust for Random and Normal Distribution. We may notice that the normal mode of preferences is better than the random. An important point to mention regarding the case of overlap with trust under the random preferences assumption is that 1% of the projects did not reach consensus because some stakeholders were not influenced by the trusted stakeholder. Therefore, an agreement had not been reached.

Table 4.4 presents the average number of rounds of the projects that reached consensus for all three cases with different consensus thresholds for Random and Normal Distribution. We may notice that decreasing the consensus threshold reduces the average number of rounds.

Table 4.5 presents the percentage of projects that reached consensus for all three cases with different consensus thresholds for Random and Normal Distribution when applying trust. It is noteworthy that when we decrease the consensus threshold, the number of projects that reach consensus increases.

The results showed that considering the assumption of the social influence theory improved the consensus decision making performance under the assumption of rational choice theory. The trust was used as the factor of influences.

Table 4.2.
Average Number of rounds for all three cases with and without trust for Random and Normal Distribution

Preferences	**Trust**			**No Trust**		
	Overlap	***No overlap***	***Semi overlap***	***Overlap***	***No overlap***	***Semi overlap***
Random	3.79	6.35	4.94	8.6	10	10
Normal	1	6.28	4.7	1	10	10

Table 4.3.
Percentage of the projects that reached consensus for all three cases with and without trust for Random and Normal Distribution

Preferences	**Trust**			**No Trust**		
	Overlap	***No overlap***	***Semi overlap***	***Overlap***	***No overlap***	***Semi overlap***
Random	99%	75%	85%	24%	0%	0%
Normal	100%	75%	88%	100%	0%	0%

Table 4.4.
Average number of rounds of the projects that reached consensus different consensus thresholds for Random and Normal Distribution when applying trust

Preferences	**Consensus Threshold**								
	1.0	***0.9***	***0.8***	***0.7***	***0.6***	***0.5***	***0.4***	***0.3***	***0.2***
Random	4.2	2.7	1.9	1.4	1.2	1.03	1	1	1
Normal	3.8	2.4	1.8	1.5	1	1	1	1	1

Table 4.5.
Percentage of the projects that reached consensus with different consensus thresholds for Random and Normal Distribution when applying trust

Preferences	**Consensus Threshold**								
	1.0	***0.9***	***0.8***	***0.7***	***0.6***	***0.5***	***0.4***	***0.3***	***0.2***
Random	87%	94%	99%	99%	99%	99%	99%	99%	100%
Normal	87%	94%	98%	99%	99%	99%	99%	99%	100%

4.9 Conclusion

Decision making becomes more challenging when dealing with multi-stakeholder decisions due to the existence of conflicts among them and the diversity in their expertise under the rational choice theory assumption. Therefore, adding the premise of the social influence theory among stakeholders, represented by trust, becomes important when they make a decision. Such trust is a result of the interactions among those stakeholders. In this chapter, we proposed a multi-stakeholder consensus decision-making framework based on trust. This framework takes into account the interest, which includes the stakeholders' perceived risk. We designed a simulation of scenarios using two assumptions: normal distribution of preferences and random. Our result showed that trust is useful in the consensus-creating process, as it decreases the number of necessary rounds and even creates a consensus when there is an extreme conflict in preferences. Also, performance is better under the assumption of having normal distribution than under random preferences. In addition, the choice of the consensus threshold has an effect on the number of rounds. The larger the threshold, the more rounds are necessary because increasing it decreases flexibility regarding the decision to select.

5. RATING MATRIX PERTURBATION

5.1 Abstract

In collective decision-making where several participants involved to agree on one selection, reaching the consensus among them is important but it is challenging when the participants have conflicting interests. Therefore, the influence that is based on the trust from one participant to another could be useful to make the others shift their interests to be similar to others. Shifting interest can be long term or short term depending on participants behaviors. In our decision-making framework, there are different rounds where participants interact by ratings. Each round creates a rating matrix. In this chapter, we study the rating convergence by analyzing the rating matrix changes by measuring its perturbations in each round and find the effect of these changes on reaching the consensus when using a trust and without it. We built a simulation that generates several decision scenarios. Our result showed that the changes in the rating matrix under the trust improve reaching the consensus in term of decreasing the required number of round and increasing the consensus value. Moreover, our result showed that changing interest in a long term performs better than short term in term of number or rounds reduction.

5.2 Introduction

In the decision-making process where several stakeholders involved, we need a mechanism to reach an agreement specifically when the stakeholders have conflicting interests. In general, the humans' nature gives them the tendency to decide rationally by selecting the decision that gives them the maximum satisfaction according to the Rational Choice Theory [3]. However, in reality, people might have different interest. Therefore, relying on rationality makes reaching a consensus decision to be challenging [137]. As a result, the stakeholders could use the influence on each other using the assumption of the Social Influence Theory [181] to make their interest similar and in turn reach the consensus.

In our decision-making framework, the trust of the stakeholder is used to influence the others. The higher the trust the higher the reputation of the stakeholder. As a result, any stakeholder with a high reputation could influence the others in term of recommending decisions or even changing their interests [144]. Changing the interest can be short term or long term [137]. In this work, the short-term change of interest is done locally during the negotiation in each round but does not affect the future choices. The long-term change of interest is done in a way that affects the stakeholder current and future choices.

In multi-stakeholder consensus decision-making, there is a network of stakeholders who might or might not influence one another. They meet, propose solutions and modify them in several rounds to reach a solution that suits everyone. During these rounds, the stakeholders rate each other to declare their opinions regarding the proposed solutions and these ratings can later be translated to trust. As a result, due to the involvement of humans who interact during the negotiation, trust among them comes into the picture.

Trust provides many benefits such as extra information through the impression the stakeholders develop of each other over time in a particular context, which helps to reach the consensus [138]. Also, trust indicates the interests similarity among stakeholders. As a result, the stakeholders' reputations can be obtained from the trust. The more ratings, the better because they increase the amount of information available about the stakeholders. The longer the history, the better because it increases the chances of having more ratings. The fact of having the stakeholders come from different backgrounds, hold different expertise and not to mention the conflicting objectives makes the multi-stakeholder decision-making to be challenging.

Combining the intelligence of the humans and the intelligence of the machine is the basis of our existing consensus decision-making framework. The humans are useful resources to add more information when finding a decision by knowing their preferences when proposing and rating. The machine is used to coordinate the decision process and to guide the participants.

In this chapter, we aim to study the rating convergence of our proposed decision-making framework by studying the rating matrix perturbation. The consensus is achieved when either all the stakeholders propose the same solution or they all give the maximum rating to one solution. The trust is an influencer factor that lead the stakeholders to adjust their selections based on the trustworthy stakeholders guides. Such influences may affect the rating behavior as well as changing their initial interests they have in a way to be similar to the highly trusted stakeholders.

The chapter is organized as follows. In section 5.3, we list the existing related works. Then we show the generic decision-making framework in section 5.4. In section 5.5, we address rating convergence measurement. After that , we explain the experimental setup and results in sections 5.6 and 5.7. Finally, in section 5.8, we conclude the chapter.

5.3 Related Work

Interactions among stakeholders when they make a collective decision is important since they negotiate while they are seeking for a solution to choose. In decision-making framework that uses machines for moderate the stakeholder negotiations, the interaction could be rating or even written comment to express the others opinion regarding the individuals choices and preferences [128–136]. Such notion of preferences occurs in decision-making field [137]. The individuals' preferences can be changed over the time due to the changes in the interests. Those interests change can be a result of the influence by the others [138], the choices made before or even other factors that are based on the individuals situation at the time of making selection. Several studies showed that the individual interest and preferences are changing [138–145] and these study are different in term of the causes that lead changing the preferences. In [141], they predicted the changes in preferences based on the feedback of the negotiation process. [142] presented the dominant theories of belief change that may be called input-assimilating models. They expressed how the subject's belief state is transformed upon assimilation of an input. In addition to the different factors that change the individuals' preferences, the choices proposed while making a decision may affect the preferences or in other word, it shapes them [145]. There is a study [138] explained the change the initial preference of an individual to match the others choices, either through coercion from others or selection by the individual team member. Preferences changes can be short term or long term [137,144,146,147]. Short term preferences affect the current choices while negotiating but the long term one affects the choices in the future. In social psychology field where they study the peoples' behavior, there are different theories that predict the preferences changes. For example, dissonance theory [139, 148, 149] motivates individuals to change their preferences to match their prior decision that can be a result of a selection they made in the past based on influence.

5.4 Multi-stakeholder Decision-Making Model Based on Trust and Risk

We have designed a generic framework for multi-stakeholder decision making based on trust and risk that produces a decision agreed upon by the participants. In this framework, the stakeholders negotiate with each other by 5-star rating to declare their agreement regarding the other solutions. In this section, we give an overview of our multi-stakeholder decision-making framework. Figure 4.1 shows our multi-stakeholder decision-making framework based on trust and risk. In the beginning of the decision making process, the stakeholder starts proposing their solutions that have corresponding interest value calculated by the utility function. This utility function is context-dependent. The trust relationship among stakeholders construct the network of them. Those trust values form the reputation of the stakeholders. The trust is computed by our existing trust system [35–43] that is based on measurement theory. Next, the stakeholders rate each other to declare their opinions of the proposed solutions. Then, the GDM (group decision making model) entity aggregates those ratings. After that, the aggregated rating values of the solutions are ranked descendingly. The consensus level is obtained by the aggregated rating values . Therefore, the top value should have a value higher than or equal to a threshold value to indicate that consensus is achieved. Otherwise, a new round will start.

5.4.1 Rating

If we assume that the rating system is 5-star rating and stakeholder a rates stakeholder b, then the rating will depend on how far the a's interest of its own decision from the interest he gets from what b proposed. f b's decision give more interest to a than what a's proposed then the rating is the the maximum, 5 stars. Otherwise, we consider the differences between the interest of decision proposed by a and the interest of decision proposed by b. The larger the difference the lower the rating and vice versa. Therefore, to compute the star rating associated with the difference, it requires to transform the difference value range ($diff$) to 5-star value range. $diff$ range is [0,1] and the start range is [0,5]. However, since the larger difference means lower rating, we need to find the transformation function, $f(diff)$, from [1,0] to [0,5], meaning to find value $rate$ in [0,5] associated with value $diff$ in [1,0]. If we assume the function to be linear, we may use the affine transformation function to find the rating from the differences. Using the affine transformation function, we can calculate the rating using (5.4)

$$f(diff) = 5 * (1 - diff) \tag{5.1}$$

5.4.2 Aggregation

The outcome of the rating's phase is the rating matrix. Suppose that there is a set of stakeholders, S, a set of decisions, D, and a set of corresponding trust values for each stakeholder. The stakeholders rate each other as represented in matrix R. In this matrix, the element r_{ij} represents the rating from stakeholder i to stakeholder j regarding j's proposed solution. Each stakeholder has an assigned trust value represented in the vector T. The sum of the trust values is W. The rating weighted average operator is RWA and computed by using R, T and W (5.5). Here, the trust ,T is used to weigh the ratings. The outcome is a vector of consensus degrees corresponding to the proposed solutions. The selected decision is the decision with the maximum consensus degree, which is later compared to consensus threshold to check the consensus achievement.

$$T = \begin{bmatrix} T_1 & T_2 & T_3 \end{bmatrix}$$

$$W = \textstyle\sum_{n=1}^{3} T_n$$

$$R = \begin{bmatrix} 1 & r_{12} & r_{13} \\ r_{21} & 1 & r_{23} \\ r_{31} & r_{32} & 1 \end{bmatrix}$$

$$RWA = \frac{1}{W} * T * R \tag{5.2}$$

5.5 Rating Convergence Measurement

As we indicated before, our framework generates rating matrices during the negotiation, the more the ratings the larger the magnitude of the matrices. Matrix norm can be used to measure for the rating matrices magnitude and then use it to find the perturbations. For example, the Frobenius norm [195] can be used for calculating the ratings matrix norm by computing the square root of the sum of the absolute squares of each rating in the matrix. Suppose, the rating matrix is M and has elements r_{ij}, which each r_{ij} represents the rating from stakeholder r_i to the decision proposed by r_j and n is the number of decision makers, the Frobenius norm is computed by equation 5.3

$$\| M \|_F = \sqrt{\sum_{i}^{n} \sum_{j}^{n} | r_{ij} |^2} \tag{5.3}$$

The matrix norm shows how big is the matrix is. Therefore, if the ratings become higher in every round then the matrix norm becomes larger than the previous round. Larger norms is an indicator of the ratings convergence to the consensus degree level. Our interpretation is that trust is an important factor to influence the stakeholders which leads to increase the matrix norm.

To find the matrix perturbations, we use the difference of norms between the current round and the previous one. Supposed that there are three stakeholders s_1, s_2 and s_3 and three consensus degree values c_1, c_2 and c_3 stored in consensus vector, $\mathbf{c}$ respectively.The rating matrix R stores all the rating for one round.

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Let's assume there is a vector,$\mathbf{x}$, of x_1,x_2 and x_3 which has a solution in the following linear system:

$$r_{11}x_1 + r_{21}x_2 + r_{31}x_3 = c_1$$

$$r_{12}x_1 + r_{22}x_2 + r_{32}x_3 = c_2$$

$$r_{13}x_1 + r_{23}x_2 + r_{33}x_3 = c_3$$

We can write the linear system above as:

$$R\mathbf{x} = \mathbf{c} \tag{5.4}$$

Suppose that after one round, changes occurred, Δ. We write the rating matrix , R$\prime$ as:

$$R\prime = \begin{bmatrix} r_{11} + \Delta_{11} & r_{12} + \Delta_{12} & r_{13} + \Delta_{13} \\ r_{21} + \Delta_{21} & r_{22} + \Delta_{22} & r_{23} + \Delta_{23} \\ r_{31} + \Delta_{31} & r_{32} + \Delta_{32} & r_{33} + \Delta_{33} \end{bmatrix}$$

There is is a vector, $\mathbf{y}$, of y_1,y_2 and y_3 such that

$$\mathbf{y} = \mathbf{x} + \Delta \tag{5.5}$$

Also, each rating from i to j is changed such that

$$r_{ij}\prime = r_{ij} + \Delta_{ij} \tag{5.6}$$

This victor has a solution in the following linear system:

$$r_{11}\prime y_1 + r_{21}\prime y_2 + r_{31}\prime y_3 = c_1 + \Delta_1$$
$$r_{12}\prime y_1 + r_{22}\prime y_2 + r_{32}\prime y_3 = c_2 + \Delta_2$$
$$r_{13}\prime y_1 + r_{23}\prime y_2 + r_{33}\prime y_3 = c_3 + \Delta_3$$

We can write the linear system above as:

$$(R + \Delta)\mathbf{y} = \mathbf{c} + \boldsymbol{\Delta} \tag{5.7}$$

To compute the perturbation, we find the difference between $\mathbf{x}$ and $\mathbf{y}$ (equations 5.4 and 5.7) using matrix (equation 5.3) and vector (equation 5.8) norms.

$$| v |_2 = \sqrt{\sum_{i}^{n} | v_i |^2} \tag{5.8}$$

In the result section, we will present whether there is a correlation or not between the amount of perpetuation and the number of rounds to reach the consensus.

5.6 Experiment

Experiment objective

The aim of the experiment is to study the ratings changes when several stakeholders want to make a decision and study the effect of the trust on those rating changes. Such an effect can be examined through the number of required rounds, the consensus degree average in each round, and the consensus achievements. We have designed and implemented a simulation to generate decision-making scenarios. We used a Netbeans framework with java language to build the simulation software. We created a database using derby and then linked it to the java program to store the data.

Experiment setup

In this experiment, we selected five users for each case of the interest overlap. So, for full overlap interests, we assigned IDs from 1 to 5 to stakeholder, for no overlap interests, we assigned IDs from 6 to 10 and finally for semi overlap, we assigned IDs from 11 to 15. Then for each user, we stored the interest vales which is the rating he/she gives to the movie. For each interest overlap scenario, We created five samples and each sample has 200 movies selection project. Also, these projects were generated one time with trust and one without. Therefore, the total projects generated for each samples were 1200 projects. Additionally, we generated these projects under two assumptions: one with long term interest and the other is short term. Table 5.1 shows the parameter setup and figure 5.1 shows the scenarios generated.

The stakeholders start a round by proposing movies of high interest to them. Then they rate each other, which create ratings matrix. After that, the consensus is computed by aggregating those ratings using RWA operator. If the consensus degree is lower than the minimum consensus threshold, a new round starts. The stakeholders have the option to modify their movies selection by choosing the movie that has more

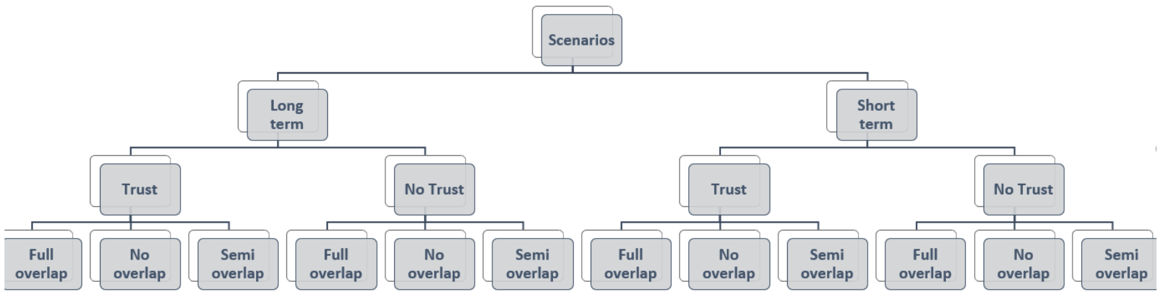


Fig. 5.1. The scenarios to generate in the simulation.

Table 5.1.
List of the parameters used in the simulation with their corresponding values

Parameter	**Description**	**Value**
$NoSH$	Number of StakeHolders	15
$numbStakehoder$	Number of StakeHolders per project	5
$globalNoD$	Total number of possible decisions to select when proposing	100
noS	Total number of samples	5
$pCount$	Number of Projects generated per sample	200
$roundCount$	Maximum Number of rounds per project	10
T	Trust Value range	[0,1]
$Interest$	Interest Value range	[0,1]
$consThreshold$	Minimum Consensus Degree	1.0

interest to others than the previous round's selection or keeping the same selection proposed in the previous round.

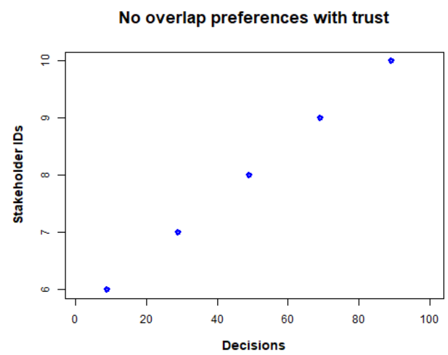
5.7 Results

In this section, we show the result of the decision making simulation. In this light, we present the stakeholders movies selection movement during the negotiation for one of the generated project of the no overlap case. Then, we present the changes of the rating norm for the projects generated for the no overlap case one when applying trust and the other without it. Next, we show the consensus degree convergence for the long term preferences with and without trust. After that, we make a comparison in term of number of rounds for long term preferences and short term preferences. One comparison with trust and one without.Finally, we find the correlation between the rating matrix perturbation and the number of rounds.

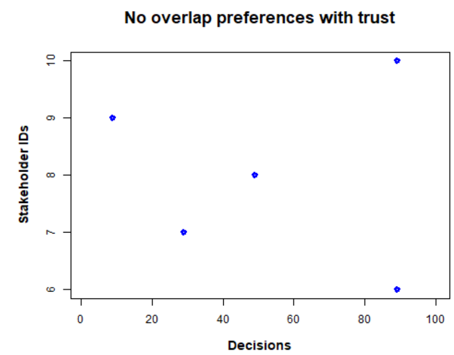
Figure 5.2 shows the stakeholders decisions movement for a project that took 5 rounds to reach the consensus. In round 0 (figure 6.3(a)), all the stakeholders proposed different decisions. In round 1 (figure 6.3(b)), stakeholder 6 changed his decision to be similar to stakeholder 10. In round 2 (figure 6.3(c)), stakeholders 7 and 9 selected decisions closer to 6 and 10. In round 3 (figure 6.3(d)), stakeholder 9 selected a new decisions closer to 6,7 and 10. Round 4 (figure 5.2(e)) is similar to round 3. In round 5 (figure 5.2(f)), stakeholder 8 changed his decision to be similar to the rest. Therefore, the consensus was achieved. Table 5.2 shows the rating matrix norm values and the consensus degree for the same project. The rating norm kept increasing as well as the consensus degree.

Figure 5.3 presents the changes in the rating matrix norm during negotiations. When considering trust, 82% of the interactions had the norm increased, 2% no change and 16% was decrease. However, without trust, the norm never increased neither decreased and it remained unchanged.

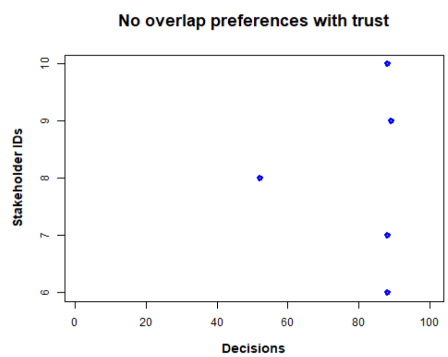
Figure 5.4 presents the number of rounds for each project without trust 5.4(a) , short-term preference with trust 5.4(b) and long-term preference with trust 5.4(c). We can notice that the number of round for no overlap and semi overlap never decreased without trust. However, the rounds can be decreased with trust and it is



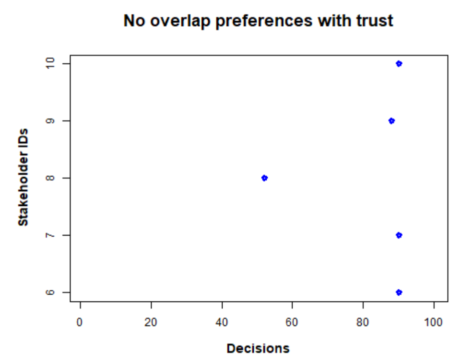
(a) Round 0.



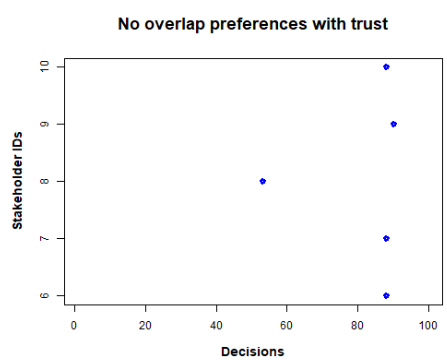
(b) Round 1.



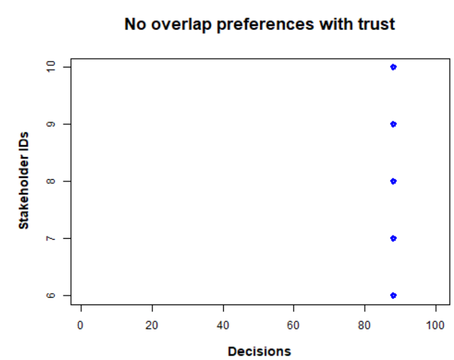
(c) Round 2.



(d) Round 3.



(e) Round 4.



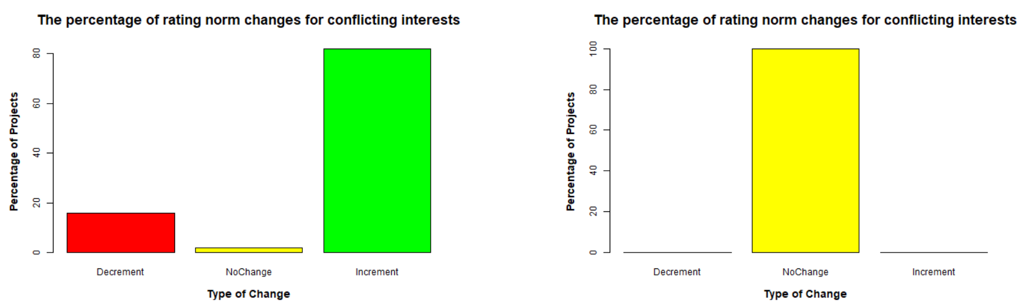
(f) Round 5.

Fig. 5.2. Stakeholders movies selection movement during the negotiation for no overlap case with trust

more decreasing for long-term preference compared with short-term preferences. The matrix perturbation has an effect on the number of round. We found that there is a

Table 5.2.
Rating matrix norm values and the consensus degree for one project.

Round Number	Rating Norm	Consensus Degree
1	3.098386677	0.81
2	3.666060556	0.88
3	3.794733192	0.89
4	3.752332608	0.92
5	4.507771068	1



(a) With Trust (b) Without

Fig. 5.3. Rating matrix norm changes for no overlap case with trust and without

moderate negative correlation, -0.45. It means that when the average perturbation of the project is high then the number of rounds is decreasing.

From the results presented, we found the following:

- Trust helps the stakeholders to reach the consensus when conflicting interest exists by the influence from the highly trusted participants.
- Trust increases the rating matrix norm in most of the cases. Increase the norm means increasing the rating which leads to increase the consensus degree.

Table 5.3.
Percentage of the projects that reached consensus for all three cases with and without trust for long term and short term preferences

Preferences	**Trust**			**No Trust**		
	Overlap	***No overlap***	***Semi overlap***	***Overlap***	***No overlap***	***Semi overlap***
Short term	100%	98%	92%	100%	0%	0%
Long term	100%	99%	99%	100%	0%	0%

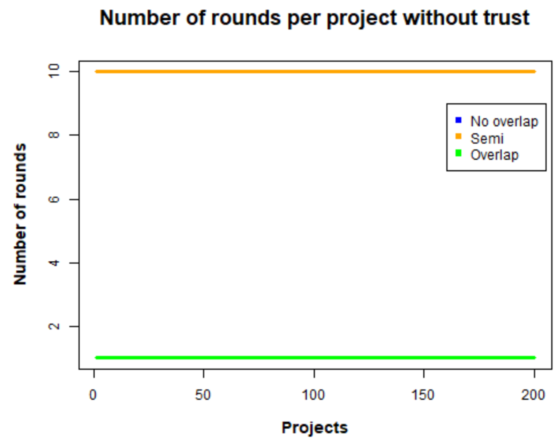
Table 5.4.
Average round of the projects that reached consensus for all three cases with and without trust for long term and short term preferences

Preferences	**Trust**			**No Trust**		
	Overlap	***No overlap***	***Semi overlap***	***Overlap***	***No overlap***	***Semi overlap***
Short term	1	5	5	100	10	10
Long term	1	1	1	1	10	10

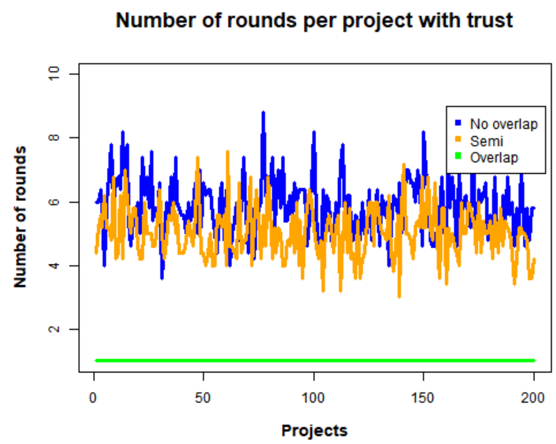
- Trust helps changing the preferences whether long-term or short term. Changing the preference in the long run helps to decrease the number of rounds in the future.
- Trust helps decreasing the number of project rounds except few cases such as when a trusted participant has his decision liked by the others and then he changes his opinion frequently for the coming rounds.
- Trust helps to increase the rating changes which leads to increase the rating norm and the matrix perturbation accordingly.

5.8 Conclusion

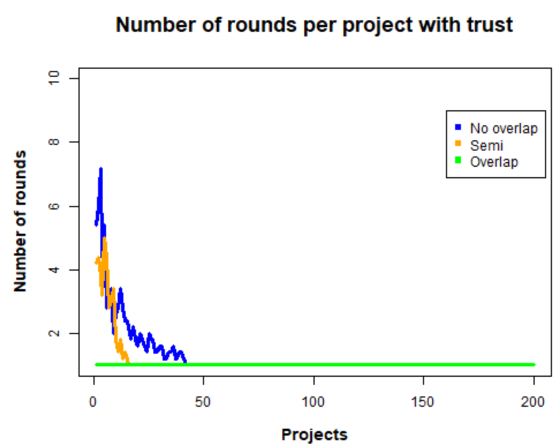
In collective decision-making where several participants involved to agree on one selection, reaching the consensus among them is important but it is challenging when the participants have conflicting interests. The influence among them can help to eliminate this challenge. Such an influence can be obtained from trust of one participant to another. The trust is useful in changing the participants preferences whether it is a long term or short term depending on participants behaviors. In this study we apply our decision making framework that is based on trust for investigating the rating convergence during negotiation. We used the matrix norm as a measurement for obtaining the magnitude of the rating matrices and then find the perturbation accordingly. The larger the magnitude the more chances to reach the consensus. Our result showed that the changes in the rating matrix under the trust improve reaching the consensus in term of decreasing the required number of round and increasing the consensus value. Also, our result showed that changing interest in a long term performs better than short term in term of number or rounds reduction. Moreover, we found that there is a negative moderate correlation between the matrix perturbation and the number of round needed to reach consensus.



(a) Without trust for both long-term and short-term



(b) With trust for short-term



(c) With trust for long-term

Fig. 5.4. Number of rounds in each project for all the three overlap cases

6. RATING AGGREGATION

6.1 Abstract

Reaching consensus is critical in a multi-stakeholder decision-making consensus process that involves many decision makers agreeing on one choice, but it is challenging when the participants have opposing interests. Hence, influence, which is based on one member's trust in another, could be useful for making people change their interests to be similar to those of others. Changes to interests can be long-term or short-term, depending on the participants' behaviors. In our proposed consensus decision-making framework, the stakeholders negotiate in many rounds by interacting through ratings. These ratings are used to compute the consensus level, which calculates the consensus by aggregating those ratings. In this chapter, we study the aggregation of the ratings and apply it in our proposed multi-stakeholder decision-making framework. Then, we measure the aggregation operators based on their correlation with the changes in the rating matrix. Our results show that operators who produce high consensus in the earlier rounds do not necessarily introduce a relationship between the changes in rating and the number of rounds. Also, the selected consensus threshold controls the operators' performance in term of consensus achievement and the speed of convergence.

6.2 Introduction

In the previous chapters, we introduced our trust-based consensus decision-making framework (Figure 4.1), in which several stakeholders are involved in proposing decisions and negotiate until they reach a final decision in consensus. We introduced the assumption of rational choice theory [3] in which people usually follow its framework when they declare preferences based on the maximum interest they provide. We also introduce the concept of social influence theory [181] to solve situations in which stakeholders have divergent preferences, which might lead them to never reach consensus.

Based on social influence theory, we use influence, represented by trust. Trust is a relationship among individuals over time based on their interactions. In our proposed trust-based consensus decision-making framework, we used our existing trust framework, which is based on measurement theory [35–45]. By adopting the trust concept, we can create influence during negotiations. Stakeholders with high trust influence others to modify their decisions to be closer to each other. We assume the temporality of the preference changes. It could be a local change to a current project or a global change for current and the upcoming projects.

In our proposed framework, we used the weighted average to aggregate stakeholders' opinions, as represented by ratings, for every selection. However, our proposed framework is fixable about applying other aggregation operators. Our aim is to find a suitable method of aggregating the ratings and using trust to weigh the stakeholders' selections or actions. Different aggregation operators have been proposed before. However, some of them are only applicable to voting-style decisions and not consensus. Therefore, the operator's choice must guarantee consensus rather than voting.

In this chapter, we aim to study different aggregation operators for our proposed decision-making framework (Figure 4.1) by finding their correlation with changes to rating matrix perturbation. Consensus is achieved when all of the stakeholders either propose the same solution or give the maximum rating to one solution. Trust is an influencer factor that lead stakeholders to adjust their selections based on the trustworthy stakeholders' suggestion. Such influences may affect the rating behavior as well as change their initial interests to be similar to those of highly trusted stakeholders.

This chapter studies the effect of using different aggregation operators under the influence of trust by answering the following questions:

- What degree of consensus is produced by those operators?
- What is the speed of convergence for those operators?
- Would starting with less consensus slow down the consensus process?
- Would increasing the ratings matrix perturbation help to decrease the number of rounds?
- How would the operators perform given changes to the consensus threshold?

The chapter is organized as follows. In section 6.3, we list the existing related works. Next, in section 6.4, we discuss the aggregation operators. After that , we explain the experimental setup and results in sections 6.5 and 6.6. Finally, in section 6.7, we conclude the chapter.

6.3 Related Work

For group decision-making applications in which the participants generate ratings regarding the alternatives, it is important to aggregate those ratings to select the best alternative among the proposed ones. In consensus decision-making scenarios, all of the participants declare their preferences through ratings. Therefore, an approach is needed to aggregate these ratings, to obtain the group's preferences and simultaneously ensure that the group's preference gives a level of satisfaction to all of the participants. In general, ratings are usually aggregated using the weighted arithmetic mean [189–194, 196–199]. When using the weighted mean approach, this means that the participants' preferences should converge to values that are close to each other, to guarantee that the aggregated value is becoming closer to the minimum accepted consensus degree. The weight can represent the member's reputation. However, many researchers have proposed schemes for rating aggregations because getting bias with the mean. These schemes are different in terms of the aggregation operators used and the applications for which the ratings are used.

Leberknight and et al. [196] presented a theoretical model using stock market metrics known as the average rating volatility (ARV), which captures the fluctuation present in these ratings. The ARV is computed based on the mean rating value over non-overlapping intervals of N consecutive ratings. Florent and et al. used collaborative filtering systems [197] to compare the accuracy and robustness of three aggregators: the mean, median, and mode. The results show that the median may often be a better choice than the mean. Liang and et al [188] systematically evaluated the effects of different rating aggregating algorithms in the context of a simple distributed trust inference model. Their results showed that the personalized similarity measure (PSM) has the best performance compared with the average, half-weighted, weighted majority algorithm (WMA), and beta models. Abdel-Hafez and et al. [189, 190]proposed a new aggregation method for generating reputation scores for items or products based on customer ratings. They used the weighted average operator and used the normal distribution to generate the weights. The results of their experiments show that this method outperforms the state-of-the-art methods of predicting ratings. They did the same in [191]to generate reputation scores for items on the basis of customer ratings but using the beta distribution for weight generation. Baltrunas and et al. [200] proposed a rank-aggregation method for group recommendations.

6.4 Aggregation Operators

Suppose that there are n stakeholders s_1, s_2, .. ,and s_n and their trust values t_1,t_2, .. ,and t_n respectively. The set W=$\{w_1, w_2, .., w_n\}$ contains the stakeholders' weights, which are calculated by using the trust values obtained from equation 6.1

$$w_i = \frac{t_i}{\sum_{i=1}^{n} t_i} \tag{6.1}$$

Suppose that there is a decision D_i proposed by stakeholder s_i and the other stakeholders rate this decision in $R = \{r_1, r_2, .., r_n\}$. The following subsections show different aggregation operators that use the values from the sets W and R as inputs.

6.4.1 Weighted Sum

The weighted sum (WS) aggregation operator is the same as computing the weighted average. This operator weighs the rating using the rater's trust value and then finds the summation. The WS of the alternative can be computed by equation 6.2

$$WS = \sum_{i=1}^{n} w_i * r_i \tag{6.2}$$

6.4.2 Weighted Product

The weighted product (WP) aggregation operator is similar to the WS. However, it is different from the WS in that the weighted ratings are multiplied instead of summed. This operator was inspired from the multi-criteria decision-making (MCDM) approaches, with one of the approaches being the WP approach. In this operator, the ratings are weighted by raising them to the powers obtained from set W. WP is computed by equation 6.3

$$WP = \prod_{i=1}^{n} {r_i}^{w_i} \tag{6.3}$$

6.4.3 Similarity Measure

The similarity measure (SM) takes into an account the distance between any pair of ratings. If the distance is high, the similarity will be low. This aggregation operator was inspired from [188]. The authors used a personalized similarity measure. To construct the similarity measure, we first consider the root mean square (RMS)(equation 6.4) for a set of values $X = \{x_1, x_2, .., x_n\}$

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} {x_i}^2}{n}} \tag{6.4}$$

In our case, these x values are the ratings of the stakeholders, R. The main point of this operator is to find the average differences for any decision and then compute the similarity measure. First, the number of interactions among stakeholders, N, must be found. It can be computed using equation 6.5

$$N = \sum_{i=1}^{n}(n-i) \tag{6.5}$$

Then. the RMS of the differences, $RMS_{differences}$ is computed by equation 6.6

$$RMS_{differences} = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=i+1}^{n}(r_i - r_j)^2}{N}} \tag{6.6}$$

Where i and j are any stakeholders pair. Based on equation 6.6, the SM is computed by equation 6.7

$$SM = 1 - RMS_{differences} \tag{6.7}$$

Weighted Product Similarity Measure

The weighted product similarity measure (WPSM) is an aggregation operator that is computed by considering the SM, and weighing the ratings. The weight of the ratings is computed by multiplying the weight W with rating, R. Equation 6.6 can be represented by adding weight to compute weighted product RMS, $WPRMS$ (equation 6.8)

$$WPRMS_{differences} = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=i+1}^{n}((r_i * w_i) - (r_j * w_j))^2}{N}} \tag{6.8}$$

The $WPSM$ can be computed by equation 6.9

$$WPSM = 1 - WPRMS_{differences} \tag{6.9}$$

Weighted Exponent Similarity Measure

The weighted exponent similarity measure (WESM) operator is similar to the WPSM but different in terms of how the weight is used. For the WPSM, weight is multiplied by the rating. For the WPSM, the rating R R is raised to the power of the weight, W. Equation 6.6 can be represented by adding weight to compute weighted exponent RMS, $WERMS$ (equation 6.10)

$$WERMS_{differences} = \sqrt{\frac{\sum_{i=1}^{n} \sum_{j=i+1}^{n} \left(r_{i_i}^{w} - r_{j_j}^{w}\right)^2}{N}} \tag{6.10}$$

The $WESM$ can be computed by equation 6.11

$$WESM = 1 - WERMS_{differences} \tag{6.11}$$

6.5 Experiment

The aim of the experiment was to study the effects of trust on the consensus process among stakeholders when applying different aggregation operators. The evaluation criteria involved studying the consensus degrees and achievement when using these aggregation operators. Moreover, we study the correlation between the consensus degree of each aggregation operator and the rating average matrix perturbation. We designed and implemented a simulation to generate decision-making scenarios. We used the NetBeans framework with Java to build the simulation software. To store the data, we created a database using Derby and then linked it to the Java program (Fig.4.3).

Table 6.1 shows the parameter setup. The stakeholders were assigned a number from 1 to 500 indicating their stakeholder ID. We generated the interests of decisions for each stakeholder to facilitate the proposing and rating process by randomly generating a number between 0 and 1.0 for the decisions corresponding to each stakeholder. When these interest values were generated, we assumed no overlap in interests, since our experiment was aimed at studying cases with extreme conflicts. The stakeholders

Table 6.1.
Parameters of the simulation and their corresponding

Parameter	Description	Value
$NoSH$	Number of StakeHolders	500
$numbStakehoder$	Number of StakeHolders per project	5
$globalNoD$	Total number of possible decisions to select when proposing	1000
$pCount$	Number of Projects generated	1000
$roundCount$	Maximum Number of rounds per project	10
T	Trust Value range	[0,1]
$Interest$	Interest Value range	[0,1]
$consThreshold$	Minimum Consensus Degree	1.0

start a round by proposing solutions of high interest to them and then rate each other. After that, the consensus is computed by aggregating the ratings using different aggregation operators. If the consensus degree is lower than the consensus threshold, a new round starts. The stakeholders have the option to modify their decisions by choosing a decision that has more interest to others than the previous round's decision or keeping the same decision proposed in the previous round.

6.6 Result

In this section of this chapter, we analyze the data generated from the simulation. We study the starting consensus degree for each operator. Then, we explore the consensus degree's convergence throughout the round for each operator. Next, we show the consensus degree throughout the project for each operator. According to the consensus degree for each project, we study the consensus achievement by assuming different minimum consensus threshold values. Finally, we study the correction between the rating matrix perturbation and the consensus degree computed by each aggregation operator.

6.6.1 Starting value of consensus degree

When the stakeholders negotiate during projects' rounds, they start with the consensus degree in the first round and then continue the remaining rounds accordingly. The consensus degree shows how close they are. Figure 6.1 shows the starting consensus degree computed by the aggregation operators. It shows that the WPSM operator produced the best results in term of the starting consensus degree throughout all of the projects. WP, in contrast, had the lowest starting consensus degree. In addition, WS and WP were noticeably close in term of performance, and WPSM and WESM were also closer to each other.

6.6.2 Consensus Degree Convergence

The consensus degree in each round changes based on the modified decisions and their ratings. Convergence to the minimum consensus threshold is required to reach consensus. Each aggregation operator behaves differently in terms of consensus convergence. Figure 6.2 shows the performance of each operator. In the figure, the WPSM operator starts with the highest consensus degree in the first round, but its degree changes slower than WS and WP. In WS, the average convergence from the first to the last round is +0.19, compared to +0.22 in WP. It was +0.01 and +0.05 for WPSM and WESM, respectively.

6.6.3 Consensus Degree per project

Projects end with a final consensus degree, whether consensus is achieved or not. Figure 6.3shows the consensus degrees for all of the projects and for each operator.

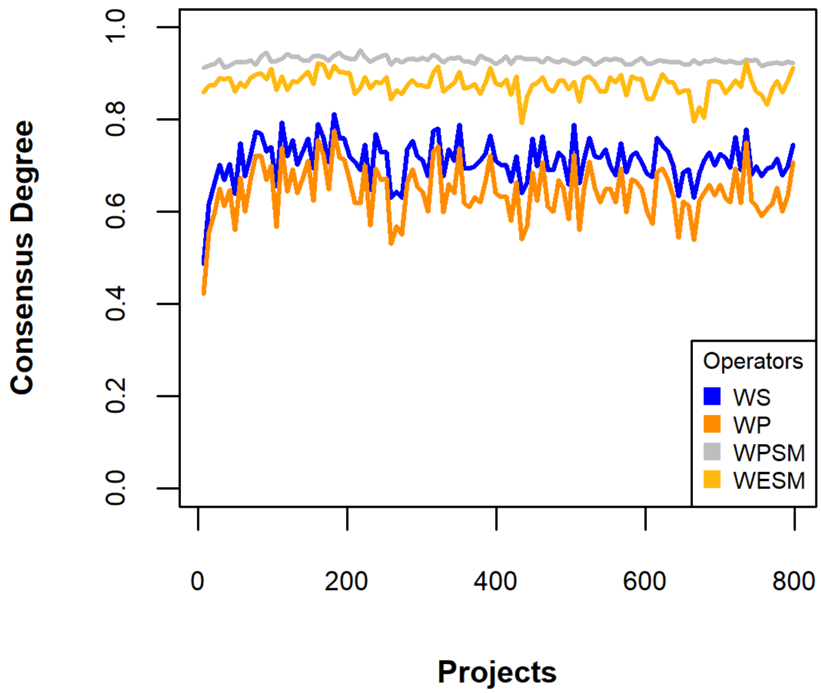


Fig. 6.1. Staring consensus degree for each aggregation operator.

For the WS operator, 6.3(a), shows that in the early projects, the consensus was low and then kept increasing because of influence, represented by trust. Similarly, the WP operator in subfigure 6.3(b)and the WPSM and WPEM operators in, 6.3(c) and 6.3(d) respectively, produced high consensus (between 0.8 and 1) from the earlier and later projects. Trust influenced these projects too, which helped to maintain the consensus degree values.

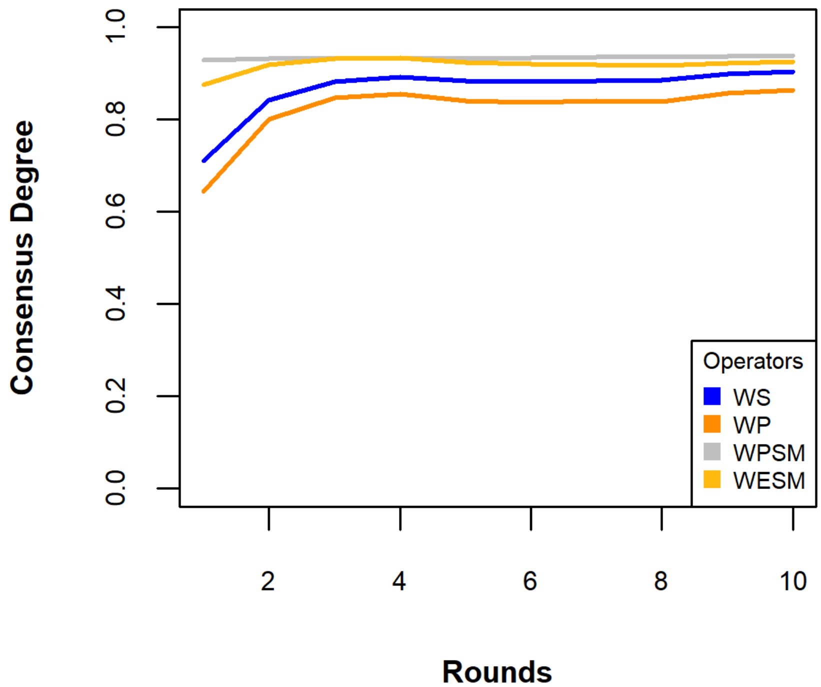
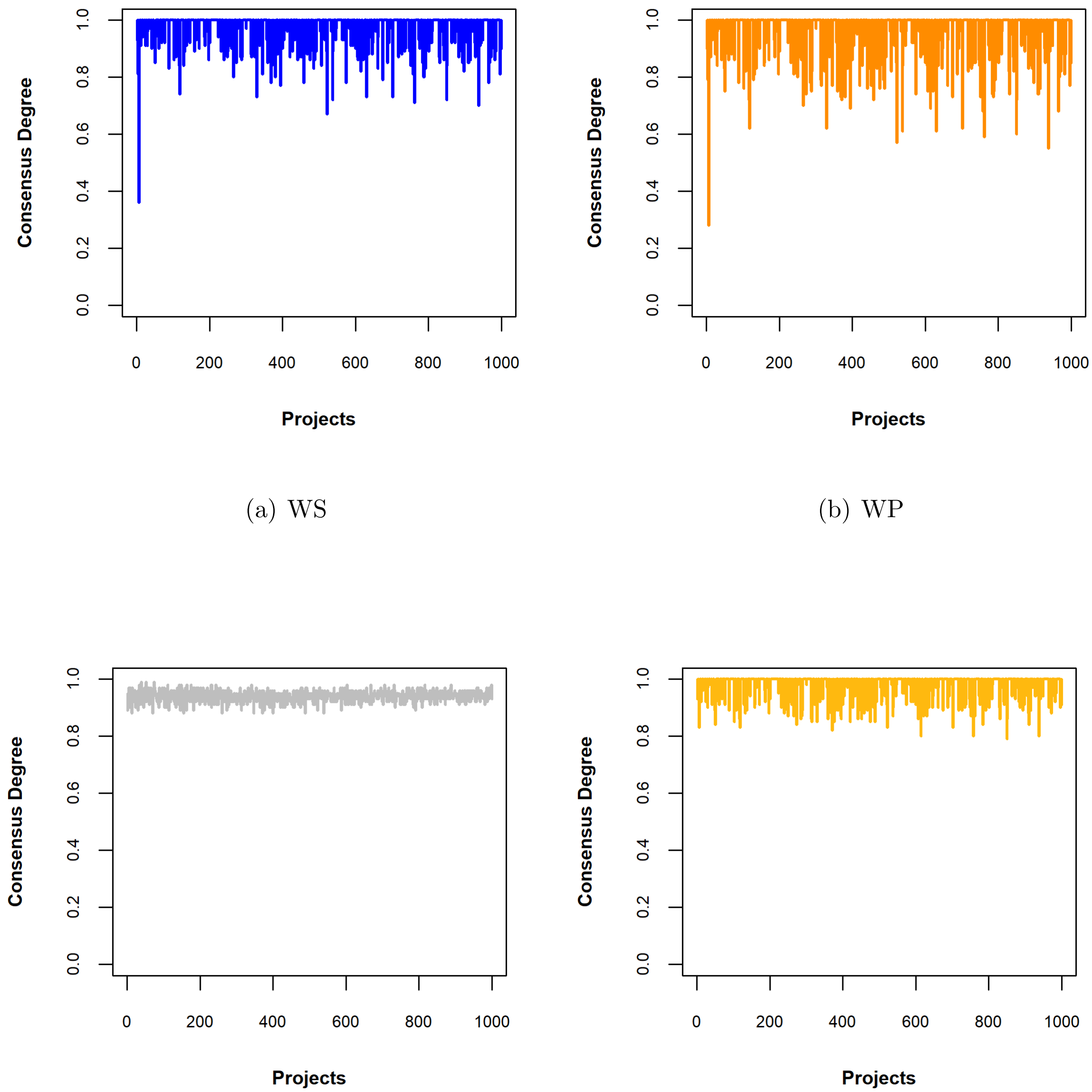


Fig. 6.2. Consensus degree convergence throughout the projects' rounds for each aggregation operator.

6.6.4 Consensus Degree Threshold

Negotiation among stakeholders ends when they achieve the consensus or when the maximum number of rounds reach the limit. Reaching the agreement depends on the chosen threshold. In this section, we evaluate the four aggregation operators under the assumption of having the negotiation held with different consensus degree threshold. The evaluation criteria are the average number of rounds needed and the number of projects that reached the consensus



(a) WS

(b) WP

(c) WPSM

(d) WPEM

Fig. 6.3. Consensus degree values for all of the projects and aggregation operators

Number of rounds

Table 6.2 shows the average number of rounds for each aggregation operators under different consensus threshold. The result shows that WS, WP and WESM has the same performance in term of number of rounds while WPSM performance is worse than them. However the performance of WPSM is the best when the minimum consensus threshold is 0.90. The performance of all operators except WP is the best when the consensus threshold is 0.75. Our interpretation is that WPSM starts with a higher consensus compared with others and could be close the consensus threshold. Therefore, the convergence of this operator is faster.

Table 6.2.
The number of rounds for each aggregation operator for different consensus threshold

Aggregation operator	**1.0**	**0.95**	**0.90**	**0.85**	**0.80**	**0.75**
WS	6	4	3	2	2	1
WP	6	4	4	3	2	2
WPSM	10	5	1	1	1	1
WESM	6	3	2	1	1	1

Consensus Achievement

Table 6.3 shows the percentage of the projects that reached the consensus with different consensus threshold. The result shows that when the threshold is 1, all the operators except WPSM has the same performance and better then WPSM. The WPSM performance becomes the best when the consensus threshold is 0.90 or lower.

Table 6.3.
The percentage of the projects that reached the consensus for each aggregation operator for different consensus threshold

Aggregation operator	1.0	0.95	0.90	0.85	0.80	0.75
WS	78%	88%	96%	99%	99%	99%
WP	78%	87%	94%	97%	98%	99%
WPSM	0%	71%	100%	100%	100%	100%
WESM	78%	94%	99%	99%	100%	100%

6.6.5 Consensus and matrix perturbation correlation

The stakeholders negotiate the decisions and choices of the projects. They rate each other, and those ratings reflect changes in the rating matrix for the next rounds. We measure these changes by finding the matrix perturbation. In this section, we found the average perturbation for each project and compared it to the number of rounds to study how the aggregation operators reacted with the matrix changes and how such a reaction affected the consensus achievement speed. The idea was to find the correlation between the consensus achievement speed and the rating matrix perturbation. The question to answer is whether increasing matrix perturbation would reduce the number of rounds. Table 6.4 shows the correlation for each aggregation operator. Table 6.4shows a moderately negative correlation between the WS and WP operators. This means that changes to the rating matrix could reduce the number of rounds, which speed up consensus being achieved. The WPSM and WESM operators do not have such a correlation. The following points summarize the results of our analysis:

Table 6.4.
Correlation between the rating matrix perturbation and the number of rounds

Operator	**Correlation**
WS	-0.547288655
WP	-0.600791601
WPSM	0
WESM	0.329661467

- Consensus degree outset: WS and WP had lower starting consensus compared with WPSM and WESM.
- Matrix perturbation: WS and WP had a negative correlation between matrix perturbation and number of rounds, unlike WPSM and WESM.
- Number of rounds: Having a larger starting consensus degree did not necessarily decrease the number of rounds.
- Consequences convergence: WP had the best performance in terms of consequences convergence throughout the rounds, while WPSM had the worst.
- Consensus degree values: Projects with WPSM and WPEM produce high consensus under the assumption of trust. The same was true with WA and WP but with lower performance.
- Round reduction: WPSM was the worst when the consensus threshold was 1 but the best when it was 0.90.
- Consensus achievement: WS,WP and WESM had the same performance when the threshold was 1 while WPSM performance was the worst. When the threshold was 0.90 the performance of the WPSM was the best.

6.7 Conclusion

In multi-stakeholder decision-making consensus processes involving many decision makers agreeing on one choice, reaching consensus is critical, yet it is challenging when the participants have opposing interests. Hence, influence, which is based on the trust between members, could be useful for making people change their interests to be similar to those of others. In our decision-making framework, we aggregate the ratings to compute the consensus. In this chapter, we studied four aggregation operators (WS, WP, WPSM, and WESM) and measured their performance based on their correlation with the changes to the rating matrix. Our results showed that a larger starting consensus degree did not necessarily decrease the number of rounds. Also, WP had the best performance in term of consequences convergence throughout the rounds, but WPSM had the worst. Moreover, there was a negative moderate correlation between the matrix perturbation and the number of rounds for the WS and WP operators. Lastly, the selected consensus threshold controls the operators' performance in term of consensus achievement and speed of convergence.

7. CONCLUSION

"When people honor each other, there is a trust established that leads to synergy, interdependence, and deep respect. Both parties make decisions and choices based on what is right, what is best, what is valued most highly." Blaine Lee

This thesis developed a framework for multi-stakeholder consensus decision-making taking into consideration the trust among stakeholders and the perceived risk included in their interests.

In Chapter 1, this thesis outlined the challenges when dealing with multi-stakeholder decision-making due to humans involvement. Those challenges involves the diversity of the stakeholders background which leads to a variety of expertise and, in turn, various proposals in the decision-making process. Also, the conflicting interests among the stakeholders, which leads to not agreeing on one decision.Moreover, the stakeholders might have a partial view of the problem domain, which leads to not knowing the others decision preferences and expectations.The last challenge is the honesty of the stakeholders which lead to mislead the decision-making process.Hence, in this thesis, trust is an essential part for addressing these challenges. Therefore, the primary thesis research question was:

> What is the trust-based consensus decision-making framework needed when the stakeholders have conflicting interests?

The proposed decision-making framework (MSCDM) has the following characteristics

- Stakeholders collaboration by interacting with each other during negotiation when proposing decisions and expressing opinions about the others decisions.

- Decision process iteration by having several rounds of negotiation.
- Collective decision outcome by aggregating the stakeholders opinions to find a decision agreed on by all of them.
- Flexibility by allowing the stakeholders to adjust their proposals.
- Trust among stakeholders.
- Risk with each decision represented by interest.
- Dynamic trust update after each round while negotiating.
- Consensus decision outcome agreed on by all the participants.
- Computer guides by using the machine in moderating the decision-making process.

In Chapter 2, this thesis summarized decision-making research using two criteria, trust and risk. Chapter 2 gave motivation of this work and related the proposed consensus decision-making framework to previous work on multi-stakeholders or group decision-making. This thesis applies trust and the risk to develop a framework that produces consensus decision outcome.

In Chapter 3, this thesis presented a Trust-Based Multi-stakeholder Decision Making in Water Allocation System. Chapter 3 built a multi-stakeholder Decision-Making Model having these characteristics: trust, damages, and benefits as criteria, trust is associated with the involvement of the human. The model is dynamic by adapting to the changes over time. The decision to select is the solution that is fair with almost everyone. This model is the basis for building the generic framework in chapter 4.

In Chapter 4, this thesis presented a generic framework for multi-stakeholder consensus decision-making (MSCDM) based on trust and risk that produced a consensus decision outcome for many decision-making scenarios. Chapter 4 presented the results of implementing MSCDM and evaluated the effect of trust on the consensus achievement and the reduction of the number of rounds needed to reach the final decision.

This thesis presented rating convergence in the implemented MSCDM framework, which is a result from the changes of stakeholders' rating behavior in each round. The result showed that the trust helps to increase the possibility of agreeing on the same decision through the influence.

In Chapter 5, this thesis presented rating convergence in the implemented MSCDM framework, which is a result of the changes in stakeholders' rating behavior in each round. Chapter 5 evaluated the effect of the trust on the rating changes by measuring the perturbation in the rating matrix. The result showed that trust is useful in increasing the rating matrix perturbation and such perturbation has a moderate negative correlation with the number of rounds.

In Chapter 6, this thesis addressed rating aggregation operators in the implemented MSCDM framework. Chapter 6 presented the design and implementation of four aggregation operators: weighted sum (WS), weighted product (WP), weighted product similarity measure (WPSM) and weighted exponent similarity measure (WESM). The result showed the performance of those aggregation operators in term of consensus achievement and number of rounds needed. The consensus threshold controls the performance of these operators. WS and WP work best with the higher threshold while WPSM and WESM work work best with the lower consensus threshold

The consensus decision-making framework needed to produce consensus decision outcomes has the combination of the humans and the machine intelligence. The humans add extra information prior making the decisions which help to combine all the stakeholders partial views of the problem domain and to know the stakeholders preferences. These extra information develop the trust relationship among those stakeholders and then such a trust can be used as an influence factor on the others to reach an agreement. Also, the humans can evaluate the interest of the decisions by computing their perceived risk, which depends on the context. The machine use to moderate and guide the stakeholders when they negotiate.

The proposed decision-making framework combines the following models

- Trust model that is based on the measurement theory.
- Risk model included in the utility component and it is associated with the interest that include the perceived risk.
- Group decision making model for stakeholders negotiations.

Trust is the core component in the proposed framework and it proved how it helped to improve the performance of consensus decision-making process by reducing the time of negotiations and achieving the consensus.

7.1 Future Work

This thesis identifies five areas of future research.

- Apply MSCDM framework in different kind of distributions in term of preferences and analyze how the framework performs in term of number of rounds and the consensus achievement.
- Assume different mathematical model of rating in MSCDM and validate the result on a real application.
- Study the capability of MSCDM framework of detecting and preventing the malicious decisions.
- Add the machine to stakeholder role, which will lead to have network of humans and machines having a trust relationship.

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APPENDICES

A. MATHEMATICAL MODEL FOR RATING

A.1 Overview

In the proposed framework, rating other stakeholders proposals is required after they propose a solution solutions phase. In the simulator we built, the rating is 5-star system. The start rating is related to the interest associated with the stakeholders solution. As a result, it is important to provide a mathematical model for ratings that take the interest values as an input and produce the star value as an output.

> **Example**: Two stakeholders A and B propose solutions D_A and D_B respectively. A rates B according to the interest to him/her from D_B, denoted by $I_A(D_B)$ and the interest from his/her decision $I_A(D_A)$. The value of the difference between $I_A(D_B)$ and $I_A(D_A)$ is used to compute the start rating.

We assume the following:

- The interest (I) value is in the range [0,1].
- The differences ($diff$) between interest is in the range [0,1].
- The star values ($star$) is in the range [0,5].
- The more ($diff$) the less ($star$).

We would like to find the mapping function from ($diff$) to ($star$) subject to the above assumptions.

A.2 Generating the Mathematical Model

Stakeholder A rates B by computing the differences of interest between their proposed decisions D_A and D_B. This difference is denoted by $diff_A$. The value of $diff_A$ is in the range [0,1]. However, if the range is represented by minimum and maximum values, then our case 1 gives the minimum rating and 0 gives the maximum rating. So, we would like to find a mapping function:
$f : [1, 0] \rightarrow [0, 5]$ such that

$$f(1) = 0$$
$$f(0) = 5$$

We would like to transform a value x in [1,0] to a value y in [0,5]. If we assume that we have affine linear transformation, then

$$\frac{5-0}{0-1} = \frac{y-0}{x-1}$$
$$\frac{5}{-1} = \frac{y}{x-1}$$
$$-5 = \frac{y}{x-1}$$
$$-5 * (x-1) = y$$

This yields to get:

$$y = 5 * (1 - x)$$

Where y is the start value and x is the difference in interests.

B. DATABASE DESIGN

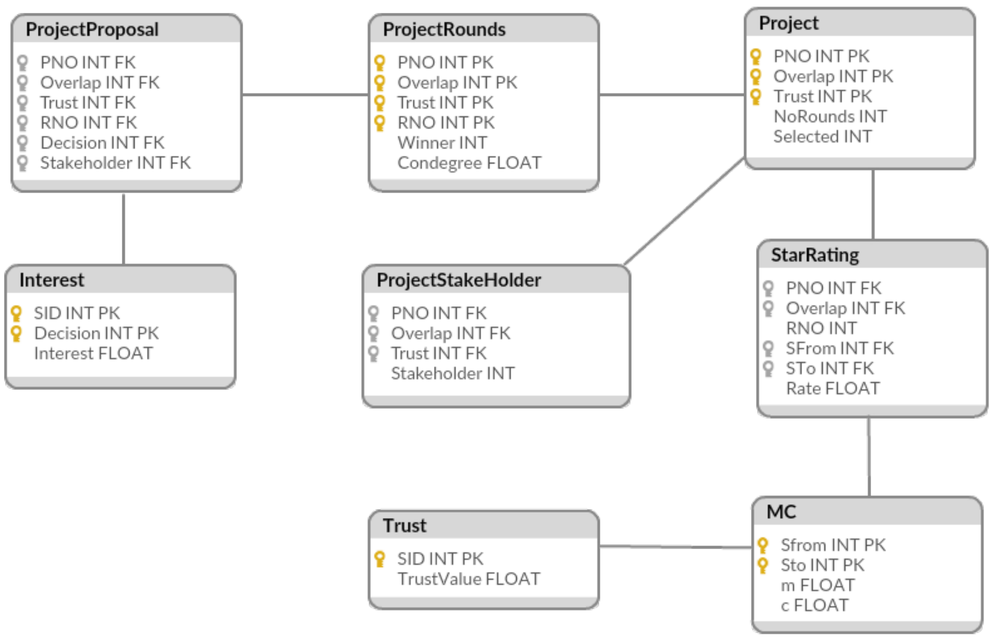

Fig. B.1. The relational Database Design of the entities in the simulation

Table B.1.
List of the tables variables used in the simulation with their corresponding description

Variable	Description
c	The confidence value
ConDegree	The consensus degree in every rounds held for each project
Decision	The decision to propose by every stakeholder in each round in the project
Interest	The interest value associated with each decision corresponding to stakeholder
m	The impression value
NoRounds	Number of rounds held for each project
Overlap	Indicate the case type (three overlap cases)
PNO	Project number
RNO	Round number in the project
Selected	The selected decision
SFrom	The Stakeholder's ID who rates
SID	The Stakeholder's ID
Stakeholder	The Stakeholder's ID proposing decision
STo	The Stakeholder's ID who is rated
Rate	The rating value received.
TrustP	Indicate whether trust is used or not.
Trust	Trust value computed by m and c
Winner	The stakeholder whose decision the highest consensus in each round.

VITA

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Relevant Coursework

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Relevant Coursework

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PUBLICATIONS

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- Techniques for collecting data in social networks. (2014)

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- Using Twitter trust network for stock market analysis.(2018)
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- Exploring stock market using twitter trust network.(2015)
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Programming:

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Programming Applications:

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OS Proficiency:

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Data Scientist and Researcher

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Media Representative and Webmaster.

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Intern, research project related to Computer Forensics.

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Security leader, security department.

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Research Technician, application Developer, and Database designer

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Trainee, networking and web development design.

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Web Development with Rational Application Developer.

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Object-oriented Coding Best Practices.

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Introduction to PLSQL.

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- STC datathon award nomination (2019)
- Member of Saudi Students Club at IUPUI that won a 1st place award among Saudi Students Clubs in USA (2017)
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- Golden Key Membership. (2012 Present)
- King Abdullah Scholarship Program. (2011 - present)