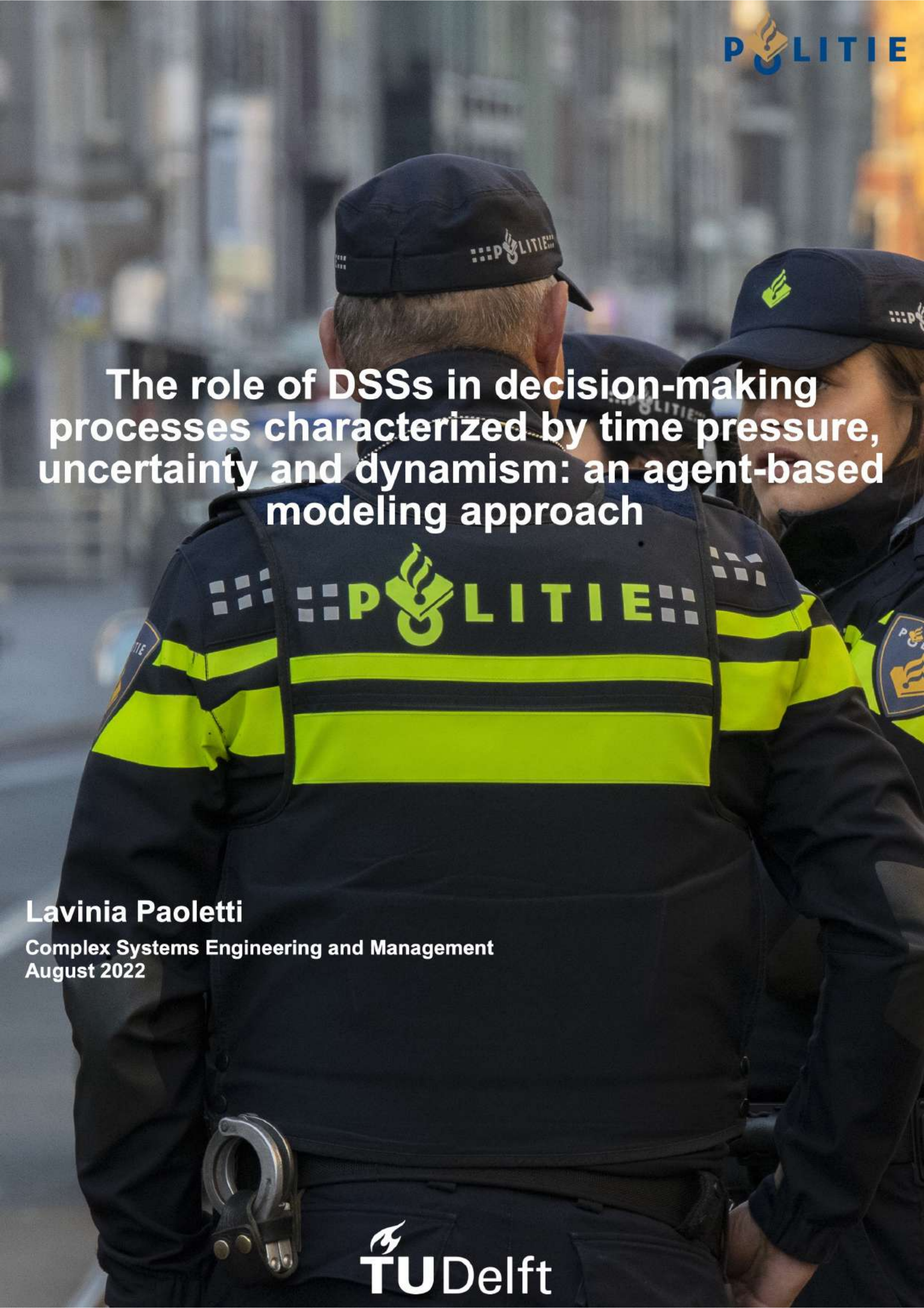

The role of DSSs in decision-making processes characterized by time pressure, uncertainty and dynamism: an agent-based modeling approach

Lavinia Paoletti

Complex Systems Engineering and Management

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TU Delft

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The role of DSSs in decision-making processes characterized by time pressure, uncertainty and dynamism: an agent-based modeling approach

by

Lavinia Paoletti

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Thesis committee:	Prof. J. Kwakkel,	TU Delft, first supervisor
	Prof. I. Nikolic,	TU Delft, second supervisor
	I. van Droffelaar,	TU Delft, advisor

TU Delft

Preface

This Master thesis concludes my journey at Delft University of Technology. While the process has not been straightforward, especially with the start in the middle of the pandemic, since the first day I have been fascinated by learning how to design and manage complex socio-technical systems with a 360-degree view. I am very grateful for the opportunities I was given during these two years, the knowledge that I gained, and the projects I have been part of.

The thesis project has been conducted in collaboration with the Dutch National Police. It has been an incredible opportunity, and a very formative experience, for me to witness the officers conducting their normal duties and listen to all their stories about the Police procedures and their experiences. This project allowed me to partially contribute to solving a societal problem that comes with many complexities and I was very honored to take part in this.

During this project, I was supported by an amazing graduation committee. I would first like to thank my supervisors, Jan and Igor, for their support throughout the process. You provided me with crucial suggestions that greatly helped me reach my goals and refine my project. I want to thank Irene, who especially supported me during these months. Thank you for your constant availability, for our weekly meetings, and for your valuable guidance.

I would like to thank the Police agents who devoted some of their time to me and who took me around with them during their shifts. I want to especially express my gratitude towards Eelco and Wout. Without your availability and the insights you provided me with, I could not have conducted this project.

Last but not least, I want to thank my family, for being an amazing support system and always valuing even the smallest achievement. I could not have reached any of my goals without you. I want to thank my boyfriend, David, for always believing in me and encouraging me to pursue my dreams. I want to thank Stephy, my roommate and main companion during this adventure at TU Delft. Sharing all our pains and gains for two years has been an extraordinary gift, it would have never been the same without you. Finally, thanks to all the friends I met during this year, you really made my journey here special.

I hope you will enjoy reading this report. I really wish this project will be the first of many occasions in which I can give my contribution to solving societal problems.

Lavinia Paoletti
Delft, August 2022

Executive summary

Decision support systems (DSSs) are commonly applied in many domains, from organizational contexts to crisis management. Despite their frequent use, little is known about the impact they have on decision-making processes. Some authors claim that they can improve these processes, either by decreasing the decision time or improving the quality of the output; other authors do not agree with this position, stating that the use of DSSs does not lead to visible improvements in the decision process or outcomes. Moreover, in circumstances of increasingly complex environments, the effectiveness of decision-making processes can be severely threatened. Factors such as time pressure, dynamism, and uncertainty, increase the complexity of decision-making processes. Thus, while a DSS might support these processes, the effect of using a DSS in such circumstances is not yet clear. Not only is it uncertain to what extent the DSS can actually be of support, but also the attitude that users have towards such a system being introduced in already established processes is a still highly discussed topic.

This research aims at investigating the effect that using a DSS in decision-making processes that take place in environments characterized by time pressure, dynamism, and uncertainty, has on the personal efficiency and productivity of decision-makers. Personal efficiency and productivity primarily refer to the time needed to structure a problem or make a decision.

The analysis is conducted by making use of a case study that concerns the procedures of finding and arresting fugitives undertaken by the Dutch National Police. We conducted interviews with practitioners to gain insights into these procedures. Currently, a DSS is being developed to support these procedures and assist the dispatchers in positioning the units. The decision-making process of establishing the best strategy to position the police officers on the street to intercept the criminals is indeed currently undertaken by the dispatchers in the control room, who uniquely rely on their experience and intuition. This task is characterized by high uncertainties with regard to the (dynamic) location of the criminals and by high time pressure. Moreover, not all the dispatchers are sufficiently expert to be aware of the best locations and strategies, especially because they might lack experience with the procedures or knowledge of the area where the crime took place. The police officers, on the other hand, are usually more experienced and they usually have some idea of where to position, but need to handle the coordination with both the control room and the other units at the same time, thus making it very complex for them to efficiently organize. For this reason, if the dispatchers were supported in the definition of specific solutions to intercept the offenders, the procedure would result to be more efficient.

The research is conducted by making use of a modeling approach. More specifically, we built a simulation model that has the structure of an agent-based model, to observe the emergent pattern that is the personal efficiency and productivity of a population of heterogeneous decision-makers involved in the practice of finding and arresting fugitives. The agent-based model is implemented to simulate the decision-making process of positioning the Police units in two versions, without and with the DSS. The simulation not only investigates the effect of introducing the system in the process but also the impact that different implementations of the system and the involvement of the actors in the design of the DSS might have on the processes. More specifically, different run lengths of the algorithm (30, 60, and 120 seconds) and different combinations of features being displayed (escape routes, associated probabilities that the fugitive took those routes, and optimal positions for the Police units) are investigated.

To evaluate the effect of the DSS on the personal efficiency and productivity of the decision-makers, we identified performance indicators based on interviews with experts and a literature research. As a result, the decision-making time and the time needed to communicate the strategy to the police officers are selected as performance indicators. Moreover, the rate of adoption of the DSS solution is collected as an output parameter, to additionally evaluate the level of effectiveness of the system.

The results of the experiments conducted highlight that, on average, the decision-making process time

increases with the use of the DSS. More specifically, when the run length is minimum (30 seconds) the increase is limited (and the DSS solution is more commonly applied), but when the run length is equal to 1 or 2 minutes, the increase is very evident, thus leading to a decrease in the personal efficiency and productivity of the practitioners. The system's solution is more frequently adopted when the DSS shows information on the optimal positions, regardless of the number of information displayed, outlining that the time needed to gather and process the information is more relevant than its level of transparency. One possible flexible strategy can be providing the dispatchers uniquely with the information on the optimal positions as a standard setting, while including an option to visualize the information on the routes and associated probabilities in case of need. The DSS is especially useful when the decision-makers either lack knowledge of the procedures, or the area, or both of them, or when they get information on the direction of the fugitive over time that is different from what they had in the beginning. The rate of adoption of the DSS solution by the dispatchers is anyways generally low (less than 50%), while the rate of adoption of the DSS solution by the police officers is pretty high on average. Finally, when the agents are included in the design of the system, have a positive experience with it, or trust it in general, not only the rate of adoption is higher, but the communication time is strongly reduced, highlighting that trust in the system can highly decrease the discussions between actors. However, this is only true for the officers, because, for the dispatchers, high trust in the system does not lead to a reduced decision-making time. In fact, the dispatchers are in direct contact with the system, and thus, for them, other aspects (such as the run length of the algorithm) play a more crucial role in the decision.

Some of the results gained from the simulation model can be generalized to all decision-making processes taking place under time pressure, dynamism, and uncertainty. First, in these contexts, the use of a DSS does not always make the process faster. This largely depends on how the DSS is implemented, especially in relation to the level of expertise of the decision-makers and the time it would take for them to make a decision without a system. This aspect is very critical in contexts of time pressure, where a high increase in the decision time is not desirable. Furthermore, in dynamic settings, when the changes in the environment lead to an increased time pressure and complexity of the decision, the DSS can lead to improved performances. Secondly, the time needed to gather and process the information in these contexts is far more important than the transparency of the information displayed by the system. Identifying a trade-off between the run length and the transparency of the information is paramount. Nevertheless, given the uncertainty and dynamism of these environments, flexibility is a very important property of such systems. Finally, trust in the DSS or past experience with it can lead to a reduction in the discussion time, meaning that the decision-makers define a strategy quicker. However, the way the system is implemented plays a more important role in the decision compared to actors' past experience with the DSS, especially for those who work in direct contact with it.

These insights can not only support the implementation of the DSS considered in the case study but also the one of all DSSs employed in similar contexts, especially given the lack of knowledge on the effect of using DSSs in environments characterized by time pressure, dynamism, and uncertainty. Moreover, this study contributes to the research regarding the use of DSSs in such contexts by underlining the extent to and the conditions under which the DSS can assist the decision-makers, with an additional focus on the effect of different implementations of the system and the role of the dynamic environmental conditions in relation to the time pressure and uncertainty of the processes. Furthermore, this research shows how a simulation model, structured as an agent-based model, can be employed to explore the behavior of decision-makers and their interactions between each other and with the DSS.

This research presents some limitations. Since the knowledge on the topic is still not deep and given the impossibility of empirically verifying some parameters, some assumptions had to be made while conceptualizing the simulation model which might partially influence the results. Moreover, due to the lack of knowledge on the behavior of the fugitives and the strategies usually adopted by the dispatchers and police officers to position the units, the environment was not modeled in this study. Further research can focus on including this aspect to evaluate whether the DSS can lead to an improvement in the decision quality, as well as more carefully investigating decision-making processes taking place under time pressure, dynamism, and uncertainty and the effect of using a DSS in such contexts. Finally, a study can be carried out that not only focuses on the effect of employing the DSS in the first stages of its implementation but also whether the behavior of the actors and the attitude towards the system change over time.

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Introduction

1.1. Decision-making processes under time pressure, dynamism and uncertainty, and DSSs

Decision support systems (DSSs) are defined as systems that support the cognitive processes of an individual decision-maker (Keen, 1980) and are currently applied in many fields, ranging from organizational contexts (Angehrn & Jelassi, 1994) to crisis management (Kamel, 2001). The impact that such DSSs can have on decision-making processes is widely discussed in the literature, with some researchers, such as Bharati and Chaudhury (2004), claiming that quality DSSs are directly linked to information relevance, accuracy, completeness, and timeliness, and other scholars not agreeing with this position and arguing that the DSSs do not generally improve decision-making processes (Skinner & Parrey, 2019).

In the circumstances of increasingly complex environments, the effectiveness of decision-making processes can be severely threatened (Salanova et al., 2002). Phillips-Wren and Adya (2020) outlines that time pressure, as well as constantly changing criteria (dynamism) and some level of uncertainty in the available information and on the possible outcomes, are factors that might negatively influence the effectiveness of the decision-making processes. While many researchers have investigated how information technology can support decision-making processes to improve the effectiveness and quality of decisions (Bohanec, 2009), many aspects are still debated, especially with regard to these complex circumstances. It is indeed not yet clear whether the employment of a DSS improves such decision-making processes and what aspects of these processes (the duration of the process, the outcome) it can improve.

Moreover, another aspect that is critical in these contexts is the attitude that users have towards such a system being introduced in already established processes. Davis et al. (1989) claims that the adoption of the new technology is influenced by the perceived ease of use and perceived usefulness of the technology itself, but those are in turn influenced by other internal and external variables (Venkatesh & Davis, 2000). Many researchers have investigated what these factors are and which ones have the highest effect, but the topic is still highly discussed.

Therefore, whilst this field has been investigated for decades, many questions still remain unanswered and more research is needed to gain a deeper understanding of the role that DSSs play in decision-making processes.

1.2. Research question

In accordance with the knowledge gap described above, this research aims at investigating the effect of using a decision support system on decision-making processes, in environments characterized by time pressure, uncertainty, and dynamism. Various are the aspects of decision-making processes that can be investigated. Forgionne (2000) distinguishes between the process itself and its outcome as aspects that can be considered. This study focuses on the effect that the use of DSSs has on the decision-making process and more specifically on the personal efficiency and productivity of the practitioners, which are two factors that, if enhanced, can determine an improvement in the decision-making processes (Forgionne, 2000). As Dean Jr and Sharfman (1993) state, an increase in personal efficiency can refer to a reduction in the time needed by the user to structure the problem or increasing the number of alternatives evaluated by the user in a given time period. On the other hand, an improvement in personal productivity might refer to the reduction of the time needed for decision making or the increase of the amount of pertinent information, knowledge, and wisdom from decision making (Kumar, 1999).

As a result, the research question for this project is defined as:

”What is the effect of using a decision support system on the personal efficiency and productivity of decision-making processes, in environments characterized by time pressure, uncertainty, and dynamism?”

To answer this research question, we will make use of a modeling approach is employed, by building a simulation model, structured as an agent-based model. An agent-based model helps to investigate the emergent patterns that originate from the interactions between agents and with the environment (Van Dam et al., 2012) and thus it makes it possible to model the decision-making process conducted by the agents to investigate the emergent behavior in terms of personal efficiency and productivity of a population of heterogeneous practitioners. The use of such computational experiments in this kind of context resembles, as Kwakkel and van der Pas (2011) underline, the “animal models”, employed in medical research. A similar approach is used to investigate the role of DSSs in decision-making processes that take place in environments characterized by time pressure, uncertainty, and dynamism.

1.3. Police case study

To conduct this research, we will employ a case study that concerns the use of a DSS to support the Dutch National Police in the complex task of finding and arresting fugitives. This task is indeed characterized by high uncertainties with regards to the (dynamic) location of the criminals and by high time-pressure, aspects that make it very challenging for the control room to position Police units. The dispatchers currently approach this task by relying on intuition and experience, however, especially given the huge amount of information the dispatchers are provided with and the short amount of time they have to formulate a strategy, they are not always able to suggest to the road officers where to position in a fast and efficient way. Moreover, not all the dispatchers are sufficiently experienced with the procedures or familiar with the area of the crime, which makes it complex for them to position the units. The police officers, on the other hand, are usually more experienced, but need to handle the coordination with both the control room and the other units at the same time, thus making it very complex for them to efficiently organize. For this reason, if the dispatchers were supported in the definition of specific solutions to optimize the chances to intercept the offenders, the procedure would result to be more efficient.

While the use of DSSs in the Police environment has a growing role in the literature (Carlsson et al., 2010), the role and the effectiveness of a DSS in the context of chasing criminals are not yet investigated. Therefore, the thesis project will aim at assessing the difference between the effectiveness of the current practice and the model-supported practice, by making use of an agent-based model where the practitioners are implemented as agents and their decision-making process is modeled.

1.4. Suitability of the research for the CoSEM program

This research focuses on the effect of using a DSS in decision-making processes that take place in environments characterized by time pressure, dynamism, and uncertainty. These kinds of decision-making processes usually take place in complex socio-technical systems, which are strongly characterized by unpredictability, the involvement of many different actors, and the human interaction with a technological component (the DSS). This requires a multidisciplinary approach and the employment of specific tools and techniques. A modeling approach is indeed applied to analyze the system. This makes this research typical for a CoSEM (Complex Systems Engineering and Management) Master thesis, which aims at designing solutions for large and complex socio-technical systems. The results of this research would indeed support the design of a DSS in a complex system, represented by the Dutch National Police.

1.5. Societal and scientific contributions

This project provides insights into the impact that DSSs have on the personal efficiency and productivity of decision-makers, in contexts of high time pressure, uncertainty, and dynamism. The research supports the design of DSSs in such contexts, by investigating which aspects are critical to ensure a successful implementation. The aspects to be considered in the design phase to maximize the increase in the personal efficiency and productivity of the practitioners are outlined in this research. While the results can be directly applied to the analyzed case study, the insights produced by this research can additionally be applied to other similar fields, for instance, contexts of crisis management.

Moreover, the project contributes to the research concerning DSSs, especially with regard to the interactions between humans and DSSs and how a DSS can support individual decision-making processes in complex situations characterized by high time pressure, uncertainty, and dynamism. Many authors (Carver & Turoff, 2007; Forgionne, 1999; Hwang, 1994; Rieger & Manzey, 2020; Skinner & Parrey, 2019), indeed underline how the effect of employing a DSS in such contexts is currently under debate and highlight the need for further research. Furthermore, the project contributes to the field focusing on the DSS design in these contexts, for instance with regards to the level of detail of the information displayed, an aspect that is still under debate (Fogli & Guida, 2013). Additionally, as (Loriette et al., 2019) underline, the effect of using DSSs in dynamic environments is yet to be determined, and this study contributes to answering this question. Finally, this research investigates how a simulation model, structured as an agent-based model, can be employed to explore the behavior of decision-makers and their interactions between each other and with the decision support system.

1.6. Outline of the thesis

This thesis is organized as follows. The next chapter describes the research approach and the research sub-questions. Chapter 3 includes a literature review that addresses the main concepts related to decision-making processes, decision support systems, and the human attitude towards new technologies. Afterward, the problem and actors identification is tackled in Chapter 4, and Chapter 5 includes the system identification and decomposition, where the components that will be part of the model are described. In Chapter 6, the conceptualization of the agent-based model is presented, and the narrative and the assumptions made are specified. In this chapter, the verification and validation of the model are also included. The next two chapters focus on the implementation of the experiments and their results, and the validation of the model. Finally, Chapters 9 and 10 include the discussion and the conclusion of this project.

2

Research Approach

In this chapter, the research approach for this project is presented. Firstly, the employed case study is introduced. Secondly, the methods used to gather knowledge and the modeling approach used to answer the research question are explained. Finally, accordingly to the modeling approach, the research sub-questions are described.

2.1. Case study

In order to answer the research question, we will employ a case study. Making use of a case study helps to understand the problem at stake by analyzing a specific situation. At the same time, it limits the range of fields of application of the results, to uniquely the situations that are inherently similar to the considered case study (Bennett, 2004). This means that the collected results can be applied uniquely to situations where the decision-makers are faced with time pressure, uncertainty, and dynamism (e.g. crisis management). Nevertheless, whilst it has been under debate in which circumstances the results of case studies can be generalized, Mohr (1982) argues that case studies are especially effective as a method to conduct exploratory research. Tsang (2014) adds to that by stating that the insights gained from case studies can be theoretically generalized, meaning that the explanations of the relationships between variables observed in the studies can be applied not only to the populations on which the studies were based but also to other populations.

As mentioned in the previous chapter, the case study for this research concerns the employment of a DSS to support the Dutch National Police in the complex task of finding and arresting fugitives. This case study fits with this research because the task undertaken by the Police is characterized by high uncertainties with regards to the (dynamic) location of the criminals and by high time-pressure, aspects that make it very challenging for the control room to position Police units. While the use of DSSs in the Police environment has a growing role in the literature (Carlsson et al., 2010), the role and the effectiveness of a DSS in the context of chasing criminals are not yet investigated. Therefore, the thesis project aims at assessing the difference in the performance of the procedures between the current practices and the (future) model-supported practices.

Currently, when a crime takes place and the offender is escaping, the dispatchers in the control room position the Police cars relying on their own intuition and experience to intercept the offender. Based on the available time and information, the dispatchers communicate to the officers the best spots to locate. However, the dispatchers do not have a lot of time to complete this task and they are usually overwhelmed with information, often lacking deep knowledge of the procedures or the area of the crime. Therefore, dispatchers sometimes have to rely on police officers located on the streets to determine the most strategic spots to locate. Police officers, whilst more experienced, need to handle the coordination with both the control room and the other units at the same time, thus making it very complex for them to efficiently organize. In this context, a DSS is being designed to provide the dispatchers with specific positioning strategies to optimize the chances to intercept the offenders.

2.2. Modeling approach

To assess the difference in the performance of the procedures between the current practices and the model-supported practices, the system needs to be analyzed. As shown in Figure 2.1, there are several ways to analyze a system (Law & Kelton, 1991). Since it is not possible to experiment with the real system, a model of the system is used. Given the case study, it would be very complex to use a physical system, since it would be almost impossible to replicate the stressors that characterize the procedures. A mathematical model, and more specifically a simulation model, support the analysis of the system in the two situations without having to physically implement it (Van Dam et al., 2012).

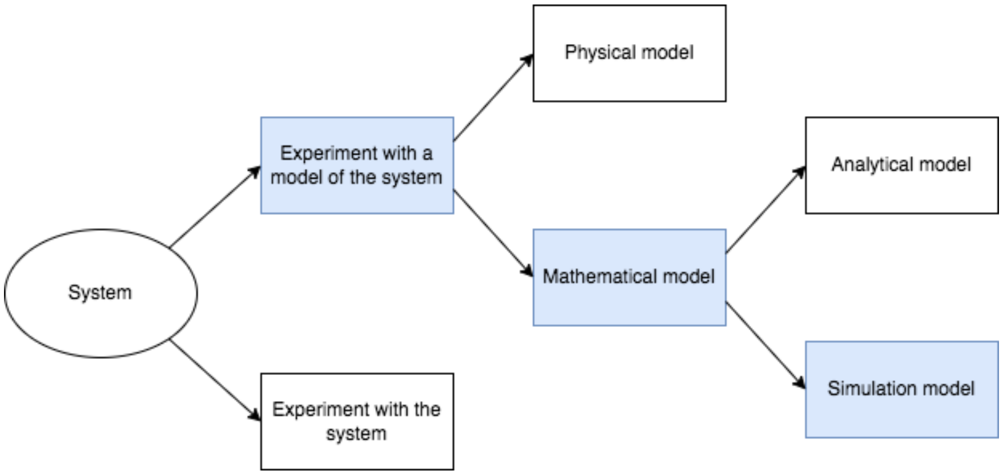


Figure 2.1: Ways to study a system, adapted from Law and Kelton (1991).

Because of the need to model a decision-making process and the interactions between different actors and with the environment, we will make use of an agent-based model approach (ABM), which helps to investigate the emergent patterns that originate from the interactions between agents and between agents and the environment (Van Dam et al., 2012). In the case under study, differently to common agent-based models, the interactions take place between a very limited number of agents and there is no real pattern that emerges from one run of the model. On the other hand, in this case, the emergent pattern is observed by running multiple runs, in which the agents have different properties and interact differently with other agents and the environment. By aggregating the results of multiple runs it is indeed possible to observe the emergent pattern that is the personal efficiency and productivity of a population of heterogeneous decision-makers involved in the practice of finding and arresting fugitives. The population of the Dutch National Police is indeed constituted by small groups of decision-makers that interact with each other but do not interact with the other groups. For this reason, the ABM approach is employed as a way to define the interactions of the agents as based on their attributes and on the inputs from the environment, and to investigate the relation between the attributes of the agents, the inputs from the environment and the outcomes, while dealing with the stochasticity that characterizes these processes. It also has to be considered that, usually, ABM is employed when the agents evolve over time, learning and adapting based on the inputs they receive from the environment and from other agents Bonabeau (2002). In this case, the evolvement of the agents over time is not investigated, but on the other hand, the focus is on the behavior of a heterogeneous population of agents, who are at different stages of the learning process (have more or less, positive or negative past experience) and act based on their personality, past experience and inputs coming from the environment. Thus, not a standard agent-based model is implemented, but a model that inherits and exploits the general structure of ABM but differs from it since just a small population is included, no learning or adaptation is involved and no emergent behavior can be seen from a single run.

The ABM approach is chosen because: the population is heterogeneous, the individual behavior is complex and it is complex to describe the individual behavior with equations (because of stochasticity and the interactions between the agents); validation and calibration of the model through expert judgment is an important aspect; stochasticity applies to the agents' behavior. These are elements that, according to Bonabeau (2002), suggest the use of ABM as modeling approach. Additionally, previous research demonstrates that ABM could extremely help in organizational contexts (Prietula et al., 1998), and that once one has a reliable model of an organization, it is possible to play with it, change some of the organizational parameters, and measure how the performance of the organization varies in response to these changes, which represents the purpose of this study.

Making use of a computational model resembles the concept of the "animal model" approach used in medicine, as highlighted by Kwakkel and van der Pas (2011). This approach can consist of both a computational model or a simulation game with students, but the disadvantage of the simulation game is that, as previously stated, it is very complex to replicate the stressors that characterize the procedures. Moreover, students are not really decision-makers and thus do not have the same experience and background knowledge as the practitioners (Kwakkel & van der Pas, 2011). However, it is important to remember that the agent-based model represents a simplification of reality and thus might fail to represent entirely all the dynamics (Wilensky & Rand, 2015). For this reason, it is important to consider this limitation while analyzing the final results of the simulation.

In order to assess the difference in the performance of the procedures with and without the DSS, we will develop the agent-based model in two versions: in one version, the current procedures are reproduced, when the decision-maker is not assisted by the DSS and relies on their experience; in the second version, the future situation is represented, with the decision-maker being assisted by the DSS. To implement the agent-based modeling, a modeling approach defined by Van Dam et al. (2012) is employed, which consists of eleven steps, as shown in Figure 2.2.

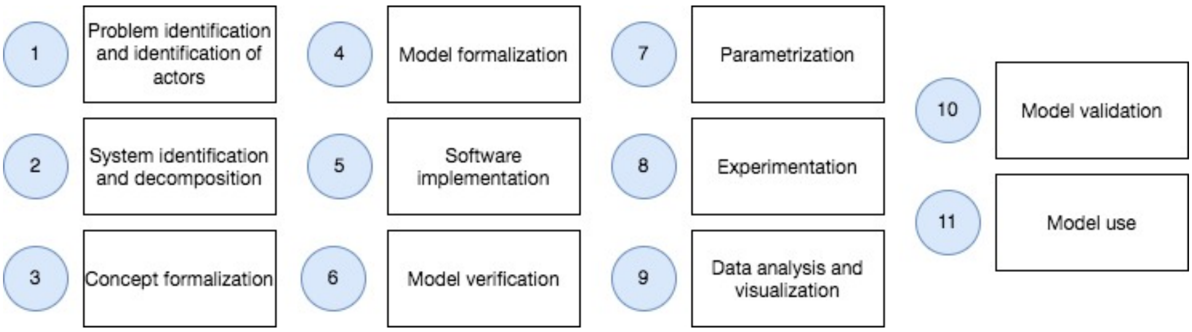


Figure 2.2: The modeling approach as defined by Van Dam et al. (2012).

The modeling approach starts with the problem identification and identification of the actors that are part of the system. Afterward, the boundaries of the system are determined, as well as the components that are going to be included in the system. Accordingly, the system is conceptualized, firstly in the form of diagrams and flow charts and then in the form of a narrative, and then translated into the agent-based model in Python by making use of a pseudo-code (model formalization) as a middle step. Python is chosen as a programming language because of its universality and versatility, whereas Netlogo is a valuable option for ABM but is less established. After implementing the model in Python, a verification phase is conducted that includes a reproducibility and variability test (to verify that the results are reproducible with fixed seeds and vary with different seeds), and a sensibility test (to assess to what extent varying the parameters may affect the results). Once the verification is concluded, the parametrization of the model and the consequent experimentation phase is conducted. The data that is obtained is then analyzed in Python and then the results are validated making use of experts and literature.

2.2.1. Gathering knowledge

To build the model, two kinds of inputs are needed. First of all, knowledge about the procedures is required to conduct the simulation. Moreover, knowledge of decision-making processes and DSSs is needed to properly model the decision-making process undertaken by dispatchers and police officers.

Interviews In order to model the above-mentioned procedures, we will conduct some interviews with practitioners. The interviews are arranged with both a dispatcher that works in a control room and three police officers that work on the streets with cars. The aim of the interviews is not only to understand how the procedures currently work, but also to understand how the decision-making processes take place, the critical factors in the process, and who is involved in these decisions. The interviews are conducted as semi-structured interviews, which allow for flexibility. Because of time and language constraints, just a few practitioners are interviewed, which represents a limitation since interviews can be sensitive to bias (Alshenqeeti, 2014). However, considering both perspectives on the procedures helps to gain a deeper understanding of the process and can partially mitigate these biases.

Literature research While interviews are used to get an understanding of the procedures, the literature research is meant to: determine how decision-making processes take place; investigate the impact of time pressure, uncertainty, and dynamism on such processes; identify a suitable decision model that is applicable to the case at stake; determine the state-of-the-knowledge concerning the impact that DSSs have on decision-making processes characterized by time pressure, uncertainty, and dynamism; identify a suitable model that explains humans' attitude to the use of a new technology (and specifically, a DSS) that is meant to support a task they are responsible for. The information gained from the literature research is critical to model the decision-making process undertaken by dispatchers and police officers. This knowledge will be thus employed in the conceptualization of the system.

2.3. Research sub-questions

Taking the modeling approach as a starting point, the main research question for this project is divided into four sub-questions.

Sub-question 1: How do the current procedures of finding and arresting fugitives work?

The first sub-question is meant to gain an understanding of the procedures of finding and arresting fugitives and the decision-making process undertaken by the practitioners and refers to the first two steps of the modeling approach: problem formulation and actor identification, and system identification and decomposition. These steps will be covered in Chapters 4 and 5.

Sub-question 2: How can the personal efficiency and productivity of the practitioners in the procedures be measured?

The second sub-question refers to the identification of some metrics to assess the above-mentioned organization's performance personal efficiency and productivity of the practitioners that are involved in the procedures of finding and arresting fugitives with and without the DSS. Personal efficiency and productivity refer to the time needed to structure a problem and make a decision and the amount of information considered (Dean Jr & Sharfman, 1993; Kumar, 1999). This sub-question will be answered in Chapter 5.

Sub-question 3: How can the procedures of finding and arresting fugitives, with and without the assistance of the decision support system, be translated into an agent-based model?

The third sub-question is related to the translation from the conceptualization of the system to the agent-based model and includes various steps of the modeling approach, from concept formalization to model verification. As an input to this sub-question, scientific literature on decision-making and DSSs and information on the DSS employed in the case study are employed, which are presented in Chapter 3. This phase is discussed in Chapter 6.

Sub-question 4: What is the difference in the personal efficiency and productivity of the practitioners, when the decision-makers are and when the decision-makers are not assisted by the decision support system?

The fourth sub-question refers to the final steps, from parametrization to validation. The data on the personal efficiency and productivity of the practitioners with and without the DSS is used to answer the main research question. This step is discussed in Chapters 7 and 8.

The Research Flow Diagram that elaborates on the research sub-questions is included in Figure 2.3.

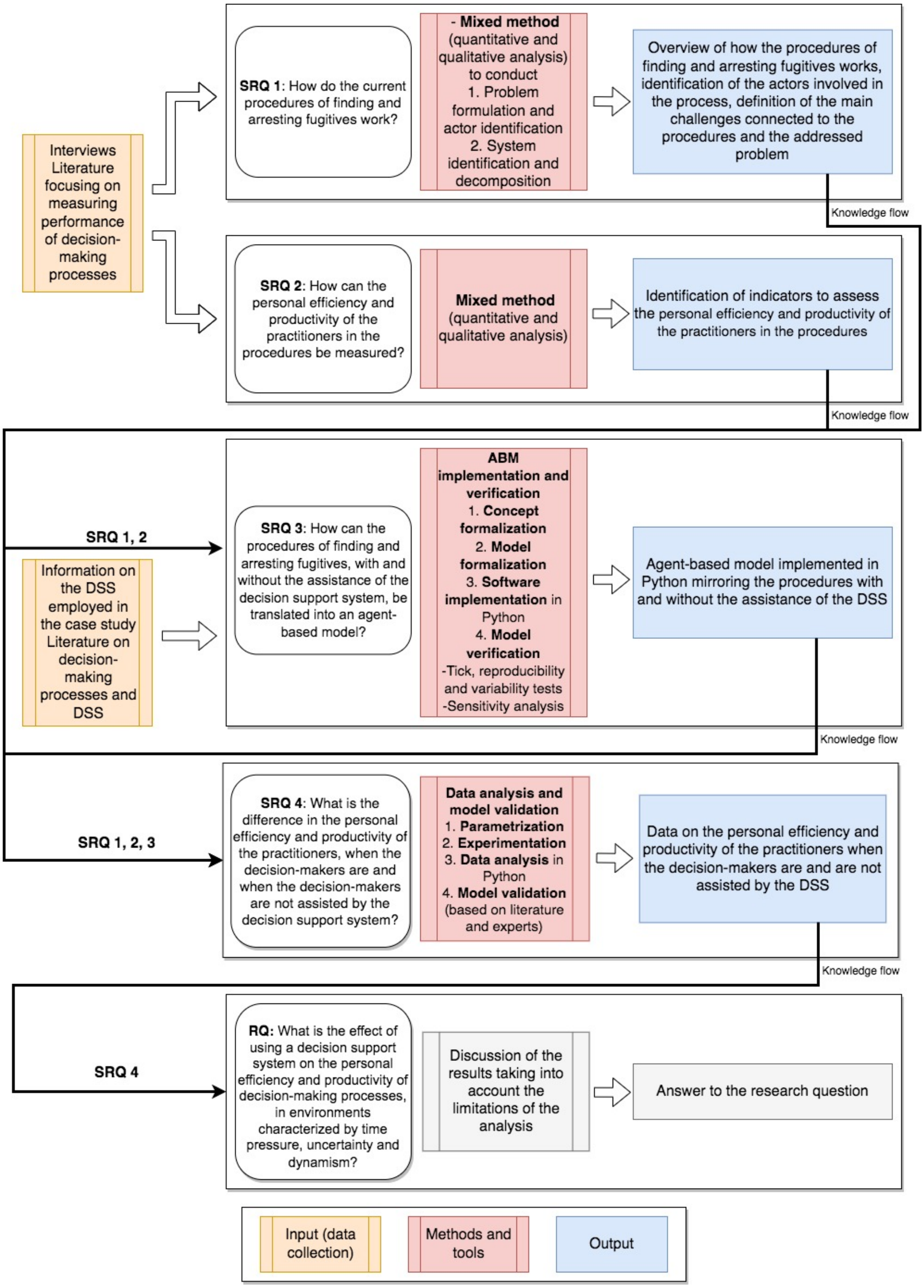


Figure 2.3: The Research Flow Diagram for this project.

3 Decision-making processes and decision support systems

In order to model the procedures of intercepting fugitives undertaken by the Dutch Police, it is paramount to investigate how decision-making processes take place under time pressure, uncertainty, and dynamism, and the factors that may influence the adoption of a DSS and humans' attitude towards it. In this chapter, a literature review is presented which aims to provide an understanding of these concepts. The insights presented in this chapter will be employed to conceptualize the model. We conducted the literature research by using a database search and a backward snowballing approach. More information on the literature review process is included in Appendix A. An important aspect to consider is that, due to the lack of knowledge on the operational decision-making processes taking place under time pressure, uncertainty, and dynamism and on the use of DSSs in such contexts, the majority of articles cited in this chapter refer to strategic, long-term decision-making processes, a research area that is more explored. This lack of knowledge with regard to the operational decision-making process and the employing of a DSS in such environments represent a limitation to this study, as will be discussed later.

In this chapter, first, the main notions on decision-making processes are presented. Afterward, the effect of time pressure, uncertainty, and dynamism are investigated and a model that explains the decision-making processes in these contexts is presented. Moreover, the concept of DSS is introduced, as well as the role that these systems have in situations characterized by time pressure, uncertainty, and dynamism. Finally, the Technology Acceptance Model is introduced as a model to evaluate users' attitude toward the adoption of a new technology. Finally, by taking this model as a starting point, the factors influencing the adoption of a new technology are identified.

3.1. Decision-making processes

Decision-making is commonly defined as a mental process that involves judging multiple options or alternatives (Bohanec, 2009). It usually requires evaluating at least two alternatives that differ from each other in a number of aspects. Among the many different decision-making models that can be found in literature, the most widely accepted are the rational decision-making one and the cognitive decision-making one (Skinner & Parrey, 2019). Both consist of three main steps: first, problem definition, secondly, identification, evaluation, and selection of alternatives, and finally, implementation. According to Forgionne (1999), the decision-making consists of four phases: intelligence, design, choice, and implementation. In the first phase, the decision-maker gets an understanding of the situation and all the relevant information. In the design phase, they develop a specific model, which includes the decision alternatives, uncontrollable events, criteria, and the relationships between these variables. The model can be used to systematically analyze the problem at stake. During the choice phase, the decision-maker evaluates the alternatives by making use of the model and consequently generates recommended actions. Finally, in the last phase, the decision-maker ponders the analysis and recommendations, considers the consequences, gains sufficient confidence in the chosen alternative, and implements the final decision. This process can be continuous, so that after implementing a decision, the reality is analyzed again and the decision-maker goes through all the steps another time.

In complex environments, decision-making processes are usually based on thousands of interrelated variables and can be highly sensitive to initial conditions with so-called ”butterfly effects”, according to which the errors can grow exponentially over time (Lei et al., 2000). For this reason, the first steps of the process become especially critical.

3.2. Decision-making processes under time pressure, uncertainty, and dynamism

As various authors state (Hu et al., 2015; Phillips-Wren & Adya, 2020; Skinner & Parrey, 2019), time pressure, uncertainty, and dynamism are factors that deeply influence decision-making processes.

Phillips-Wren and Adya (2020) focus on stressful decision-making in contexts where there is a wide range of decisions to be made and in which the user makes a decision autonomously while considering the consequences of poor choices, as police officers in their normal duties. In their analysis, they highlight that stressed decision-makers take more risks. Time pressure can positively impact the process in certain situations, such as when time pressure is not avoidable (Rieger & Manzey, 2020) or when time pressure is moderate (Speier-Pero, 2019) improving the focus of the individuals, but usually leads to poor performance quality, for instance when the amount of information overwhelms the decision-maker. Skinner and Parrey (2019) add that some studies have proven that under time pressure, “people limit their information choices to that which can be attained quickly and easily”.

On the other hand, regarding dynamism and complexity, Phillips-Wren and Adya (2020) state that while making complex executive decisions, decision-makers tend to choose satisfactory but sub-optimal alternatives. Dynamism, which refers to constantly changing criteria or decision environment, tends to increase complexity and becomes especially intense when the decision-maker is forced to make rapid decisions under dynamic conditions, for instance, those associated with threat assessment (Kowalski-Trakofler et al., 2003).

Finally, with regards to uncertainty, Hu et al. (2015) state that uncertain decisions require more complicated cognitive processes and that factors such as time pressure and negative emotions negatively impact the decisions. Similarly, Phillips-Wren and Adya (2020) explain that uncertainty negatively impacts a decision maker’s ability to process data and information in a decision situation.

3.2.1. Recognition-Primed Decision model of rapid decision-making

Among the models of decision-making that are present in literature, the Recognition-Primed Decision model of rapid decision-making by Klein (1993) strives to explain the decision-making processes undertaken in situations characterized by time pressure, dynamism, and uncertainty. The research this theory is based on focuses on decision-making processes undertaken by the firefighter commanders in their normal duty. This model can be efficiently applied to the Police case study and to all those situations characterized by uncertainty, time pressure, and dynamism, since it explains those situations where the decision-maker recognizes situations as typical, recognizes typical courses of action, and evaluates actions through mental simulation, thus basing decisions on their experience. Klein (1993) explains how in these situations, the decision-maker is not making choices, considering alternatives, or assessing probabilities. On the other hand, they act based on their prior experience: they generate, monitor, and modify plans to meet the needs of the undergoing situations. Decision-makers tend to recognize the case, and then they automatically know how to react. They make use of the time at their disposal to evaluate an option’s feasibility before implementing it. By imagining how the option would be implemented, they evaluate whether anything important might go wrong. If problems are identified, then the alternative might be modified or completely rejected, and another very typical reaction analyzed.

While assessing a situation, a decision-maker considers four important aspects:

- the types of goals that can be reasonably achieved in the undergoing situation,
- the relevant cues, which represent the information that is needed to understand the situation,

- the expectations, which can be helpful to check the accuracy of the situation assessment conducted by the decision-maker (meaning that if the expectancies are violated, the situation was misunderstood),
- the typical actions to be implemented.

The Recognition-Primed Decision (RPD) model is shown in Figure 3.1, where three cases are highlighted. The first one is the simple match: the easiest case, where the decision-maker recognizes the situation right away and implements the obvious solution. The second case is slightly more complex: the decision-maker performs a mental simulation of the chosen action, typically using imagination to uncover problems before implementing the final solution. In the third case, the evaluation conducted by the decision-maker reveals some flaws in the selected option. This requires either modifying the chosen option or rejecting it completely in favor of the next most typical reaction. If the decision-maker has sufficient time, they would verify if the expectancies are being violated and if that is the case, the assessment is conducted again, eventually by seeking more information.

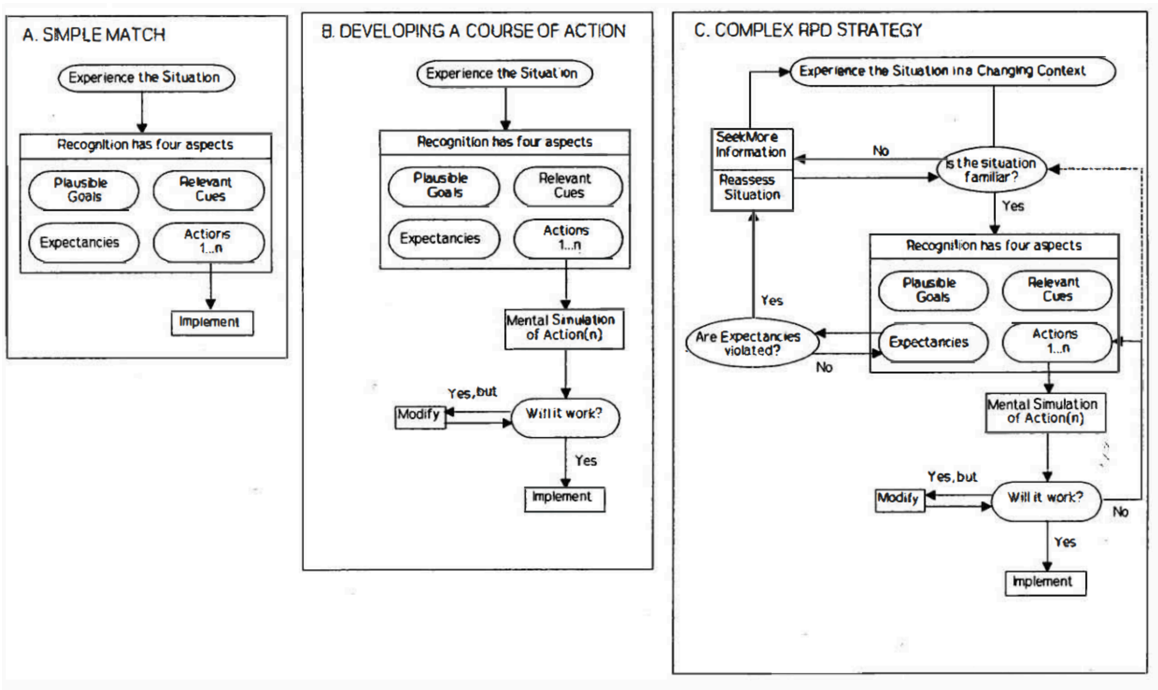


Figure 3.1: Recognition-primed decision model of rapid decision-making as defined by Klein (1993).

In short, the RDP model claims that experienced decision-makers can identify a reasonably good option as the first one they consider, instead of undertaking a semi-random process of option generation. This implies that the decision-maker looks for the first option that works and not necessarily for the best option. Moreover, the model highlights how decision-makers do not evaluate the strengths and weaknesses of an option, but instead they evaluate an option by conducting mental simulations of a set of actions to see if the solution will work.

3.2.2. Institutional Model of Operational-Level Decision Making

Another model that focuses on operational decision-making processes, although not in contexts of high time pressure as the Recognition-primed decision model of rapid decision-making, is the Institutional Model of Operational-Level Decision Making by Heikkila and Isett (2004). This model describes the effects of institutions on operational-level choices in public organizations, based on complementary theoretical insights from political science and sociological notions of institutions. The model explains that, when the actors face a problem, their assessment of the situation is highly influenced by exogenous factors (rules, resources, laws, the physical environment) and endogenous ones (factors that take place within the decision maker's internal cognitive processes). Based on these factors, the decision-makers define a choice set, being the perceived set of viable options available to them. Then the best option is chosen and discussed with the other actors involved, so that the solution is adjusted based on the other actors' opinions and actors' normative conformance. Finally, the strategy is adopted. Heikkila and Isett (2004) underline that this process is not linear. While the stages are sequential, the process may move back and forward multiple times, also with multiple stages being addressed at once, until stability is finally reached.

3.3. Decision support systems

Decision-makers can make use of computer technology (hardware and software) to process the inputs into problem-relevant outputs. According to Forgionne (2000), this processing involves:

- organizing problem parameters (accessing the database, extracting the useful data, and organizing the information in the form needed by the solution model and methodology);
- structuring the decision problem (accessing the model base, retrieving the appropriate decision model, and operationalizing the decision model);
- simulating policies and events (using the operationalized decision model to perform the computations needed to simulate outcomes from user-specified alternatives and then identifying the alternative,or alternatives, that best meets the decision criterion, or criteria, among those tested);
- finding the best problem-solution (accessing the model base, retrieving the appropriate solution method, and using the retrieved method to determine the alternative, or alternatives, among all possible alternatives, that best meets the decision criterion, or criteria).

Forgionne (1999) outlines that many definitions of DSSs have been phrased throughout time. Keen (1980), one of the first researchers who studied DSSs, defined them as systems that support the cognitive processes of an individual decision-maker. Within DSSs, "computer hardware and software are used interactively to perform analyses and evaluations with data and models that result in status reports, forecasts, and recommended actions" (Forgionne, 1999). DSSs imply the use of computers to: assist managers in their decision processes in semi-structured tasks, support, rather than replace, managerial judgment and improve the effectiveness of decision making rather than its efficiency (Scott-Morton & Keen, 1978). When properly implemented, DSSs can improve the output and the process of decision-making by leading to gains in the decision-making performance and the maturation of the user as a decision-maker (Forgionne, 1999). However, in the literature, there is no consensus on the actual level of effectiveness of DSSs (Skinner & Parrey, 2019). Among the supporters of the effectiveness of DSSs, Kumar (1999) states that the use of DSSs enables the decision-maker to be aware of the options before they expire, thus increasing the time the user has to exercise the option, improving the flexibility of decision scenarios. Similarly, Lei et al. (2000) highlight that in complex non-linear dynamic systems where information rapidly changes over time, DSS can deeply improve the decision-making process. Nevertheless, many researchers have conducted experiments during which it was determined that the presence or the absence of a DSS has little influence on the effectiveness of the decision-making process (Skinner & Parrey, 2019).

3.4. The role of DSSs in situations with time pressure, uncertainty, and dynamism

Steiner et al. (2015), in their paper, provide a framework illustrating the human information processing in emergencies through a triangle of the user, the information, the decision support system, and their interactions. In contexts of emergency management, the information is usually presented to the decision-maker through a warning system or a DSS. Users perceive and process the information and analyze and evaluate the situation based on the information at their disposal. The way information is presented and the information system is designed, can support decision-makers in the perception and management of information (Steiner et al., 2015).

As mentioned above, many researchers (Forgionne, 1999; Skinner & Parrey, 2019) highlight how the different opinions on the effectiveness of DSSs in the literature suggest the need for further research. Hwang (1994) states that no research has addressed the effect of DSSs under time pressure. Some authors, such as Phillips-Wren et al. (2019), Rieger and Manzey (2020), Phillips-Wren and Adya (2020) and Sealy and Feigh (2020) argue that DSSs might be helpful in situations with time pressure, uncertainty, or dynamism, but more research is needed. In fact, while there is a lot of literature that concerns DSSs and decision-making under time pressure, uncertainty, and dynamism, little is specified on the actual effectiveness of using DSSs to support decision-makers in this kind of situation (Skinner & Parrey, 2019). Moreover, to the best of our knowledge, most of the research on the topic focuses on strategic decision-making and there is a lack of knowledge regarding the effect of using a DSS in operation decision-making processes. Authors that focus on decision-making processes undertaken during emergency situations, as Carver and Turoff (2007), state that the role of information systems in such contexts is to be further investigated. Loriette et al. (2019) underline that the effect of using DSSs in dynamic environments is yet to be determined. Moreover, many questions still remain unanswered on how DSSs should be implemented to maximize their effectiveness, for instance with regards to the level of detail of the information displayed (Fogli & Guida, 2013). Therefore, by making use of a case study, this thesis project aims at contributing to this research area.

3.5. Technology Acceptance Model and DSSs

While there is no consensus in literature over the effect of employing a decision support system, various studies have been making use of the Technology Acceptance Model (TAM) to evaluate the users' attitude towards the adoption of a DSS (Al-Rahmi et al., 2019; Dulcic et al., 2012; Lu et al., 2001; Rigopoulos et al., 2008).

The TAM defined by Davis et al. (1989) is depicted in Figure 3.2. According to this model, the adoption of a technology is highly dependent on two beliefs, the perceived usefulness and the perceived ease of use of the technology. Perceived usefulness is defined as the "user's subjective perception of the ability of a computer to increase job performance when completing a task", while the perceived ease of use is the "person's subjective perception of the effortlessness of a computer system, which affects the perceived usefulness thus having an indirect effect on the user's technology acceptance" (Rigopoulos et al., 2008). These two aspects, which are influenced by external variables, shape the attitude users have toward the technology and their behavioral intention of using it. This determines the probability that the user will actually make use of the technology. While both aspects highly influence the attitude towards a technology, according to Davis et al. (1989) perceived usefulness has a stronger influence on people's willingness to use systems, while perceived ease of use has a smaller but still significant effect. Although various studies in the past have proven this to be true, perceived ease of use still remains very relevant, since it often represents the first impression of a system (Lu et al., 2001).

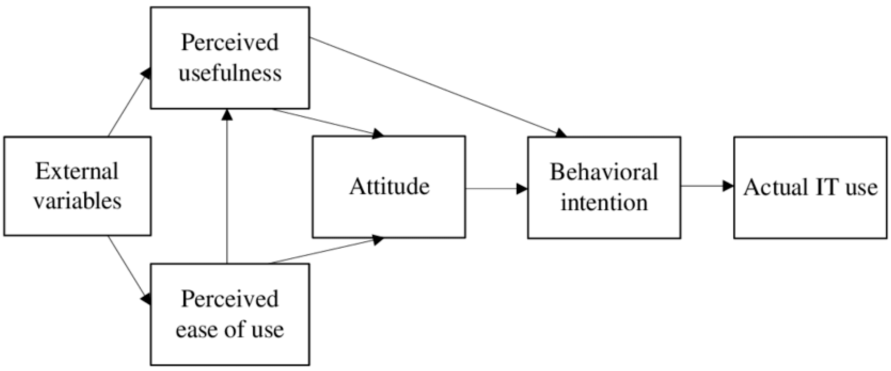


Figure 3.2: Technology Acceptance Model (Davis et al., 1989).

Rigopoulos et al. (2008) conducted a study to assess the statistical correlation between these variables, especially focusing on the perceived usefulness, perceived ease of use, behavioral intention, and actual IT use. In their research, they made use of a case study concerning the introduction of a new DSS to assist the employees of a Greek bank in their daily tasks. The results of this research are shown in Figure 3.3. While the context used in the study conducted by Rigopoulos et al. (2008) is different from the case study employed in this research, both cases are characterized by the introduction of a DSS in a process that beforehand did not include one, and since the research just focus on the adoption of a new technology, the results can also be applied to this case. The results show that the variables have strong relations with one another and that the perceived ease of use deeply influences the perceived usefulness, as highlighted above.

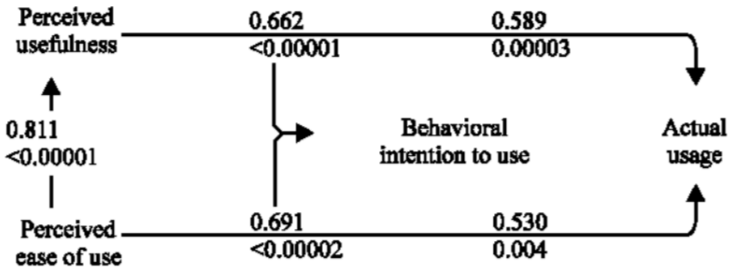


Figure 3.3: Statistical correlation between the variables of the Technology Acceptance Model, according to Rigopoulos et al. (2008).

In order to explain the perceived usefulness and usage intentions in terms of social influence and cognitive instrumental processes, and thus better specify the external variables that have an influence on perceived usefulness and ease of use, Venkatesh and Davis (2000) developed a second version of TAM (called TAM2), that adds other seven aspects to the model:

- subjective norm, defined as a person's perception that most people who are important to them think they should or should not perform the behavior in question;
- image, being the degree to which the use of an innovation is considered to enhance one's status in their social system;
- job relevance, being the perception of the degree to which the system is applicable to their job;
- output quality, being the perception of how well the system performs the tasks;
- result demonstrability, meaning the tangibility of the results of using the innovation;
- experience, referring to the extent to which the user has experience with the system;
- voluntariness, defined as the extent to which potential adopters perceive the adoption decision to be non-mandatory.

While this version of the TAM is more elaborated and explains more in-depth what the factors that influence the usage of a technology are, there are no previous studies that apply this second version of the model to the use of DSSs.

3.6. Factors influencing the adoption of a new technology

As previously mentioned, the TAM underlines that the perceived ease of use and perceived usefulness are the aspects that influence the adoption of a new technology. To properly model the decision-making process behind this eventual adoption, it is important to determine what influences these two aspects. As with TAM2, there are many researchers that investigate this and strive to answer this question. In fact, many authors tried to identify the factors that influence the attitude toward a new technology, and many studies have been undertaken to understand which ones have a deeper impact than others. The majority of these studies do not focus on DSSs specifically and are very case-dependent, so their quantitative results are not directly applicable to other cases. However, these researches are very relevant to identifying what influences the attitude of users towards a new technology.

Among the others, Djamasbi et al. (2010) investigate the impact of positive mood on TAM. The results of their research highlight that under high task uncertainty, there is no high correlation between positive mood and perceived ease of use or perceived usefulness.

On the other hand, Alavi and Joachimsthaler (1992) explain that the level of success of a DSS implementation is determined by user factors, task environment, organizational environment, and external environment. Regarding user factors, the authors differentiate between cognitive style, personality, demographics, and user-situational variables. Cognitive style refers to the habitual ways individuals process information personality refers to the cognitive and effective structures maintained by individuals to facilitate adjustment to events, people, and situations. Demographic variables mainly include sex, age, and education and user-situational variables include training, experience (with the DSS and with the job), and user involvement. The research shows that democratic variables and cognitive style do not have a meaningful impact on the adoption of the DSS. Among the aspects related to personality, risk aversion (the extent to which a user is inclined to take a risk) seems to be the property with the highest impact, whilst the others properties are less relevant. On the other hand, user-situational variables (training, experience, and user involvement) seem to have the highest impact on the attitude of users towards the DSS adoption, thus highly influencing the success of its implementation and the performance of the system. Involvement refers to the extent to which the user is involved and participates in the design and implementation of the DSS; training refers to the provision of hardware and software skills sufficient to enable effective interaction with the system; experience refers to the level of experience with both the system and the activities the system is supposed to support.

Another research that investigates how individual differences influence DSSs use and satisfaction is the one conducted by Zinkhan et al. (1987). The authors analyze the effect of cognitive differentiation (the number of independent dimensions a decision-maker can identify), risk aversion, experience with the DSS, managerial experience (which refers to the experience with the activity related to the DSS, which improves the ability to process various information at the same time), age and involvement (personal interest in the system, meaning the extent to which the decision-maker evaluates the system as important). As a result of this research, age is considered not to highly affect the decision-making process, while cognitive differentiation, risk aversion, and user involvement influence the use and attitude towards the DSS. Moreover, the results highlight that involving the users in the design of the system can positively contribute to the acceptance of the DSS.

Furthermore, Shibl et al. (2013) defined a model which indicates the four main factors influencing the level of DSS acceptance and its use, being: usefulness, facilitating conditions (incorporating workflow, training, and integration in the design of the system), ease of use, and trust in the knowledge base. This model is defined by using the studies conducted by Venkatesh and Davis (2000) as a starting point.

In addition to the studies that focus on decision support systems, there are other studies that focus more specifically on the concept of e-trust. E-trust refers to the online trust and plays a central role in helping users overcome perceptions of risk and insecurity (Tang et al., 2012). Even if this concept is mostly applied to web applications, some aspects related to it result to be very relevant also with regards to the acceptance of DSS. Among the other researchers, Doney and Cannon (1997) affirm that the reputation of a system is very critical in determining its level of acceptance. On the other hand, Boyle and Bonacich (1970) underline that past interactions with a system deeply affect the level of trust in the system. Finally, Kim et al. (2009) highlight the importance of the interface design, which strongly influences the perceived ease of use of a system and defines the first impression on the system itself.

Although the researches on the topic are numerous and applied in different fields, there are some recurring concepts that can be generalized. It must be considered that, as Alavi and Joachimsthaler (1992) state, more research is needed in this field to corroborate the insights gained by the past studies, underlining the need for additional empirical studies in this area. In this project, the factors that seem to be more relevant according to the state-of-the-knowledge and that can be applied to the use of DSSs, and to the case study in analysis, are going to be considered. These factors, which have been mentioned in this section, are summarized in Table B.1 in Appendix B.

4

Problem and actors identification

In this chapter, the identification of the addressed problem and of the actors that are part of the investigated system is discussed. In order to understand how the procedures of finding and arresting fugitives work, we conducted interviews with three police officers and one dispatcher. These interviews highlighted the main actors involved in the process, how the procedures work, and the main criticalities of the current arrangement.

4.1. Problem identification

4.1.1. The Dutch National Police

The Dutch National Police is currently distinguished into ten Regional Units, one Central Unit, and the Police Service Centre (Government of Netherlands, n.d.). The Police Units are divided into different sections, being for instance the road police, the train police, and the water police. This distinction is based on the area in which they focus on their work.

In addition to their independent tasks, the National Unit supports the Regional ones on the motorways, the railway network, on the water, and in the air, in case of complex operations or the need for more units. Moreover, they supervise operations that concern serious, organized forms of criminality of a national or international character, deploy mounted police, sniffer dogs, and forensic expertise, and combat all forms of serious violence and terrorism.

The Regional Units, on the other hand, consists of districts divided into Frontline Teams. Each team provides basic Police services in a municipality, part of a large municipality, or a group of smaller ones. Their main duties consist of answering calls for emergency assistance, patrolling the streets, advising on crime prevention, resolving traffic-related issues, conducting basic investigative activities, assisting the public, processing official reports, and sharing information within their networks (Government of Netherlands, n.d.).

The Police Services Centre (PDC) provides operational management services, such as finance, ICT, communications, and human resources, so that officers in the Regional Units are able to spend more time on actual Police work (Government of Netherlands, n.d.).

4.1.2. Intercepting fugitives

Interviews with the practitioners were conducted to understand how the procedures of intercepting fugitives work. In these procedures, the most critical task is identifying the best strategy to position the units. Currently, this task is conducted primarily by the dispatchers, who rely on their own intuition and experience to define the best strategies. However, especially given the huge amount of information the dispatchers are provided with and the short amount of time they have to formulate a strategy, the dispatchers are not always able to suggest to the officers where to position. Moreover, not all the dispatchers are sufficiently expert to be aware of the best locations and strategies, especially because they might lack experience with the procedures or knowledge of the area where the crime took place.

The police officers, on the other hand, are usually more experienced but need to handle the coordination with both the control room and the other units at the same time, thus making it very complex for them to efficiently organize. For this reason, if the dispatchers were supported in the definition of specific solutions to intercept the offenders, the procedures would result to be more efficient.

4.1.3. DSS

In this context, a decision support system is being developed to support the procedures of finding and arresting fugitives. The DSS is meant to provide the dispatchers with information on the optimal positioning in order to help them handle this task.

Currently, the DSS interface is not completely defined and there are various options for its implementation, especially with regard to the features to be displayed. The possible information that might be included in the interface regards the possible fugitive routes, the associated probabilities that the fugitive will take those routes, and the optimal strategy for positioning the units. Different approaches for the interface concern the use of just the first feature, just the first two, just the last aspect, or all of them. The goal is to find a trade-off between transparency (ensuring that the dispatchers do understand the reasons behind the solution displayed by the DSS and thus might be more likely to adopt it) and avoiding displaying too much information so that the dispatchers would not be overwhelmed by those.

Another aspect at stake is the maximum run length of the algorithm that will not damage the decision-making time. In fact, if the algorithm takes too long to run, the dispatchers might decide not to wait for it and thus the system would not offer proper support. Currently, it is under debate whether a run length of one minute is sufficient, whether that is too long or whether even a run length of two minutes will make the procedures more efficient.

4.1.4. Problem formulation

As mentioned above, one of the most critical challenges in these procedures is that it is hard for dispatchers to define the best strategies to position the units, not only because of the time pressure, the uncertainty, and the dynamism that characterize these procedures but also because the dispatchers are usually overwhelmed by many different kinds of information and they sometimes lack knowledge of the procedures or the area of the crime. The DSS that is being designed has the purpose to support this process. However, it is not yet clear what characteristics the system should have and what the actors' level of acceptance of the new system would be.

Therefore, this research evaluates the impact of the different DSS implementations and the contexts in which the DSS can mostly support the procedures. This will be achieved by making use of an agent-based model, where the procedures will be implemented as they are now and as they will look like when the DSS will be in place, to evaluate not only the difference in the performance of the procedures but also the level of acceptance of the DSS by the dispatchers and the police officers.

4.2. Actors

In the procedures of finding and arresting fugitives, many actors play a role. Some of them are always taking part in the procedures, some are just contacted in case of need. The list of the actors, their power, and interest is included in Table 4.1.

Actor	**Power**	**Interest**
Dutch National Police	Determines the organization of the procedures, defines rules and regulations.	Reducing crime and victimization, calling offenders to account, enhancing security and the efficient and fair use of public resources (Moore & Braga, 2003).
National (road) police officers	If involved, position to maximize chances of intercepting the offender.	Intercepting the offender, getting as much information as possible about the situation.

Regional (road) police officers	Position to maximize chances of intercepting the offender.	Intercepting the offender, getting as much information as possible about the situation.
Regional dispatchers	Receive 112 calls and get information on the situation. Contact other corps in case of need and tell police officers where to position.	Intercepting the offender, getting as much information as possible about the situation.
National dispatchers	Involved if the situation is of national interest and coordinates the positioning of (National) Police officers.	Intercepting the offender, getting as much information as possible about the situation.
Dispatchers answering to 0900-8844	Receive calls for non-emergency matters that still require Police assistance; in case of need forward it to national or regional dispatchers.	Getting an understanding of the situation to know whether they need to forward the call.
Offender	Eventual time advantage, might act strategically to ensure to escape.	Escaping.
Witnesses / victims	Contact 112 or 0900-8844 / Provide the Police with information.	Ensuring their safety and helping Police find the offender.
Other corps outside the Police (firefighters / paramedics / etc)	Act in case of need (for specific situations).	Supporting the Police officers; helping citizens and ensuring their safety.
Other police officers (sniffing dogs / train police / water police).	Act in case of need (for specific situations)	Supporting the police officers.
CityGIS	Provides Police with software for critical and non-emergency work (CityGIS, 2022).	Economic interest; supporting the Police.
Researchers	Provide the Police with innovative solutions to optimize procedures.	Supporting the Police.
Rijkswaterstaat	Owns Dutch geographic data on roads (Overheid.nl, 2022).	Ensuring the efficiency of the Police.
Other affiliated companies (cars etc.)	Provide the police with tools and vehicles.	Economic interest; supporting the Police.
Government	Provides the Police with resources.	Efficiency of the Police force.

Table 4.1: The actors involved.

Whilst many actors are involved, some of them play a key role in the procedures of finding and arresting fugitives: first, the dispatchers, who primarily determine where to position the units, secondly the (road) police officers, who interact with the dispatchers and collaborate on defining the best strategies, and finally the offender, whose behavior deeply influences the procedures. Therefore, by assuming that no other corps are involved, the only actors that actually play a critical role in the decision-making process are the dispatchers and the (road) police officers. Additionally, it can be assumed that there is no distinction between National and Regional police officers, since the corp they are part of does not have an impact on the decision-making process. Thus, by uniquely considering the actors that are involved in the decision-making process, which is the main scope of this research, the only actors whose behavior is to be modeled are the dispatchers and the (road) police officers.

5

System identification and decomposition

Most socio-technical systems are so large and complex that they can only be interpreted by simplifying and assuming the system (Van Dam et al., 2012). While there are many different actors involved in the process and many different aspects influence them, as discussed in the previous chapter, it would be impossible to include them all. Thus, abstraction and reduction techniques are needed to efficiently model the system.

In this section, the main elements of the system that are going to be included in the model are identified and explained. In order to achieve this, the agents are clearly defined, and their properties are listed. Furthermore, the decision-making process that the actors undertake is described and the time frame and the chosen time step are specified. Finally, the performance indicators are identified, based on insights gained from literature and from interviews with experts.

5.1. The system

The system that we are going to model represents the procedures of finding and arresting fugitives, with and without the assistance of the DSS. This system includes the environment, the actors that play a role in it (and especially the fugitive, the dispatchers, and the road police officers), and the technological infrastructure that supports the procedures (eventually including the decision-support system). The two versions of the system that we are going to model are represented in Figures 5.1 and 5.2, where the flow of information is also highlighted.

5.2. The environment

The environment is constituted by the street network, the event of the crime that takes place in it, the Police units, and the offender that moves in the street network. What happens in the environment influences the decisions of the dispatchers in the control room. Moreover, changes in the environment or new information usually lead to a re-evaluation of the situation and the definition of a new solution. For this reason, to define the efficiency of the process of finding and arresting fugitives (the percentage of time the fugitives are found) it would be necessary to model the street network and the decision-making outcome of both the dispatchers and the police officers. However, this would be too complex to implement for three main reasons. First, the decision-making process of both the dispatchers and the officers is implicit and they are not completely aware of the reasons behind their decisions or what the factors that influence the decision are. The dispatchers and the officers completely rely on their knowledge and experience to define the positioning strategies and thus, the decision-making process can be represented by making use of the Recognition-Primed Model of rapid decision-making by Klein (1993). However, the cues, the possible actions, the expectancies, and the plausible goals of the decision-making processes are very complex to model since the actors are not completely aware of this mental process and thus an algorithm that defines, given a crime and its location, the solution that the dispatchers would come out with, is too complex to implement and would require separated research. Secondly, there is no data available on fugitive routes of past crimes and the consequent

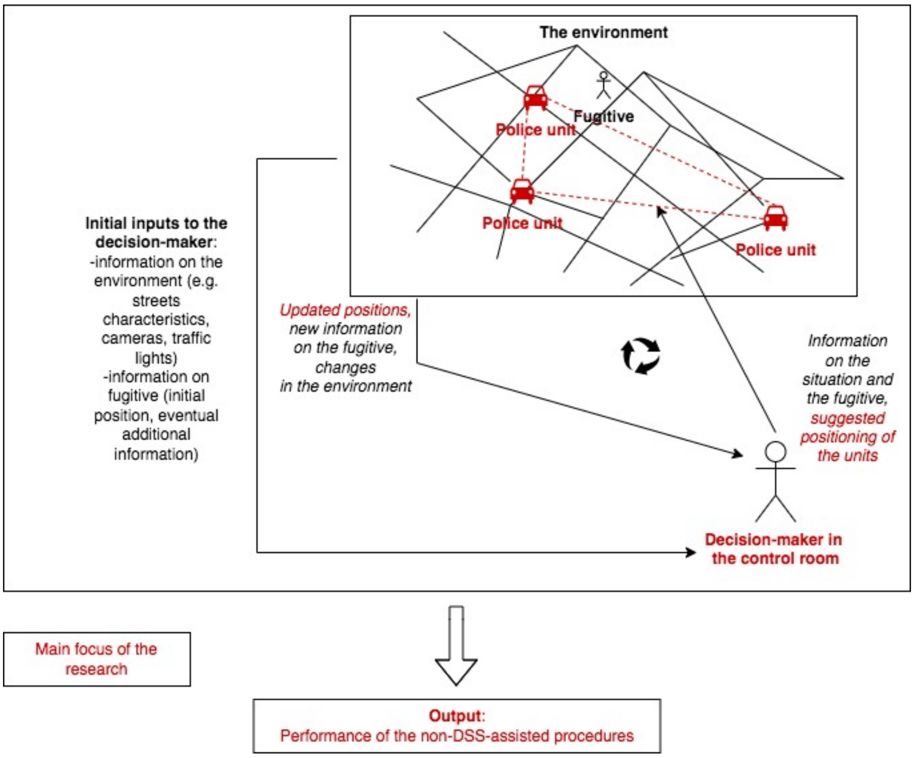


Figure 5.1: The system to be translated into the agent-based model, in the version without the DSS.

solutions implemented by the Police. Thus, not only it is not possible to model the content of the decision-making process based on the data, but also it would not be possible to realistically simulate fugitive routes and thus investigate whether the fugitive is found or not. Lastly, the DSS has not been completely implemented yet, and making use of an incomplete algorithm would come with many limitations, comprising the validity of the results. Therefore, we decided not to model the environment or the decision-making outcome but to uniquely focus on the decision-making process. The only factors of the environment that are considered are the level of urgency of the crime, the number of units that are needed, the information that is available on the direction of the fugitive, and the area of the crime.

5.3. DSS

As mentioned in the previous section, the DSS cannot be directly included in the model, since it has not been completely implemented yet, and thus will be included more abstractly. In the model, the DSS is characterized by two properties: the time that is needed to run the algorithm, and the combination of features displayed. Since the DSS is currently not finalized and there are some factors that are currently under debate, it was decided to include the DSS as implemented in different versions. Thus, the time that is needed to run the algorithm varies from 30, to 60, to 120 seconds. On the other hand, the combination of features displayed are:

- uniquely the possible fugitive routes,
- the possible fugitive routes and the associated probabilities that the fugitive took those routes,
- the possible fugitive routes, the associated probabilities, and the optimal positions for the units,
- uniquely the optimal positions for the units.

5.4. Dispatchers

In the procedures of intercepting fugitives, the most crucial actor is the dispatcher. In the model, the dispatchers are implemented as agents. In each simulation, two dispatchers are initialized: one works on the phone and the second one works on the radio. The two dispatchers collaborate to define the

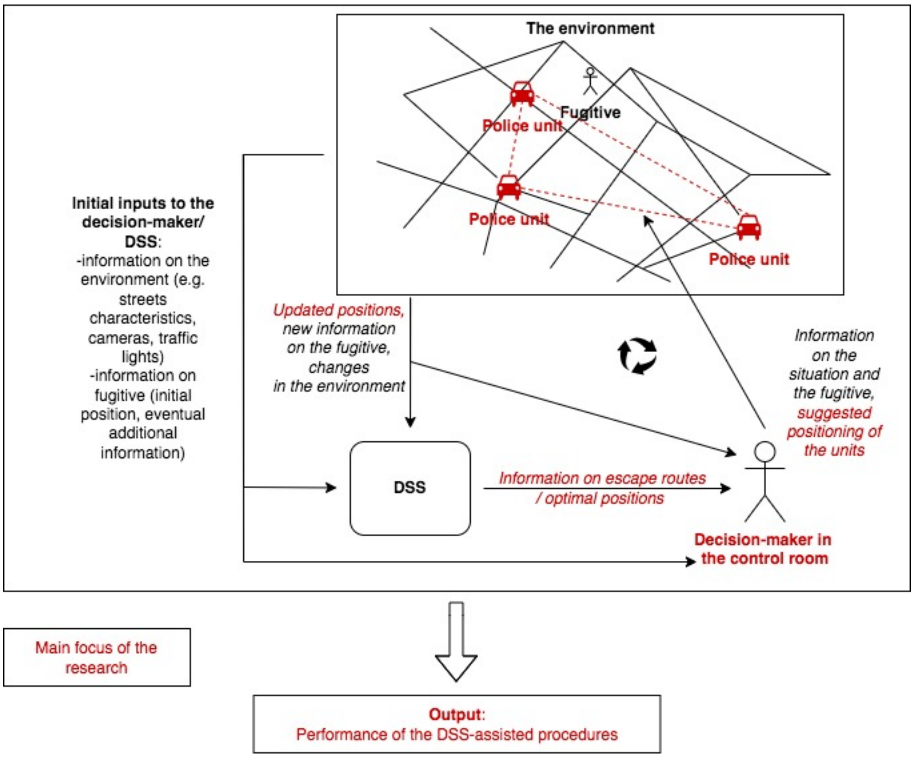


Figure 5.2: The system to be translated into the agent-based model, in the version with the DSS.

best strategy to position the units. The radio dispatcher is the one that primarily makes decisions, while the phone dispatcher is there to support their colleague in case of need. The dispatchers are characterized by their level of experience, their attitude towards the DSS, and their level of authority with the police officers. The attitude of the actors towards the system is defined based on the factors identified in Section B. The properties that characterize the dispatchers are:

- the level of experience they have with the procedures of finding and arresting fugitives;
- the areas that they are familiar with among the ones where the crime can take place;
- their role (whether they work with the phone or the radio);
- the percentage of times they had a positive experience with the decision support system;
- the percentage of times their colleagues had a positive experience with the decision support system;
- their personal involvement and interest in the system and in how it works;
- their perception of the quality of the output offered by the system (meaning the extent to which the system is perceived to display solutions that actually work);
- the extent to which they are willing to take risks (risk aversion);
- the extent to which they are able to consider multiple concepts when making a decision (cognitive differentiation);
- the extent to which they were trained to use the DSS;
- the extent to which the dispatcher was involved in the design of the DSS;
- the level of experience they have with the system in general;
- the extent to which they consider the design of the DSS intuitive;
- the extent to which they consider the system easy to use;

- the extent to which they consider the system useful;
- the level of authority they have with the police officers.

5.5. Police officers

The Police officers work on the street network and move around in a car. It is assumed that the other Police corps (e.g. water police or train police) or other actors outside the National Police are not involved in the procedures, and thus just the police officers that work in the streets are considered in the model. The police officers are initialized as agents and interact with the dispatchers who communicate to them where to position. It is assumed that just one police officer for each unit participates in the discussion with the dispatchers, and thus the number of officers initialized is equal to the number of units needed for each crime. The officers are characterized by their attitude towards the DSS, their experience with the procedures, and their attitude towards the dispatchers. The properties that characterize the dispatchers are:

- the level of experience they have with the procedures of finding and arresting fugitives;
- the percentage of times they had a positive experience with the decision support system;
- the percentage of times their colleagues had a positive experience with the decision support system;
- their personal involvement and interest in the system and in how it works;
- their perception of the quality of the output offered by the system;
- the extent to which they were trained to use the DSS;
- the extent to which the officers were involved in the design of the DSS;
- the level of experience they have with the system in general;
- the extent to which they consider the system easy to use;
- the extent to which they consider the system useful;
- the attitude they have towards dispatchers.

5.6. Decision-making process

5.6.1. Recognition-Primed Model of rapid decision-making

The decision-making process of the dispatchers is modeled by making use of the Recognition-Primed Model of rapid decision-making by Klein (1993) as a starting point. The original model explained in Chapter 3, is adapted to the case study and the system boundaries, so that:

- the plausible goals refer to the chances to catch the fugitive with a specific number of units that are at disposal;
- the relevant cues generally refer to the information at disposal about the crime, which can be partial or complete, and the knowledge of the area where the crime took place;
- The expectancies refer to the expected direction of the fugitive based on the information at disposal;
- The actions refer to the various possible strategies to position the units.

In the model, whether the decision-maker recognizes or not a situation depends on their knowledge of the area where the crime took place and the level of experience they have with the procedures.

Accordingly to the Recognition-Primed Model of rapid decision-making, during the decision-making process, the expectancies might be violated. This leads to the need to re-assess the situation and re-establish whether the situation is familiar or not, and might lead to the need to restart the decision-making process.

5.6.2. Institutional Model of Operational-Level Decision Making

The Institutional Model of Operational-Level Decision Making by Heikkila and Isett (2004) is also partially applied to this case. The definition of choices by the dispatchers is indeed highly influenced by the information they have at disposal (exogenous factors) and their personality and past experience which influences their cognitive processes (endogenous factors). Based on these factors, the dispatchers conduct their operational choice. Afterward, the communication phase between the dispatchers and police officers represents the alignment phase that takes place in public organizations and supports the optimization of the strategies and the coordination between the different actors.

5.6.3. The decision-making process of the dispatchers

The process of defining the best strategy to position the units is made of three steps:

- the definition of the possible escape routes that the fugitive took;
- the identification of the associated probabilities that the fugitive took each route;
- the definition of the optimal positions for the units.

This process happens implicitly in the mind of the dispatchers, who are not completely aware of going through these steps. In this process, the experience of the dispatchers with the procedures is paramount to efficiently performing all the steps. The knowledge of the area of the crime is also a very critical requirement, especially for the first two steps.

In reality, what often happens is that if the dispatchers cannot define a strategy quickly enough, because of their lack of experience with the procedures or knowledge of the area of the crime, they rely on the police officers to coordinate and organize themselves. For the sake of this research, and to properly compare the situation with and without the DSS, it will be assumed that the dispatchers always define a solution. This is needed to draw a valid comparison between the time that is needed to make a decision if the dispatchers are not assisted by the system and the time that is needed if they are.

5.7. Time frame

The procedures of finding and arresting fugitives happen in a very short time frame. The decision-making process of the dispatchers and the communication with the police officers rarely exceed ten minutes in total. Since the fastest action is equal to both the fastest decision-making process and the fastest run time option for the DSS algorithm, the time unit is defined to be 30 seconds. The time frame, on the other hand, is set to be ten minutes (20 ticks), because by that time the parameters that are collected as output have already been defined. This value is checked through a tick test after the model is built, to ensure that nothing actually happens after tick 20.

5.8. Performance indicators

One important aspect to define before conceptualizing and implementing the model is how performance will be measured. As previously mentioned, this research focuses on the personal efficiency and productivity of the practitioners involved in the procedures, meaning that the aspect that is going to be investigated is whether and to what extent the use of a decision support system improves the decision-making processes time. In this perspective, defining personal efficiency and productivity is paramount. For this reason, knowledge gathered from literature is combined with the information gained through the interviews to identify the indicators that are to be analyzed to answer the main research question.

5.8.1. Evaluating decision-making processes

According to Forgionne (2000), there are two ways to evaluate decision-making processes: one is focusing on the outcome of the decision and another one is focusing on the process itself. With regards to the outcome, positive decision outcomes can include:

- gains in organization performance, such as increases in returns, reductions in costs, or boosts in information flows (Lawrence & Sim, 1999);
- the maturation of the decision-maker, which would occur when there is progress in the person's (or group's) understanding of the current problem and solution or a gain in the person's (or group's)

general problem-solving skills (Raghunathan, 1999).

With regards to process, process improvements can involve:

- enhancements in the person's or group's ability to perform the phases or the steps of the decision-making (Lipshitz & Bar-Ilan, 1996);
- an increase in personal efficiency, such as reducing the time needed by the user to structure the problem or increasing the number of alternatives evaluated by the user in a given time period (Dean Jr & Sharfman, 1993);
- an improvement in personal productivity, such as reducing the time needed for decision making or increasing the amount of pertinent information, knowledge, and wisdom from decision making (Kumar, 1999).

As Forgionne (2000) states, the effectiveness of decision support systems can be assessed by considering both the process and outcome aspects, depending on the goal that the DSS strives to achieve. However, Le Blanc and Kozar (1990) underline how, to assess the effectiveness of decision support systems it is important not only to focus on the improvements that the use of a DSS leads to but also to consider the extent to which the DSS is actually employed by the users. This is due to the fact that often the main problem concerns the (non-)acceptance of the technological system rather than the improvements that the system itself could ensure to the decision-making process and output.

5.8.2. Measuring performance in the Police environment

Measuring performance is a very critical task in the public sector. In these contexts, it results very important to measure performance not only to ensure transparency of public decisions and the use of public funds but also to establish how to boost performance itself (Diana, 2014). In the context of the Police, another reason is that Police executives may have no choice but to do so, because of the pressure coming from local communities and governments (Moore & Braga, 2003). However, measuring performance is not an easy task: defining performance, identifying suitable performance indicators, and implementing a performance management system are all very complex goals to achieve.

A performance measurement system is defined as a system that allows one to make some decisions and implement some specific actions because it is based on quantifying the efficiency and effectiveness of past actions using appropriate information infrastructure (Neely et al., 2002). To have such a system in place, it is thus important to gather all the relevant information and identify relevant indicators. These indicators should mirror the efficiency, effectiveness, financial, environmental, and social aspects (Chai, 2009) and for this reason, it is very complex to build a single model that covers all the features.

According to Moore and Braga (2003), in the context of the Police environment, five factors are very important when it comes to performance measurement systems:

- The extent to which the internal system of performance measurement is aligned with the external reporting system;
- The extent to which it is aligned with the organization's internal organizational structure;
- The frequency of the measurements, and the speed of the feedback from managerial acts to measured effects;
- The visibility and publicity of the reports;
- The extent to which the results of the measurement system are taken as definitive.

Moore and Braga (2003) also underline how one of the key issues is what to measure: while it is important to measure the outcomes of the activities, which represent the value that the Police seek to produce, it is also important to focus on the process. This means that the performance measurement systems should not only consider the final results but also how these results are achieved. This can either refer to the way the Police are using authority and money to accomplish their results or the efficiency and effectiveness of the activities undertaken.

5.8.3. Insights from experts

The police officers that have been interviewed underlined how, obviously, the final goal of the organization is to actually find the fugitives, and thus, the percentage of times the offender is intercepted is a relevant indicator to measure performance.

However, the police officers highlighted that time is a very critical factor in the operations, and the more time passes, the harder it is to catch the fugitive. For this reason, the average time that is spent to find the fugitive is a very critical factor to consider and a very interesting indicator to employ.

5.8.4. Conclusion: selected performance indicators

Considering both the knowledge gathered from literature and the insights gained thanks to the interviews, it results clear that in general, measuring performance in such contexts is very complex. While the outcome of the decision-making process (and thus the extent to which the Police succeed in finding and arresting fugitives) is a very important aspect, as previously mentioned, it was decided not to model the environment. For this reason, it is not possible to measure the outcome of the process, but on the other hand, it is possible to focus on the process itself, and investigate the impact of the DSS on the personal efficiency and productivity of the practitioners. The improvement of these aspects is indeed directly linked to the eventual improvement of the decision outcomes, since reducing the time needed to structure the problem and make decisions leads to quicker and more efficient processes. Decreasing the decision-time is, as mentioned by the practitioners, indeed paramount to improving the organization's performance, which is linked to the main goals and values of the Police organization: arresting offenders and enhancing security (Moore & Braga, 2003). Moreover, as Moore and Braga (2003) underlines, analyzing how the results are achieved is even more important than analyzing the final outcome. Therefore, the personal efficiency and productivity of the practitioners, as defined by Dean Jr and Sharfman (1993) and Kumar (1999) and remarked by Forgionne (2000), are used to measure the performance of the procedures. In this case study, personal efficiency and productivity are translated in the time that the dispatchers need to define a strategy and the time they need to communicate the strategy to the officers, which altogether constitute the decision-making process time.

Finally, as Le Blanc and Kozar (1990) underline, to assess the effectiveness of decision support systems it is important not only to focus on the improvements that the use of a DSS led to but also to consider the extent to which the DSS is actually employed by the users. For this reason, the results of the performance of the procedures with and without the DSS assessed by the aforementioned indicators will be analyzed in relation to the percentage of time the solution that comes from the DSS is actually employed to catch the criminal

6

Agent-based model conceptualization

In this chapter, the system described in the previous chapter is conceptualized. First, the high-level conceptualization is specified. Then, the narrative of the model is included, with clear references to the assumptions made. Finally, the software implementation, validation of the model, and verification are discussed.

6.1. High-level conceptualization

In Figure 6.1, the high-level conceptualization of the model is depicted. The model works such as, based on the attributes of the agents, the information on the crime and its level of urgency, agents' previous experience with the system, and the characteristics of the DSS (how it is implemented), the dispatchers take more or less time to define a strategy and then the radio dispatcher communicates it to the police officers, who might or might not agree with it.

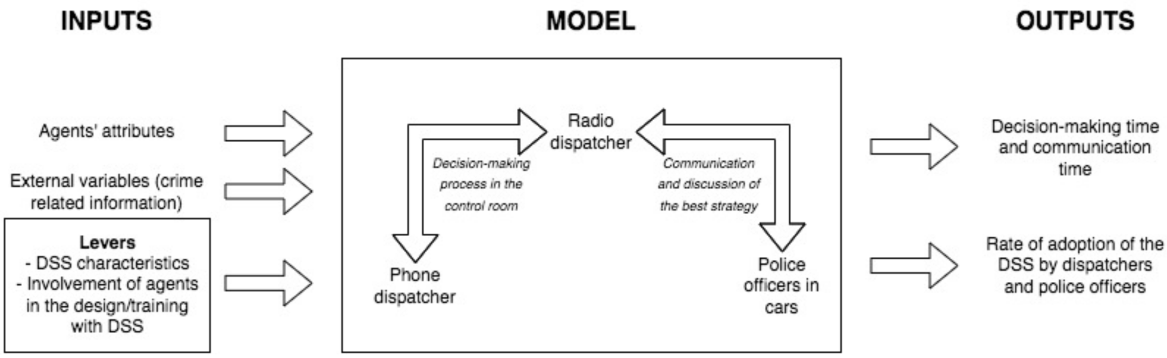


Figure 6.1: High-level conceptualization.

6.2. Narrative

The narrative of the model is divided into two phases: the decision-making process of the dispatchers and the communication of the established strategy to the police officers. The model investigates the time that is needed for these two phases when the decision-makers are and are not assisted by the DSS and the rate of adoption of the DSS by the actors. The narrative is based on the insights gained from the interviews and the theories mentioned in the previous chapters.

6.2.1. Assumptions and parameters

While conceptualizing the model, we made a number of assumptions to efficiently translate the real system into the ABM. The assumptions have to be stored to always be able to check the rationales behind the decisions made.

Most of the parameters employed in the model directly derive from the insights gained from the interviews or the literature. The only exceptions are the values in Figure 6.2 and a few other parameters that could not be empirically verified. In those cases, while the insights from literature and the interviews are taken into consideration (e.g. in Figure 6.2, higher values are associated with higher correlations according to the literature findings included in Section 3.6), an analysis will be carried out in the following sections to determine the impact of those values on the outcomes and the extent to which further research is needed to better specify them.

6.2.2. Agents

At the start of the simulation, two types of agents are initialized. In the model, it is indeed assumed that only these two actors are involved and that there is no distinction between National and Regional Police. The first agent is the dispatcher: in every simulation, two are initialized, one representing the dispatcher that works on the radio and the second being the dispatcher that works on the phone. The dispatchers are characterized by their level of experience with the procedures, their knowledge of the different areas where the crime might take place, and some other properties that describe their knowledge of the DSS and their attitude towards it. The relations between these properties are shown in Figure 6.2, and are defined accordingly to the literature research presented in Chapter 3, as specified in the previous section. In Figure 6.2, it is also specified if the parameters are controllable or uncontrollable and the weights of the relations between these parameters as implemented in the model. The attributes of the dispatchers, a short description of them, and the possible values they might have are summarized in Table C.1 in Appendix C.

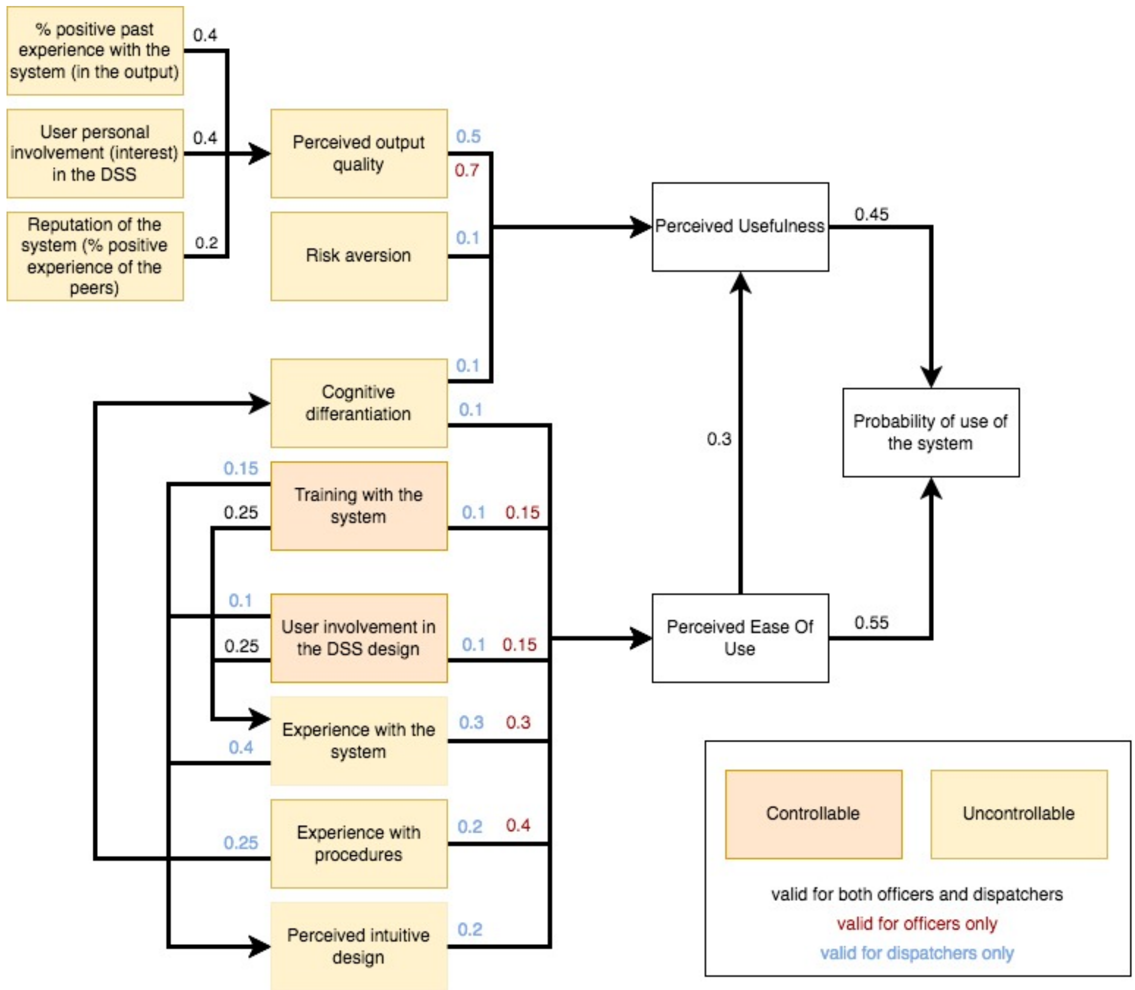


Figure 6.2: Factors influencing perceived ease of use and perceived usefulness and their relation.

Moreover, the officers are initialized. The officers are characterized by some attributes that define their experience and their attitude towards the dispatchers and the DSS. Since they are not in direct contact with the system, not all the properties that are relevant for the dispatchers are also relevant for them. The properties of the officers are listed in Table C.2 in Appendix C. The weights of the relations between the properties influencing officers' attitudes towards the DSS are specified in Figure 6.2. The number of initialized officers depends on the units at disposal and the crime urgency. Each officer might or might not agree with the dispatcher and has the freedom to follow their guidelines or to apply their own decision. In this model, it is assumed that there is just one officer for each unit that decides whether to follow the dispatchers' advice or not. Thus, communications (or discussions) always take place between one officer and one dispatcher (the one that works on the radio).

6.2.3. Base case: current procedures without the DSS

The beginning of the simulation (tick=0) represents the moment when the dispatchers get to know about the crime and start to decide where to position the units. The dispatchers always define a solution. The crime can have three levels of urgency (high, medium, and low) and a specific number of units that are needed to handle the situation. The urgency of the crime can be low, medium, or high with the same probability. The number of units employed is randomly defined and determines the number of police officers that are initialized. The crime is also characterized by the area in which it takes place. There are five different areas where the crime can take place, and the dispatchers might or might not be familiar with the areas.

The decision-making process consists of three phases: identifying the possible escape routes, determining which one the fugitive took with the highest probability, and, based on the first two steps, identifying where to position the units. This process is implicit for the dispatchers. Two aspects that are very important to undergo this process are the level of experience with the procedures and the knowledge of the area of the crime. More specifically, knowing the area is very important for the first two phases (identifying the possible escape routes, and determining the probability that the fugitive took those routes), while the experience with the procedures is paramount in all of the three phases. Having information on the direction of the fugitive might ease the process. Accordingly, at tick = 0, several different situations can take place:

1. The dispatcher that works with the radio recognizes the situation and is familiar with the area. In this case, the dispatcher can work alone and undergo the three decision phases without additional help.
2. At least one of the dispatchers knows the area and at least one of the dispatchers recognizes the situation. In this case, the dispatchers collaborate to define the best strategy to position the units.
3. Both the dispatchers do not know the area, but at least one of them recognizes the situation. In this case, the two dispatchers will need additional time for the first two phases of the decision-making process.
4. Both the dispatchers do not recognize the situation, but at least one of them knows the area. In this case, will need additional time for all of the three phases of the decision-making process.
5. Both the dispatchers do not recognize the situation and do not know the area. In this case, all three phases are especially hard for the dispatchers and it will take very long for them to reach a solution.

Whether the dispatcher knows the area depends on the related attribute. On the other hand, whether they recognize the situation largely depends on their level of experience with the procedures. Moreover, the dispatcher might or might not have sufficient information at the beginning (based on the scenario). If they do not have sufficient information and they do not have a very high experience, then the time needed to make a decision will increase by 1 or 2 ticks. This depends on the radio dispatcher if they make the decision alone (in situation 1); whereas in all the other situations (when they jointly look for a solution), it depends on both dispatchers: if one of the two is highly experienced, there will not be consequences on the duration of the decision-making process.

In some cases, when the two dispatchers collaborate, they do not agree right away on the best strategy (based on probability_agreement_dispatchers), but instead, they discuss what strategy to apply. This happens randomly and might add up to 60 seconds (1 or 2 ticks) to the time needed to make the decision.

At times, it might happen (based on the scenario) that even if the dispatchers do not have information at the beginning on the direction of the fugitive, based on some new piece of information they get over time, they manage to identify it. This can happen either right after the decision-making process starts or closer to the end, based on the scenario, and might lower the time needed to make the decision by 30 or 60 seconds (1 or 2 ticks).

Sometimes, during the decision-making process, new information is gained which leads to the need to restart the decision-making process. This is linked to new information on the direction of the fugitive that is different from what was expected at the beginning. When this happens (based on the scenario), the dispatchers have to restart the decision-making process. This refers to the event of the expectancies being violated, as in the RPM of rapid decision-making by Klein (1993) and can happen either right after the decision-making process starts or closer to the end, based on the scenario.

After the decision is made, the strategy has to be communicated to the police officers. It is assumed that new information will not be gained from this moment onwards. Communicating the situation to all police officers by radio takes 30 seconds. Then each police officer might agree or not agree with the dispatchers, and thus the communication time (communication_time) can increase by 30 or 60 seconds for each officer that does not agree and discusses with the dispatchers on the best strategy. Whether they agree or not depends on the authority of the dispatcher that works with the radio, the general attitude that the officers have towards dispatchers, and the experience of the actors with the procedures, so that if the dispatcher is more experienced than the officer or if the authority of the dispatcher is stronger than the negative attitude the officer has towards the dispatchers, there is a high chance (probability_agreement_officers_good_attitude = 90%) of agreement. In all of the other cases, the chance of agreement is lower (probability_agreement_officers_bad_attitude = 50%).

When the strategy is communicated to all the officers and shared solutions are found, the simulation ends. The total time that is needed for both the decision-making process (decision_time) and the communication (communication_time) are stored as output parameters.

6.2.4. Procedures with the DSS

In the version with the DSS, the two phases look different. In the first phase of the procedure, the system automatically displays the optimized solution to position the units. The DSS takes a specific time (run_length_algorithm) to run, which is equal to either 30, 60, or 120 seconds (1, 2, or 4 ticks), depending on the policy. Moreover, again depending on the policy, the DSS might display different kinds of information: the possible routes (a), the associated probabilities that the fugitive took those routes (b), and the best locations to position the units (c). Different scenarios are defined where the DSS displays either just a, just a and b, just c, or a, b and c all together.

At tick = 0, the decision-making process starts. During this process, the dispatcher evaluates whether to define their solution and directly use it, to wait for the DSS, or to directly use the solution advised by the DSS. In the control room, the same five different situations that were previously described can take place. Based on the situation, and thus the time that is needed to make the decision, the probability that the dispatcher will wait for the solution of the DSS (waiting_probability) changes. This probability is also influenced by whether the DSS can offer to the dispatchers the information they need: if they have a low experience with the procedures (since that would help with all the steps of the decision-making process) or if they are not familiar with the area and the DSS displays a or b, it is more likely that they will wait for it. If the DSS displays both the possible routes and the associated probabilities, the help it can provide to the dispatchers that do not know the area is higher compared to the case where the DSS just displays the possible routes. In some cases, the probability is 100% because the dispatchers need an amount of time to make the decision that is either equal to or higher than the time needed to run the algorithm and process its solution, and therefore, the solution would anyway be displayed before they have made their final decision. The experience of the dispatchers with the procedures has the highest weight on the waiting_probability. In case the dispatcher that works on the radio decides alone, only their knowledge will determine this, whereas when the dispatchers work together (in every situation except the first one), the probability will be influenced by both dispatchers, and the experience of the more experienced dispatcher will be considered. Moreover, the probability that they will wait is affected by the crime urgency, so that, when the probability is not 100%, the waiting probability will decrease by 5% for crimes of medium urgency and 10% for crimes of high urgency. Additionally, the probability is affected by the information at disposal, so that if the dispatchers have full information on the direction of the fugitive and a high experience (>= 0.7), the probability will decrease by another 10%.

After the solution is displayed, the dispatchers need some time to evaluate the solution, which will differ based on the information displayed by the DSS. If the DSS displays the information on where to position the units, the evaluation will take 30 seconds (1 tick); if the DSS just shows the possible route and the associated probabilities, the dispatchers will also have to define a strategy in addition to evaluating the information that is displayed, and thus the time needed to process the information will be higher (60 seconds, 2 ticks). The total time needed to make the decision, depending on the situation, will thus either be equal to the sum of the time needed to run the algorithm and the time needed to process the solution or to the time the dispatchers need to formulate their decision (decision_time).

If the dispatchers decide to wait for the DSS, they will compare the solution defined based on their intuition and experience with the one proposed by the system. There is a probability (matching_probability) that the solution will match with the one defined by the dispatchers, which partially depends on the experience that the dispatcher has with the procedures and the familiarity with the area where the crime took place. If the dispatchers have high experience, this probability will be higher. Similarly, if the dispatchers know the area of the crime, the matching_probability is higher. If the two solutions match, it means that the dispatchers will adopt the solution proposed by the DSS.

In some cases, when the DSS displays its solution the dispatchers have not yet defined another strategy and thus they might decide to directly use the solution advised by the DSS. This happens when the dispatchers would still require a long time to define a solution (decision_time - run_time >= 5) and the crime is highly urgent or when they would still require some time to decide (decision_time - run_time >= 3) and their perception of the DSS is very positive (based their perceived ease of use and usefulness). When the dispatcher that works on the radio decides alone, just their perception is relevant, whilst when the two dispatchers are collaborating, the one with the highest experience with the procedures decides.

On the other hand, when the dispatcher has already defined a solution or is about to define it, based on the matching_probability, the dispatchers might or might not agree with it. If the two solutions differ, the dispatchers will discuss and decide which solution to use. This depends on the perceived ease of use and usefulness of the DSS by the dispatchers so that the probability that each dispatcher will use the solution advised by the DSS (probability_DSS_use) is equal to 0.55 multiplied by the perceived usefulness, summed to 0.45 multiplied by the perceived ease of use. This probability increases or decreases depending on the kind and quantity of information displayed by the DSS. The presence of many features will indeed increase the chance that the dispatcher will understand the solution and agree with it, based on the fact that having more information increases the transparency of the system. If the level of transparency is low (displaying few features means that it is harder for the dispatcher to understand the strategy proposed), the probability that the dispatcher will adopt the solution decreases. Moreover, the probability is influenced by the level of cognitive differentiation of the dispatchers, so that if many features are displayed and the level of cognitive differentiation of the dispatcher is low, they will find it difficult to interpret the DSS solution, and thus the probability that they will adopt the solution decreases. The relationship between the combinations of the information displayed, the level of transparency and the issues connected to a low cognitive differentiation are shown in Table 6.1. This probability will be calculated for both dispatchers, and, in case the two dispatchers do not agree on whether to apply the solution, the dispatcher with more experience with the procedures decides. If the dispatcher that works with the radio decides alone, just their point of view is considered. For the other situations, the opinions of both dispatchers are relevant.

While the DSS processes its solution, in the eventuality that at the beginning the dispatchers do not have information on the direction of the fugitive, it might happen, based on the scenario, that they will get it afterward. If and when this happens, the DSS needs to restart to run. Thus, the situation is reassessed and the dispatchers decide again whether to wait for the DSS, again based on the waiting_probability. However, in this case, it needs to be considered that the dispatchers will need less time to make their decision (thanks to the additional information) and thus the probability that they will wait for the DSS is

Features displayed	Gain in probability of use because of transparency	Loss in probability of use if dispatchers have cognitive differentiation <= 0.66 and > 0.33)	Loss in probability of use if dispatchers have cognitive differentiation <= 0.33
[routes]	0.1	0.1	0.2
[routes, probabilities]	0.2	0.2	0.4
[routes, probabilities, positions]	0.3	0.3	0.6
[positions]	0	0	0

Table 6.1: Relationship between the combinations of information displayed, the level of transparency, and the issues connected to a low cognitive differentiation.

lower.

Sometimes, during the decision-making process, new information on the direction of the fugitive is gained that is different from what was expected at the beginning. When this happens (based on the scenario), the dispatchers have to restart the decision-making process and the DSS has to be re-run. Also in this case, the situation is reassessed and the dispatchers decide again whether to wait for the DSS.

After the decision is made, the solution is communicated to the police officers, similarly as in the previous version. In this version, however, the probabilities of agreement between the dispatchers and the police officers vary if the dispatchers decide to employ the solution suggested by the DSS. In order to define this variation, the probability that the officer would use the solution displayed by the DSS is calculated in the same way as for the dispatchers and then:

- if the probability that the officer would use the solution displayed by the DSS is < 0.2, the chance of agreement decreases by 20%;
- if the probability that the officer would use the solution displayed by the DSS is >= 0.2 and < 0.4, the chance of agreement decreases by 10%;
- if the probability that the officer would use the solution displayed by the DSS is >= 0.4 and < 0.6, the chance of agreement does not change;
- if the probability that the officer would use the solution displayed by the DSS is >= 0.6 and < 0.8, the chance of agreement increases by 10%;
- if the probability that the officer would use the solution displayed by the DSS is >= 0.8, the chance of agreement increases by 20%.

Based on this probability, it is determined whether the officer and the dispatcher agree right away. If the dispatchers decided to employ the solution suggested by the DSS, the fact that they agree implies that this solution is actually implemented. On the other hand, when they do not agree right away, whether they will apply the solution advised by the DSS depends on their perceived usefulness and perceived ease of use, so that the probability that each dispatcher will use the solution advised by the DSS is equal to 0.55 multiplied by the perceived usefulness, summed to 0.45 multiplied by the perceived ease of use. This probability can increase based on the features displayed by the DSS: a higher level of transparency means that the dispatches can more easily explain the reasons behind the solution to the officers and thus the chance that the officers will be convinced by the explanations of the dispatchers is higher. Based on that, the percentage of officers that employ the DSS solution is stored as an output parameter.

When the strategy is communicated to all the officers and shared solutions are found, the simulation ends. The total time that is needed for both the decision-making process (decision_time) and the communication (communication_time) are stored as an output parameter, as well as the rate of adoption of the DSS solution by both the dispatchers and the police officers.

6.3. Software implementation

After defining the narrative, the conceptualization of the model must be translated into the actual model. This model is implemented in Python (Van Rossum & Drake, 2009). Python is chosen as programming language because of its universality, which would facilitate a future eventual extension of the model (e.g. by including the environment). As an intermediate step, a pseudo-code is written, which is a textual description of the exact flow of the algorithm (Van Dam et al., 2012). This step is needed to translate the elements of the narrative into programming elements (iterations, conditions, input, and output operations). The pseudo-code has then been translated into the Python files, which constitute the ABM defined in Python making use of the MESA library (Project Mesa Team, 2016), that support the implementation of ABM in Python.

6.4. Model validation

Before running the experiments and analyzing the data coming from the simulation model, it is paramount to conceptually validate the model, by determining whether the theory and assumptions underlying the model are justifiable (Sargent, 1984).

Most of the assumptions underlying the model derive from the insights gained in the interviews. Although just a small sample of practitioners was interviewed, the road police officers and the dispatchers interviewed are very experienced in the practices of finding and arresting fugitives. Given that the practitioners never contradicted one another and are very expert on the topic, the assumptions made based on the interviews can be considered to be justifiable.

Additionally, some assumptions are made to generalize the case study and make it possible to apply the results to all decision-making processes taking place under time pressure, dynamism, and uncertainty. For instance, it is assumed that dispatchers always make a decision, to allow for the comparison of the decision-making time when the decision maker is and is not assisted by the DSS.

Finally, some assumptions are made based on the knowledge gained from literature and presented in Chapter 3, for instance with regards to the attitude of the actors towards the DSS. Given the lack of knowledge on the factors influencing the adoption of a new DSS in an operational decision-making process, a literature review was conducted that did not specifically focus on these contexts, but, on the other hand, the knowledge on the general attitude towards the adoption of a new technology also in strategical decision-making processes was considered. For this reason, we cannot be sure of the validity of the assumptions made, but, given the aforementioned lack of knowledge, the use of more general knowledge and the assumptions made can be justifiable.

Furthermore, we used three main theories to define the model. First, the Recognition-Primed Decision model of rapid decision-making was employed, since it models the decision-making processes undertaken in situations characterized by time pressure, dynamism, and uncertainty, where the decision-maker recognizes situations as typical, recognizes typical courses of action, and evaluates actions through mental simulation, thus basing the decision on their experience. Thus, this model is very appropriate for this research and for the case study. The Institutional Model of Operational-Level Decision Making was employed to model the effects of institutions on operational-level choices in public organizations, which is very relevant for this case study and explains the influence of exogenous and endogenous factors on the decisions made. Finally, the Technology Acceptance Model is used to model the attitude of the actors towards the DSS, which is an important factor in these procedures since a technology is introduced in a process where such a system had never been in place before.

As a result, the model can be considered suitable to conduct this investigation, since it is based on the knowledge of the experts and on relevant literature, and allows to investigate the effect of using a DSS in a decision-making process characterized by time pressure, uncertainty, and dynamism.

6.5. Verification

After implementing the model, the verification phase is carried out which consists of a tick test, reproducibility and variability tests, and a sensitivity analysis.

The tick test is meant to determine what the run length of the simulation should be. The initial hypothesis is that the run length can be set to 15 ticks since nothing happens after that time. The test is run for both versions of the model and the run length for this experiment is set to 60 ticks. For both versions, one thousand repetitions are performed. The results are shown in Figures D.1 and D.2 in the Appendix. The test highlights that in both versions, the decision-making time is never higher than 15 ticks, with the maximum being 10 in both versions of the model. Since the communication time is determined in one tick after the decision-making process is completed, nothing happens after tick 10 and thus, there is no need to run the simulation for more than 15 ticks. As a consequence of this test, 15 is set as the run length for the simulation. A margin is left to make sure that all the replications are properly run in the following tests and experiments.

The reproducibility and variability tests are meant to verify that the simulation provides the same results with the same seeds and different results with different seeds. The results of the tests, included in Appendix D, show that the model runs can be reproduced but also varied.

The sensitivity analysis is employed to understand the impact that some values that are not defined based on literature or experts' interviews but also based on logic, have on the outcome of the model. These values correspond to the numbers in Figure 6.2 and the impact that having or not having some components of the DSS that might help the dispatchers that are not familiar with the area of the crime has on the adoption of the DSS (weight_area_component_probability_DSS_use). These values are not quantified in literature and cannot be validated by experts either. Thus, they are defined based on the qualitative knowledge gathered from previous studies, where the correlation between the variables is researched. However, since the case studies are very context-dependent and the contexts are different from the ones at stake, these values cannot be directly applied but can only provide some insights on what variables have a strong or weak correlation. For this reason, it was decided to conduct a sensitivity analysis (Saltelli, 2002), which is included in Appendix D.

Overall, it can be noticed that some input parameters have a higher correlation than others with the output parameters. It also needs to be considered that the correlations are calculated as the impact that each parameter has on each output in relation to the impacts that all the other input parameters have on the same outcome. This means that these values do not show an absolute correlation but just a relative one. It is however very useful to conduct this analysis because it highlights the limitations with regard to the definition of input parameters that cannot be empirically determined. More specifically, the results of this analysis highlight that the definition of the weight of the experience with the procedures of the police officers in the definition of their attitude towards dispatchers and the weight of the experience with the procedures of the police officers in the definition of their perceived ease of use of the DSS do partially impact the communication time and the adoption of the DSS by the police officers. This means that different definitions of these values might lead to different results, and thus, since it is not possible to verify them further, it must be considered that the results obtained with regards to the communication time and the adoption of the DSS by the police officers might be subject to this limitation.

7

Experimentation

In this chapter, the experimentation phase is presented. The experimentation consists of a base case, which represents the current procedures without the DSS, and of other five experiments, which mirror the procedures with the assistance of the decision support system. First, the hypotheses, with regard to the expected results of the experiments, are presented. Then, after explaining how the experiments are implemented, the results of the experiments are included.

7.1. Hypothesis

The literature research and the interviews provide some insights into the hypothesized effect of employing the DSS in procedures. Accordingly, we hypothesize that:

H1: The aspects that have the highest influence on the personal efficiency and productivity are the knowledge of the area of the crime and the knowledge of the procedures by the dispatchers.

H2: The employment of the DSS does not deeply improve the decision-making process time or the communication time compared to the base case.

H3: When the DSS has a run length equal to 4, the rate of DSS adoption is significantly lower than when the run length is 1 or 2.

H4: The cases where the run length is equal to 1 are associated with the fastest decision-making time. The cases where the run length is equal to 4 are associated with the slowest decision-making time, which is just slightly better than the base case.

H5: The inclusion of the actors in the DSS design and the training with the system leads to an increase in the rate of adoption for both dispatchers and officers compared to the cases when the actors are not involved. It also leads to shorter communication time, since the probability that the officers agree right away with the dispatchers increases.

H6: A positive experience with the system leads to an increase in the rate of adoption for both dispatchers and officers compared to the cases when the actors are not involved. It also leads to shorter communication time, since the probability that the officers agree right away with the dispatchers increases.

H7: The cases where the DSS displays the fugitive routes and the associated probabilities are the ones with the highest rate of adoption because the actors are thus able to understand the reason behind the solution displayed.

H8: The DSS is mostly adopted by the dispatchers in the scenarios where the dispatchers have low experience and no knowledge of the area of the crime.

H9: When the agents always trust the system, the rate of adoption is higher but the decision and communication time will not be impacted.

H10: Different distributions of the matching_probability do not have a visible impact on the rate of adoption of the DSS.

H11: Different distributions of the impact of the attitude of the officers towards the system on the probability of agreement between dispatchers and officers have a visible impact on the communication time and on the rate of adoption by the police officers.

H12: The DSS is mostly useful in the scenarios where the information on the direction of the fugitive is gained right away and no more information is gained throughout the process.

7.2. Implementation of the experiments: Exploratory Modeling Workbench

All the experiments are implemented by making use of the EMA Workbench library in Python. The logic of the Workbench is based on the XLRM framework (Kwakkel, 2017), which is shown in Figure 7.1. In this framework, X represents the exogenous or external factors, which are not controllable by the decision-maker; L refers to the policy levers or the controllable factors; R stands for the relationships within the system; M refers to the performance metrics or outcomes of interest. In the EMA Workbench, this framework is used to structure the problem, so that the external factors are called uncertainties, policy levers are called levers, and performance metrics are called outcomes. These three are attributes of a model, which contains the relationships in the system.

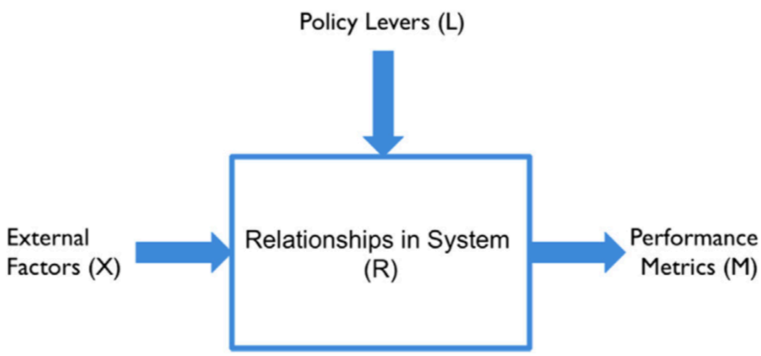


Figure 7.1: The XLRM framework (Kwakkel, 2017).

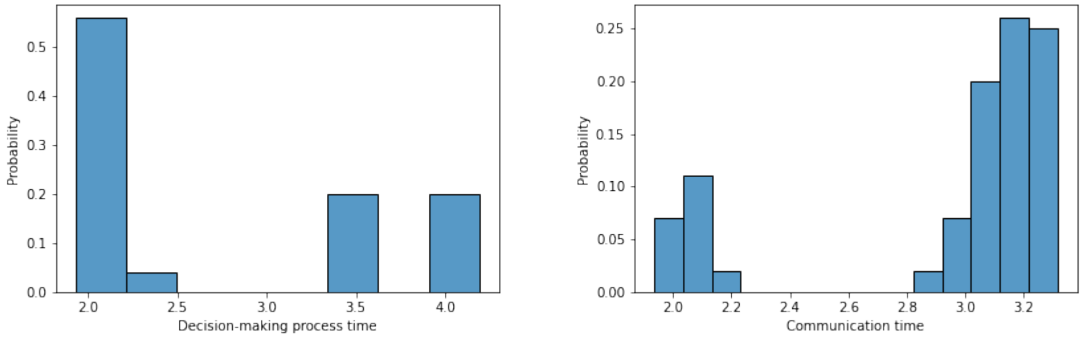
In the EMA Workbench, the simulation model is run as if it were a function (Kwakkel, 2017). Employing the XLRM notation, a simulation model is considered a function called with a set of parameters X and L. The return of the function is a set of outcomes of interest M. Making use of this library, various experiments are run that explore the impact of the specified policy levers on the outcomes, given a set of scenarios that are defined based on the considered uncertainties. The way the experiments are implemented in the EMA workbench, as well as the policies, scenarios and outcomes considered in each experiment, are explained in detail in Appendix E.

7.3. Results

7.3.1. Base case: current procedures without DSS

In the base case, it can be observed that the average decision-making process time for each scenario ranges between around 2 and 4 ticks (1 and 2 minutes), as Figure 7.2a highlights, with an overall average of 1.38 minutes. On the other hand, the graph in Figure 7.2b shows the distribution of the communication time. In all the scenarios, the average communication time ranges between around 2.0 and 3.2 ticks (1 and 1.6 minutes), with the overall average being 1.46 minutes.

Additional analysis is conducted that investigates the relation between the different input and output parameters. The results of this analysis are included in Appendix F. An interesting insight gained from this analysis is that the information scenario has a deep correlation with the outcomes, as it is also visible in Figure 7.3.



(a) Decision-making process time in the base case.

(b) Communication time in the base case.

Figure 7.2: Decision-making process time and communication time in the base case.

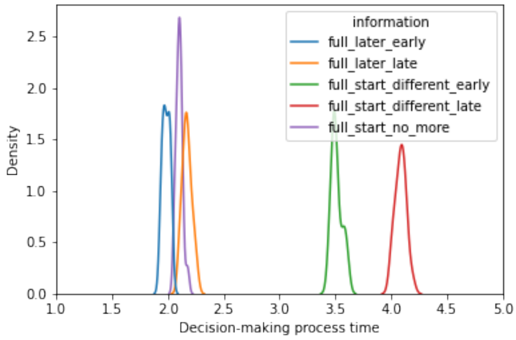


Figure 7.3: The distribution of the decision-making process time in the base case, based on the different information scenarios.

7.3.2. Experiment 1: varying the run-length of the algorithm and the components of the DSS

Experiment 1 investigates not only the effect of using a DSS on the personal efficiency and productivity but also the impact of different implementations of the system (different run lengths and different combinations of information displayed. First, an analysis is conducted to identify what levers or uncertainties have a deeper impact on the outputs. The results of this analysis are shown in Figure 7.4 and highlight that the experience the radio dispatcher has with the procedures has a very deep impact on the communication time (correlation = 0.71). The relation between these two parameters is also plotted in Figure G.1 in the Appendix, where their correlation is very evident. The fact that the correlation is very high is due to the fact that other parameters that influence the communication time are the properties of the officers that are not selected as input parameters. From Figure G.1, it is evident that a higher experience corresponds to a lower communication time. This is connected to the fact that the probability of agreement is higher if the dispatcher is more experienced with the procedure. The parameters that are most correlated with the decision-making time are the information scenario, the run length of the algorithm, and the experience with the procedures and knowledge of the area of the radio dispatcher. On the other hand, the rate of adoption of the DSS by the dispatchers and the officers is mostly influenced by the information scenario and the run length of the algorithm.

Furthermore, the variation of the outcomes based on the different policies is analyzed. Figure 7.5 shows the decision-making time based on the different policies. The average values for each policy can be found in Table G.1 in the Appendix.

When the run length is 1, the decision-making is evidently faster, with the average time ranging from 1.643 to 1.975 minutes. When the DSS displays the information on the optimal positions, the process is faster than when it does not. This is due to the fact that if the DSS does not display information

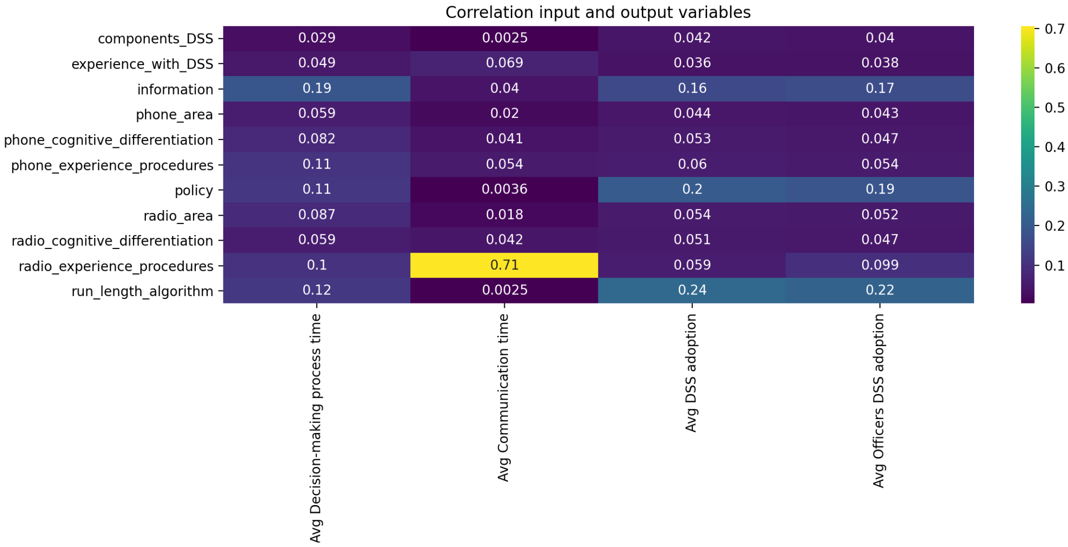


Figure 7.4: Correlation between input and output parameters in Experiment 1.

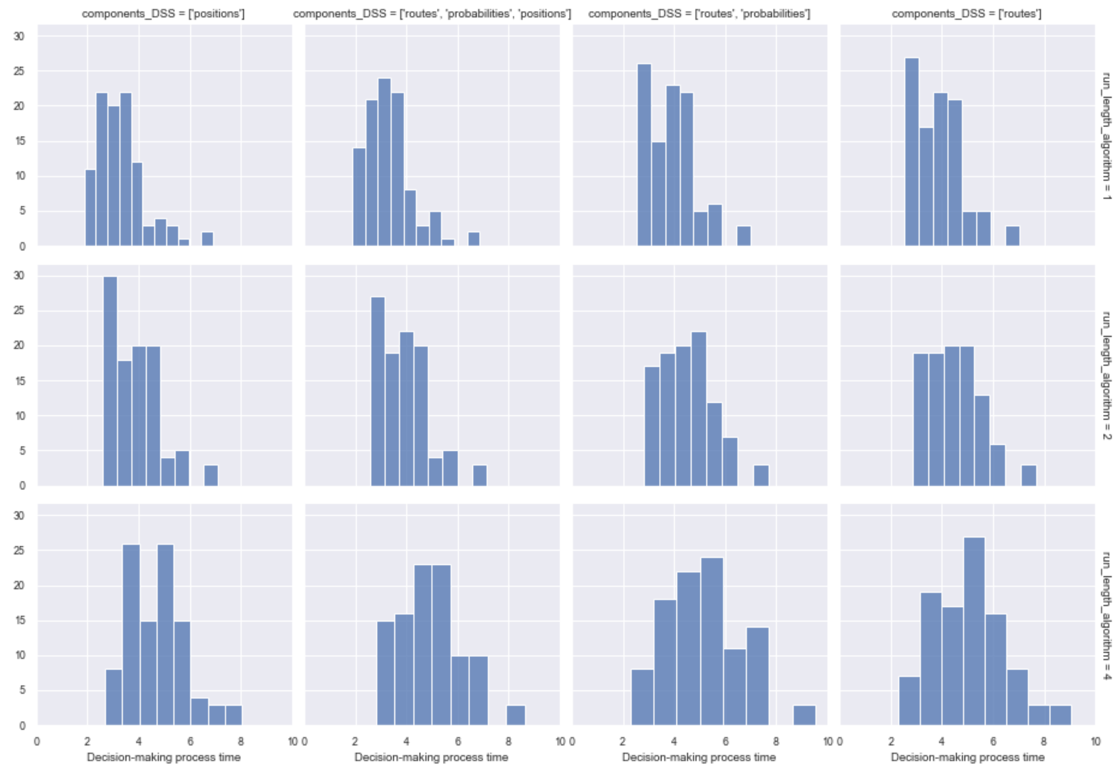


Figure 7.5: The distribution of the decision-making time based on the different policies in Experiment 1.

on the optimal positions, the dispatchers need more time to evaluate the information and define a strategy. The fastest process is thus when the run length is 1 and the DSS shows the information on the optimal positions. In these cases, the average decision-making time is around 1.65 minutes, thus being similar to the base case. When the run length is equal to 2 and the DSS shows the information on the optimal position, the decision-making time just slightly increases, whilst when the run length is 4, the process is much slower, with the average being around 2.5 minutes. Through a two-sample Kolmogorov-Smirnov test, it was established that the distributions in all the policies are different from the one in the base case. Moreover, the test highlights that, regardless of the specific policy, the distribution of the decision-making time is the same when the time needed to gather and process the information is the same. Moreover, the impact of the number of features displayed, and thus the level of transparency of the solution, and the impact of the cognitive differentiation of the dispatchers are very low, as also highlighted in Figure 7.4.

On the other hand, when it comes to communication time, there is no difference between the various policies, as shown in Figure G.2 in the Appendix and as a two-sample Kolmogorov-Smirnov test confirmed. The average communication time for each policy is displayed in Table G.1 in the Appendix. The averages per policy are close to 1.46 minutes, thus being very similar to the base case.

Another aspect that has to be investigated is the rate of adoption of the solution advised by the DSS by the dispatchers. The results are shown in Figure 7.6, where it is visible that the rate of adoption is higher when the run length is lower and where the optimal positions are shown. Figure 7.6 also shows that, in general, the rate of adoption is not high. The values in Table G.1 also highlight that, with the rate always being below 50%. The best cases are the ones where the DSS displays information on the optimal positions and the run length is equal to 1 (the average being around 46%), which correspond to the best cases also for the decision-time. In the worst cases, when the run length is 4 and the DSS does not display information on the optimal positions, the rate of adoption does not reach 30%.

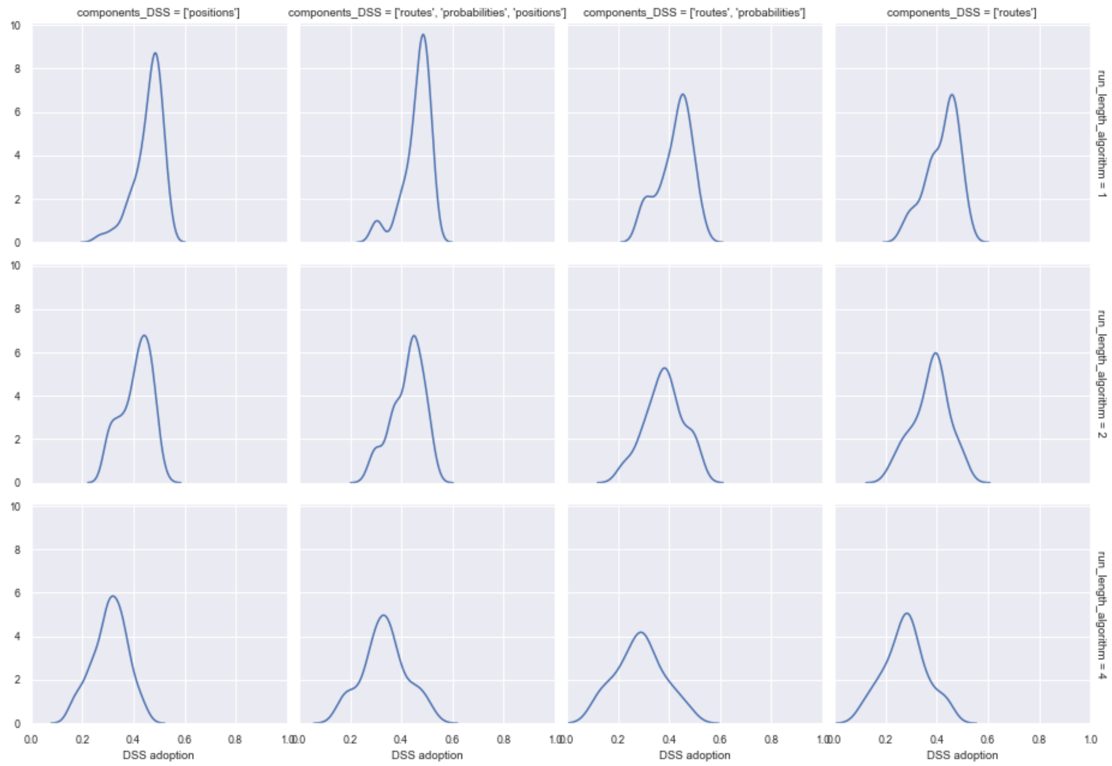


Figure 7.6: The distribution of the rate of adoption of the solution advised by the DSS by the dispatchers based on the different policies in Experiment 1.

Furthermore, the rate of adoption of the DSS solution by the police officers is investigated. The net rate of adoption (out of times that the dispatchers adopt the DSS solution) is shown in Figure G.3 in the Appendix. A two-sample Kolmogorov-Smirnov test showed that the rate of adoption of the DSS has the same distribution in all the policies. The average net rate of adoptions is indeed always very high (87% or 88%), as shown in Table G.1 in the Appendix, meaning that it is highly probable that the officers would trust the system and adopt the solution advised by DSS.

Additionally, more insights are gained into the relation between the DSS adoption, the experience of the radio dispatcher with the procedures, and their knowledge of the area of the crime. Figure 7.7 shows the results. It is visible in these graphs, that when the run length is lower, the adoption of the DSS is generally higher. On the other hand, when the run length is higher, it is clear that the DSS solution is adopted by the dispatchers who either have low experience with the procedures, or no knowledge of the area of the crime, or none of them.

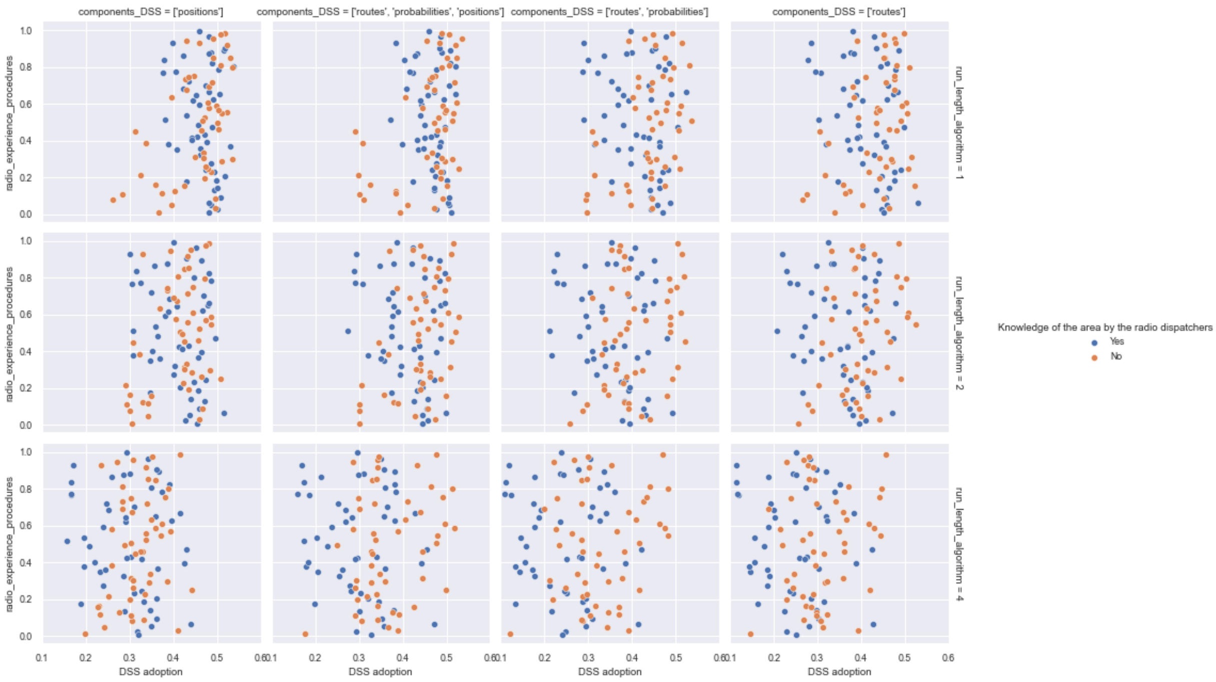


Figure 7.7: The relation between the rate of DSS adoption, the knowledge of the area of the crime and the experience with the procedures of the radio dispatcher.

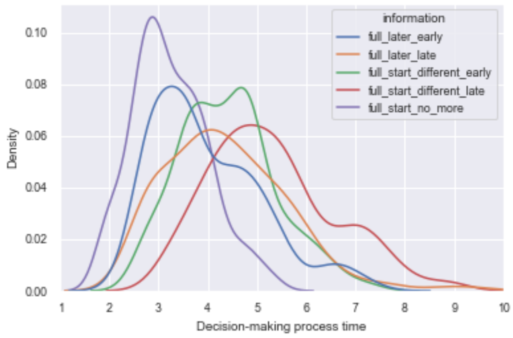
The last analysis performed regards the difference between the various information scenarios and is shown in Figures 7.8a and 7.8b. Compared to the base case, where the distributions are visibly different when the dispatchers get different information on the direction of the fugitive throughout the process, when the DSS is in place, the differences are lower. When the DSS is in place, these scenarios are the ones linked to the highest decision-making time but are also the cases where the DSS is mostly adopted, highlighting that the DSS especially provides support in these circumstances. Moreover, the decision-making time does not evidently increase compared to the base case. On the other hand, the scenarios where the dispatchers gain more information on the direction of the fugitive throughout the process, are the ones where the DSS is adopted the least. The scenarios where the dispatchers have full information at the start and do not get any more afterward, is characterized by the lowest decision-making time, but also a pretty high rate of adoption of the DSS.

7.3.3. Experiment 2: varying the involvement of the agents in the design and training with the DSS and the percentage of positive past experiences with the system

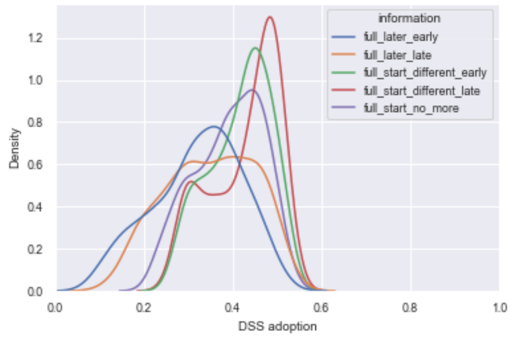
Once the impact of the different implementations of the DSS is investigated, in Experiment 2 the impact of the involvement of the actors in the design of the DSS and in training with the system, as well as the impact of having positive past experience with the system is analyzed.

Also in this case, the first analysis regards the correlation between the inputs and the outputs. In Figure H.1 in the Appendix, it is visible that, the variable representing the inclusion of the actors in the design of the DSS and in training with the system, has a high impact on both the communication time (correlation = 0.12) and the rate of adoption of the DSS by the officers (correlation = 0.17). The variable representing the percentage of positive experience with the system is partially correlated with the rate of adoption of the DSS by the officers (correlation = 0.079) and the communication time (correlation = 0.052).

Then, the distributions of the decision-making time and the communication time in the different policies



(a) Decision-making process time in Experiment 1, based on the different information scenarios.



(b) Rate of adoption of the DSS by the dispatchers in Experiment 1, based on the different information scenarios.

Figure 7.8: Decision-making process time and rate of adoption of the DSS by the dispatchers in Experiment 1, based on the different information scenarios.

are analyzed. The distribution of the decision-making time does not change much between policies with different levels of inclusion_training or positive_experience, as shown in Figure H.2 in the Appendix and confirmed by a two-sample Kolmogorov-Smirnov test. This is partially related to the fact that the rate of adoption of the DSS solution is not too high and thus, the impact of the inclusion of the dispatchers in the decision is limited overall. Moreover, there are a lot of other factors that play a role in the decision (for instance, their level of experience and their knowledge of the area) and thus, the impact of this parameter is even more limited. In Table H.1 in the Appendix is indeed visible that the average decision-making time is almost the same for all the policies.

On the other hand, when it comes to the communication time, Figure 7.9 shows that the impact is more visible. This is due to the fact that if all the officers have some kind of previous experience with the system, this leads to a higher probability of direct agreement with the dispatchers (since the level of trust in the system is generally higher). The average values, shown in Table H.1 in the Appendix, confirm this: no relation is visible between the inclusion_training or the positive_experience parameters and the decision time, while the communication time is clearly higher when the agents are not involved in the DSS design or with training with the system or do not have a completely positive experience with the system (between 1.5 and 2 minutes). On the other hand, when agents are involved and have a positive experience with the system (when both the parameters are equal to 0.5 or 1), the communication time is lower (less than 1.5 minutes). Thus, when agents are not included or have a negative experience with the system, there is a clear loss in the communication time compared to the base case.

Moreover, the impact of the inclusion_training and positive_experience parameters on the rate of adoption of the DSS is investigated. As visible in Figure H.3 in the Appendix, the parameters do not have a clear correlation with the DSS adoption. Similarly, by looking at the average DSS adoption in Table H.1 in the Appendix, it is possible to notice that all the policies are associated with almost the same average rate of adoption. On the other hand, as Figure 7.10 shows, the parameter does have an impact on the rate of adoption by the police officers, with the rate being generally lower when the officers do not have previous experience with the system or when they have a negative experience with it. This is also visible in the averages in Table H.1 in the Appendix, where the rate of adoption of the DSS by the police officers reaches 98.7% when both parameters are equal to 1 (highest inclusion and positive experience) and is equal to 59.7% when both parameters are equal to 0 (lowest inclusion and negative experience).

7.3.4. Experiment 3: investigating what happens if all the agents always trust the system

Experiment 3 investigates what happens if all the agents always trust the system. This means that when agents evaluate whether or not to adopt the solution advised by the DSS, they always decide to adopt it, and thus the perceived usefulness and ease of use do not have any effect in this experiment.

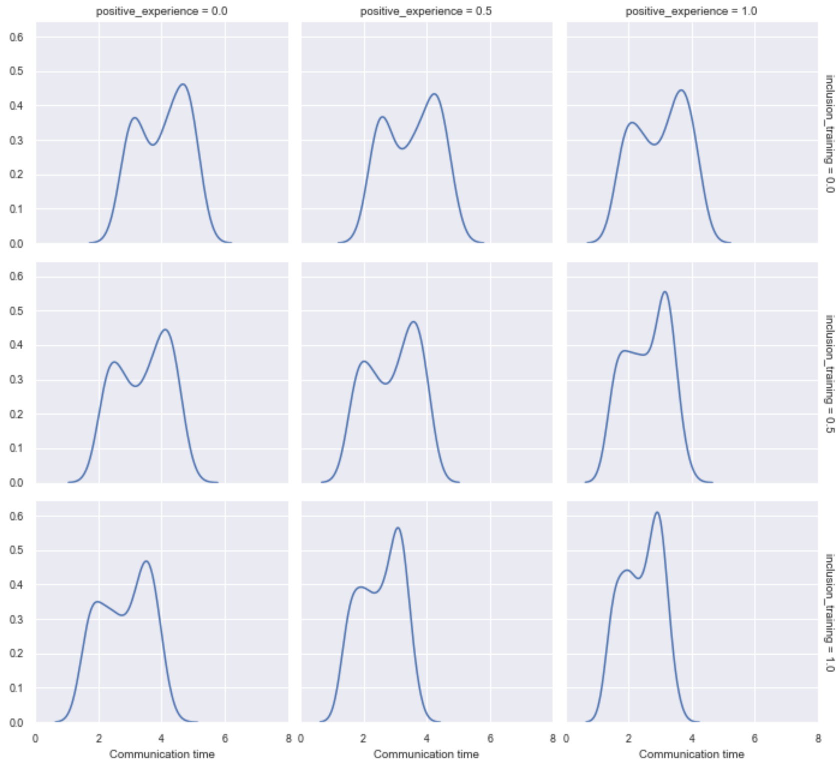


Figure 7.9: The distribution of the communication time based on the different policies in Experiment 2.

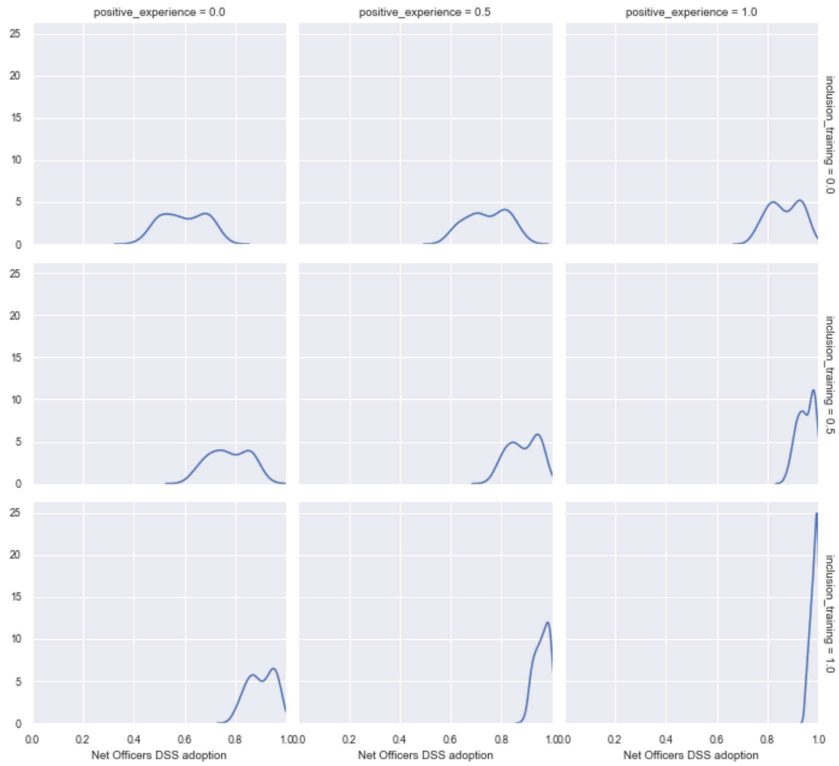
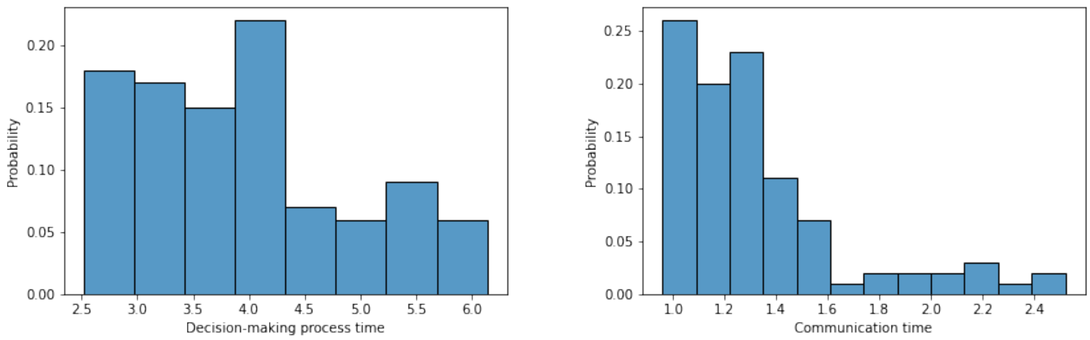


Figure 7.10: The distribution of the rate of adoption of the solution advised by the DSS by the police officers based on the different policies in Experiment 2.

In Figure 7.11a, the distribution of the decision-making time is included. Compared to the base case (Figure 7.2a), where the decision-making process takes around 2, 3.5 or 4 ticks, in this experiment, the decision-making is more distributed, ranging between 2.5 and 6 ticks. The average time in this context is almost 2 minutes, thus being higher than in the base case. This value, as seen in Experiment 1, is highly influenced by the way the DSS is implemented and indeed is in line with the average in Experiment 1 when the run length of the algorithm is 2 and all the features are displayed by the DSS. On the other hand, the communication time is much shorter, with an overall average of 0.66 minutes, thus less than half of the one in the base case. This is due to the fact that, in this experiment, the officers always trust the system, and thus when the DSS solution is used, they always agree to adopt the solution without the need to discuss with the dispatchers. As Figure 7.11b shows, in most scenarios the communication between dispatchers and officers lasts between 1 and 1.5 ticks (30 and 45 seconds).

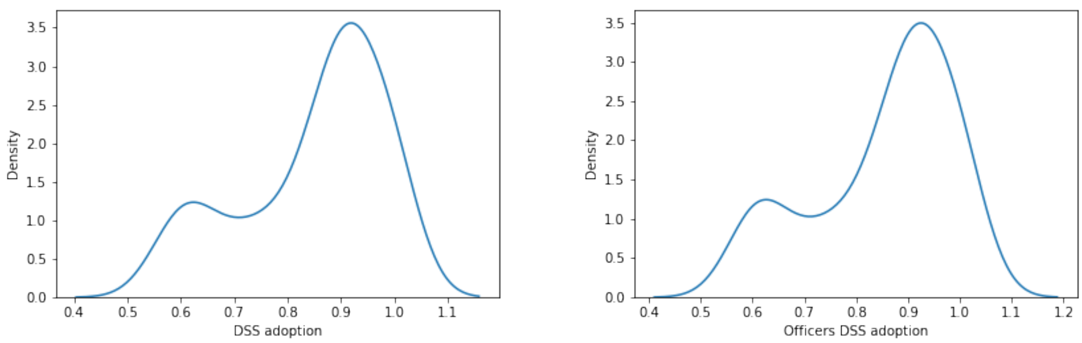


(a) Decision-making process time in Experiment 3.

(b) Communication time in Experiment 3.

Figure 7.11: Decision-making process time and communication time in Experiment 3.

Furthermore, the rate of adoption of the DSS is analyzed. As Figure 7.12a shows, the rate of adoption by the dispatchers is very high compared to the previous experiments, with the average being 0.85. This value also highlights that 85% of the time the dispatchers decide to wait for the DSS to run (when the DSS has a run length equal to 2). By looking at the rate of adoption of the DSS by the officers in Figure 7.12b, it is clear that the distribution is exactly the same as in Figure 7.12a. This is due to the fact that the officers always trust the system and always adopt the DSS solution when it is adopted by the dispatchers. Consequently, the net rate of adoption of the DSS by the police officers is equal to 1.



(a) Rate of adoption of the DSS by the dispatchers in Experiment 3.

(b) Rate of adoption of the DSS by the police officers in Experiment 3.

Figure 7.12: Rate of adoption of the DSS by the dispatchers and the police officers in Experiment 3.

7.3.5. Experiment 4: varying the matching_probability distribution

Experiment 4 investigates the impact of using different distributions for the matching_probability, which is the probability that the solution advised by the DSS matches with the one defined by the dispatchers based on their experience.

In this experiment, four different distributions are implemented (two normal distributions and two uniform ones, with different upper and lower bounds, as explained in Section E.5 in the Appendix). The results are shown in Figures I.1 and I.2 in the Appendix.

A two-sample Kolmogorov-Smirnov test highlighted that the distributions of all the outcomes are the same regardless of the input matching_probability distribution. Thus, it is thus possible to assume that the impact of the matching_probability on the outcomes is not too high and thus, even if the matching_probability distribution is not defined based on evidence, this just has marginal consequences on the results.

7.3.6. Experiment 5: varying the impact of the attitude of the officers towards the DSS on the probability of agreement between dispatchers and police officers

The last experiment verifies the consequences of using different distributions in the definition of the impact of the attitude of the officers towards the DSS, on the probability of agreement between dispatchers and police officers.

In this experiment, three different distributions are implemented, defined as different variations, as explained in Section E.6 in the Appendix. Since the different distributions just impact the second part of the procedures (the communication phase), the only outcomes considered are the communication time and the net rate of adoption of the DSS by the police officers. The results are shown in Figures J.1 and J.2 in the Appendix.

By looking at the graphs, it can be noticed that the distributions do present some differences. However, by conducting a two-sample Kolmogorov-Smirnov test, it was established that the distributions just have marginal differences and can be considered to be the same, since the p-value always results to be higher than 0.1. It is to be noticed that in a few cases, the p-value is equal to 0.15, thus highlighting that a few differences are present.

These results not only suggest that using different values for the variation parameter might lead to slightly different results, but also that, the higher the impact, the higher the trust in the system and the probability of direct agreement with the dispatchers, thus slightly impacting the insights gained from the experiments. Since it is not possible to empirically verify which one of these values is more representative of reality due to the lack of data, it is paramount to consider this limitation when discussing the results.

7.4. Summary

In this section, the results gained from the experiments are analyzed in light of the hypotheses initially made. The insights are summarized in Table 7.1.

Hypothesis	Satified?	Explanation
Hypothesis 1	Partially	Based on the data presented above, it is very clear that the experience of the dispatchers with the procedures and their knowledge of the area of the crime deeply influence the procedures of finding and arresting fugitives and the decision-making and communication processes. This result is coherent with Hypothesis 1 and highlighted both in Figure 7.4 and in Figure H.1 in the Appendix. However, the information scenario is another very critical aspect in the procedures.

Hypothesis 2	Partially	The use of a DSS does not deeply decrease the decision-making time or the communication time compared to the base case, which is coherent with Hypothesis 2. As Experiment 1 highlights, in most cases, the decision-making time actually increases, especially when the DSS has a higher run length and does not displays information on the optimal positions, as shown in Figure 7.5 and in Table G.1 in the Appendix. Moreover, the results in Table G.1 in the Appendix and in Figure G.2 highlight that the communication time does not really decrease with the use of the DSS. When looking at these results, it must be considered that the rate of adoption of the solution advised by the DSS is generally low, ranging from around 27% to a maximum of around 44% in some cases, thus the effect of using the DSS on the decision-making and communication time is just partial.
Hypothesis 3	Yes	Accordingly to Hypothesis 3, when the DSS has a run length equal to 4, the rate of DSS adoption is lower than when the run length is 1 or 2.
Hypothesis 4	Partially	It is visible from the data that the lowest run time is associated with the fastest decision-making time. When the run length is 2 or 4, the presence of the DSS leads to an evident increase in the decision-making time compared to the base case, as Table G.1 in the Appendix highlights.
Hypothesis 5	Partially	As shown in Figure 7.10 and highlighted in Table H.1 in the Appendix, the involvement of the agents has a visible impact on the rate of adoption by the police officers. The rate of adoption goes from 76% when the decision-maker has no knowledge of the system to 94% when the decision-makers have deep knowledge of the system. This shows that employing a DSS increases the probability of agreement between dispatchers and police officers if they have experience with the system. On the other hand, the impact of the involvement of the dispatchers on their rate of adoption of the DSS solution is not visible, as shown in Figure H.3. The dispatchers indeed work in direct contact with the system and aspects such as the different implementations of the DSS are more critical in this part of the process. Finally, the communication time is also shorter the more the actors are involved in the DSS design and trained to use the system, as shown in Figure 7.9.
Hypothesis 6	Partially	As Table H.1 in the Appendix highlights, when the actors are partially involved in the design of the system, the rate of adoption by the officers varies between 74% when the actors have a completely negative experience with the system and 95% when actors have a completely positive experience with it. On the other hand, as Figure H.3 shows, the impact on the rate of adoptions by the dispatchers does not vary depending on the level of positive experience with the system. This result can be interpreted very similarly to the previous hypothesis. Finally, the communication time does result to be shorter the more the level of positive experience is high, as shown in Figure 7.9.
Hypothesis 7	No	Results show that the highest rate of adoption is associated with the implementations of the DSS where the information on the optimal positions is shown. Having the DSS specifying just the routes or just the routes and the probabilities makes it longer to make a decision compared to the other cases because in that case, the time needed to process the information is higher. On the other hand, the cases where all the features are displayed are associated with the highest rates of adoption. The impact of the quantity of information displayed is low, meaning that the time aspect is more important than the level of transparency of the information, as the averages in Table H.1 suggest. It is indeed visible that, if the DSS displays all the information or just the ones of the optimal positions, the rate of adoption is almost the same.

Hypothesis 8	Yes	As shown in Figure 7.7, especially when the DSS has a higher run length, the highest rates of adoption of the DSS are associated with the scenarios where the radio dispatcher has a low experience with the procedures or does not know the area of the crime, or both. Sometimes, a low experience with the procedures or the non-knowledge of the area is associated with low rates of adoption, but this can be easily explained by considering the impact of the phone dispatcher, who might know the area or the procedures and thus support their colleague.
Hypothesis 9	Partially	When the agents always trust the system, the rate of adoption by both the dispatchers and the officers is higher, as mentioned in Hypothesis 9. The decision time is not really impacted, and the distribution is in accordance with the one in Experiment 1 where the same implementation of the DSS is considered. However, the communication time is much shorter, with the overall average being less than half of the one in the base case.
Hypothesis 10	Yes	The results are coherent with Hypothesis 10, since, as shown in graphs in Figure I.2a, the rate of adoption of the DSS by the dispatchers and the officers are not particularly impacted.
Hypothesis 11	Partially	As shown in Figures J.1 and J.2, using different distributions in the definition of the impact of the attitude of the officers towards the DSS, on the probability of agreement between dispatchers and police officers does have a slight impact on the outcomes. More specifically, the higher the impact, the higher the rate of adoption, and the lower the communication time, meaning that the higher the impact, the higher the trust in the system and the probability of direct agreement with the dispatchers.
Hypothesis 12	No	While the scenarios where the information is gained right away are actually characterized by a pretty high rate of adoption of the DSS, the scenarios where the DSS is most useful are the ones where the dispatchers get information on the direction of the fugitive that is different from what they thought in the beginning, as it is evident by comparing Figures 7.3 and 7.8. These scenarios, in Experiment 1, are indeed characterized by the highest rates of adoption of the DSS.

Table 7.1: Summary of the results in relation to the hypothesis initially made.

8

Results validation

Validating the results is paramount to ensure that the model is applicable for its domain and can support the understanding of the problem under study (Van Dam et al., 2012). Since it is not possible to perform a real-world experiment, validation can be achieved by making use of several techniques: historical replays, experts, literature, or model replication (Van Dam et al., 2012). In this chapter, the model validation through literature and experts is presented. We combined these two validations since it is not possible to make use of historical records (the DSS is not yet implemented and the Police do not have any data on the decision-making time employed in the procedures).

The main results gained from the model, which are validated in this Chapter are the followings:

1. The choices of the agents and their performances are, in general, very influenced by the level of experience of the dispatchers with the procedures and their knowledge of the area;
2. Employing the DSS does not deeply reduce the decision-making and communication time, but in most cases, it increases them;
3. The decision-making process time is similar to the one of the procedures without the system just when the run length of the DSS is minimum (30 seconds);
4. The DSS is mostly adopted when the system shows the information of the optimal position and thus the time needed to process the information is lower;
5. The rate of adoption of the DSS by the dispatchers is not too high on average, while the rate of adoption of the DSS by the police officers is quite high on average;
6. The DSS is mostly adopted by the dispatchers when they do not have high experience with the procedures or knowledge of the area of the crime;
7. The DSS is mostly useful when the dispatchers have all information at the beginning and when, over time, they get different information from what they previously had;
8. Involving the agents in the design of the DSS and training with the system increases the rate of adoption by the police officers and decreases the communication time but does not affect the decision-making time or the rate of adoption by the dispatchers;
9. Having a past positive experience with the DSS increases the rate of adoption by the police officers and decreases the communication time but does not affect the decision-making time or the rate of adoption by the dispatchers;
10. When the agents always trust the system, not only the rate of adoption is higher, but the communication time is strongly reduced.

8.1. Literature validation

In this section, the results will be discussed by making use of scientific literature. The papers employed to conduct this validation refer to the adoption of a decision support system, but not specifically to environments characterized by time pressure, uncertainty, and dynamism, because the knowledge regarding these kinds of contexts is still very limited, as highlighted in Section 3.2.

Result 1 This result is very context-dependent and only expert validation is applied to this insight.

Result 2 Various case studies have been conducted that analyzed the impact of using a DSS on the decision time. Skinner and Parrey (2019) affirm that there is no universal agreement on this, but many researchers highlight how the use of a DSS actually increases the decision-making time, while also increasing the quality of the decision. Among the others, Sharda et al. (1988) conducted a case study comparing the decision-making time of two user groups, one that was assisted by the DSS and one that was not. The results show that the group that was assisted by the DSS spent more time making decisions. This validates the first result, since, when the DSS is employed, the actors have more information to process and thus, it takes more time to reach a decision compared to the base when they are not using the DSS.

Results 3 and 4 The third and fourth results show that the DSS is mostly adopted when it takes less time to gain and process information. This is in line with many studies that show that under time pressure, the information processing strategy is altered and people limit their information choices to those that can be gained quickly and easily (Savolainen & Kari, 2006). If the DSS takes too long to run or it takes too long to process the information, it is less probable that the dispatchers would adopt the DSS solution. Shibl et al. (2013) agree with this position, claiming that the users would not adopt the DSS if it is too complex to use it. In this case, not displaying information on the optimal positions increases the difficulty of using the system and thus its adoption is reduced. Gönül et al. (2006) show that adding a lot of information or many explanations on why the suggestions are given, does not increase the rate of adoption or improve the opinion on the system; the information value results to be more important for the decision-makers. Chan et al. (2017) also support this result, since they claim that "decision performance improves if a DSS is a good fit for a task and supports the user through reduced effort". In general, users look for a reduction in their cognitive effort and will uniquely adopt a decision strategy that improves their performance if it also reduces their effort. Chan et al. (2017) additionally explain how the response time of a DSS has a high impact on users' motivation to use the DSS, as also the results of this research highlight.

Result 5 This result is very context-dependent and only expert validation is applied to this insight.

Result 6 and 7 Gönül et al. (2006) highlight that the use of a DSS is influenced by the perceived information value. If a dispatcher does not have experience with the procedures or knowledge of the area, the information displayed by the DSS has a higher value for them, and thus the probability that they use the DSS is higher. Similarly, if the dispatchers at some point in the process get different information from what they previously had, they would have to restart the decision-making process, and thus, if they have low experience, the DSS might be useful to accelerate it. In accordance with these results, Chan et al. (2017) state that an "accurate decision strategy that attenuates the information processing effort and at the same time meets the users' expectations of attaining their goals should increase DSS motivation and subsequent usage of the DSS to complete a task". Perry et al. (2012) affirm that DSS can help less-experienced personnel perform better during emergencies by processing more information in less time, thus also corroborating this point.

Results 8 and 9 The insights highlighted by these two results are widely sustained in the literature. Among the others, Alavi and Joachimsthaler (1992) underlines that manipulating user-situational variables (involvement, training, and experience) can improve the implementation success rate of a decision support system. Zarate (1991) claim that it is important that the decision-makers understand the decision model in principle, even if they are not familiar with the specific techniques employed. Moreover, they highlight that if a developer provides some training on the software system, the users understand it better, and the model has a greater chance to be used in practice. Additionally, Lawrence et al. (2002) mention that involving the users in the design increases the chance that they agree with the system. In this research, the direct consequence of the fact that the users would more frequently agree with the system is that the communication time is reduced, and thus these insights conform to the literature. These results are just valid for the police officers, because for the dispatchers, many aspects play a role in the overall decision-making process (primarily, the way the DSS is implemented) and thus the experience with the system just has a partial impact.

Result 10 This last result is complex to validate through literature since a situation in which all the actors trust the system is not realistic and no research observes or investigates such a case. Nevertheless, the fact that if users believe that a system provides information of high value or if they generally trust it, the DSS is more likely adopted (Gönül et al., 2006; Shibl et al., 2013), is in line with this result. Moreover, as stated in the previous paragraph, higher trust in the system leads to a higher probability of agreement with it and thus the discussion time between the actors is reduced.

8.2. Expert validation

The expert validation was conducted by interviewing the same dispatcher that was interviewed to gather information on the system. The fact that the same expert that collaborated with the definition of the inputs of the model also contributed to validating the results partially represents a limitation. However, given the deep experience of the dispatcher with the procedures, we considered his perspective on the results to conduct the validation. According to the expert, the results are overall reasonable.

Result 1 According to the dispatcher, it is true that the experience of the dispatchers with the procedures and their knowledge of the area is directly linked to the personal efficiency and productivity of the practitioners.

Result 2, 3, and 4 The expert agrees on the fact that a run length of 1 or 2 minutes would not decrease the decision-making time, since it would represent a very long time to wait in most situations. The expert agrees that 30 seconds could be a reasonable time to wait to communicate the solution to the officers and that this could lead to improved performance. He also believes that it would be better if the DSS would show the information on the optimal positions, to minimize the time needed to process the information.

Result 5 The expert agrees that the rate of adoption of the DSS by the dispatchers will not be high, because at the beginning there will be resistance to change and they might perceive the system negatively. The dispatchers will probably not adopt the system when it displays solutions that are not coherent with their ideas and past experiences. The police officers will not experience such a change with the introduction of the system and thus they will be less resistant to change.

Result 6 and 7 The expert agrees that the system would mostly be adopted by the dispatchers with less experience with the procedures or knowledge of the area. The dispatchers with more experience will be more resistant to using the system and also do not need the system as much as the novices. It also seems reasonable that the DSS would be less useful when the dispatchers get information on the direction of the fugitive over time because, at that point, the dispatchers would require less time to formulate a strategy, whilst the DSS would need to run again.

Result 8, 9, and 10 The dispatcher agrees on the fact that if the actors trust the system, have a positive experience with it, or are trained to use the system, they would adopt the system more and the decision-making process would be more efficient. Moreover, he believes that, while for the officers the past experience with the system would be a very critical factor for them to decide whether or not to trust it, for the dispatchers there would be additional evaluations. For instance, the time needed to get information about the system and the extent to which the information gained from it is needed by the dispatchers, are aspects that would be considered in this evaluation. This means that, for the dispatchers, many factors would play a role in this decision and thus, their past experience with the system would not be directly linked to the probability to use it.

9 Discussion

In this chapter, the results are summarized and discussed, first with regard to the case study and then generalized to all decision-making processes under time pressure, uncertainty, and dynamism. Afterward, a reflection on the method used is included. Finally, the limitations of this analysis are included, with regard to the research approach and the lack of data and information.

9.1. Discussion on the model results

As already mentioned in Section 7.4, the implementation of the agent-based model led to a set of expected and unexpected results. These results, as for every simulation model, are affected by the principle ”garbage in, garbage out” (Kilkenny & Robinson, 2018), meaning that the results gained are very sensitive to the inputs and to how the model is built. The simulation model is built by making use of the insights gained from interviews and from literature, but it also includes some aspects that could not be verified empirically due to the lack of data. Also for this reason, it is important to clarify that the model results are to be interpreted purely in qualitative terms, and not on the basis of the quantitative outcomes of the simulation (Bonabeau, 2002). While these aspects are to be taken into consideration, the model did lead to some interesting results which can be used for the specific case at stake but can also be generalized. In this section, the insights presented in the previous chapters will be interpreted and discussed.

The model results show that, on average, the decision-making process time increases with the use of the DSS. This is in line with the literature findings presented in the previous chapter (Sharda et al., 1988; Skinner & Parrey, 2019), but in contrast with other researchers, as Thompson et al. (2006). More specifically, when the run length is minimum (30 seconds) the increase is limited, but when the run length is equal to 1 or 2 minutes, the increase is very evident, thus leading to a decrease in the personal efficiency and productivity of the practitioners. This is critical because a long decision-making process can threaten the chances to catch the fugitives.

In some information scenarios, the DSS is more useful than in others. If the dispatchers have information on the direction of the fugitives already at the beginning, the DSS is often adopted, and its use can lead to an improvement in the performance (depending on the run length of the algorithm and the time needed to process the information gained). On the other hand, when the dispatchers do not have this information at the beginning and gain it afterward, the DSS does not lead to high improvements in the performance. In fact, while the decision-making process at that point becomes faster thanks to the additional information, the DSS has to rerun and thus, depending on the time needed to gather and process the information, if the decision-makers decide to wait for the system’s solution, the decision time might increase. However, in the cases where the dispatchers get, during the decision-making process, some information on the direction of the fugitive that is different from what they previously had, the DSS can offer more support. In these cases, in fact, as the DSS has to restart running, also the dispatchers have to restart the decision-making process, leading to an increased time pressure and complexity of the decision, and thus relying on the DSS can lead to improved performances. However, it must be considered that this information scenario, in reality, does not happen very frequently.

Another situation in which the DSS is especially helpful is when the dispatchers are not very experienced with the procedures or do not have a deep knowledge of the area of the crime. The model results show that these two aspects indeed have a large influence on the performance of the actors. While the DSS is commonly adopted when the run length is minimum, when the algorithm takes the longest to run, it is visible that the DSS solution is mostly used when the decision-makers lack experience with the procedures or knowledge of the area. Although this result seems to identify a scenario in which employing the system helps the practitioners, it is to be noted that, in the real procedures, the dispatchers would not wait for the system to run for one or two minutes, but would most probably rely on the police officers to define a strategy to intercept the fugitives. Thus, it is not clear whether the DSS might actually support the procedures in these cases. In fact, based on the officers' interviews, when crimes have low or medium urgency, it is sometimes possible to wait more to gain a high-quality suggestion, but in the case of crimes of high urgency, even one minute can be a very long time to wait. Thus, it is important to determine what the most efficient trade-off is between the run length and the accuracy of the solution. In general, also considering the insights gained from the interviews with the dispatcher, a run length of 30 seconds can be considered adequate.

An additional aspect highlighted by the results is that when the DSS shows information on the optimal positions, the system is more frequently adopted. This shows that minimizing the time needed to gather and process information is a very critical aspect for the practitioners, more important than the level of transparency of the information displayed by the system. Based on the results, the level of transparency of the information displayed does not seem to play a role, with the implementation that just presents the information on the optimal positions and the one that displays all the information having almost the same rate of adoption. However, it is to be noted that the population included in the simulation is constituted by heterogeneous agents who might or might not have the ability to process multiple information (high or low cognitive differentiation), and where this ability is evenly distributed. It is not clear if this is the case for the Dutch National Police. If the practitioners were characterized by a low cognitive differentiation on average, an excessive amount of information displayed would have consequences on the efficiency of the system. For this reason, while it is anyways important to display the information on the optimal positions to minimize the processing time, it is not clear whether, for the Dutch National Police, getting the information on the escape routes and associated probabilities can be useful or counterproductive. One possible flexible strategy can be providing the dispatchers uniquely with the information on the optimal positions as a standard setting while including an option to visualize the information on the routes and associated probabilities in case of need.

In general, the results show that the rate of adoption by the dispatcher is not high on average, while the net rate of adoption by the officers is. This is coherent with the point of view of the dispatcher interviewed, who mentioned that the dispatchers would experience resistance to change and challenge the system's validity more than the officers, who would not experience the same change, since they would receive instructions from the dispatchers similarly as before. Furthermore, it is visible that trust in the system leads to higher adoption of the system, but also to faster communication between dispatchers and officers, because if most agents trust the system, the discussions are reduced. Similar results are visible in case the actors have a positive past experience with the system, or in general, have a lot of experience with it. On the other hand, for the dispatchers, this effect is not visible. In fact, the dispatchers are in direct contact with the system, and thus, for them, other aspects (such as the run length of the algorithm) play a more crucial role in the decision. Anyways, the results show that involving the actors in the design of the system can be very helpful to reduce the discussion time and thus make the process smoother.

9.1.1. Generalizing the results: from the case study to decision-making processes taking place under time pressure, uncertainty, and dynamism

The results presented above specifically refer to the case study at stake: the procedure of finding and arresting fugitives undertaken by the National Police. Clearly, it is not possible to quantitatively generalize the results gained from the model or the factors that are typical of the case study of the Dutch National Police, as the information scenarios in which the DSS is more useful or the effect of the specific implementations of the DSS. However, some insights can be generalized, as shown in the following paragraphs.

First, the model results suggest that in situations characterized by time pressure, uncertainty, and dynamism, the use of a DSS does not always have the effect of making the process faster. This largely depends on how the DSS is implemented, especially in relation to the level of expertise of the decision-makers and the time it would take for them to make a decision without a system. On the other hand, the DSS does have a positive effect on the process, by assisting the decision-makers who lack experience with the activities and processes at stake, and thus either would require a long time to make a decision, or would not be able to make a high-quality decision at all without the assistance of the system. While for less experienced actors the DSS can lead to better performances, for more experienced ones its use can lead to an increase in the decision-making time, depending on the time needed to gather and process the information coming from it. On the other hand, in dynamic settings, when the changes in the environment lead to an increased time pressure and complexity of the decision, the DSS can be very helpful and lead to improved performances.

Moreover, the results highlight that time is a very critical factor in these contexts and is far more relevant than the level of transparency of the information displayed. The DSS is more frequently employed when it takes less time for the decision-makers to gather and evaluate the information provided by it. This also suggests that it might be better to reduce the run length of the algorithm and to quicker display the information rather than to invest in showing more information to increase transparency. As a consequence, it is important to determine the trade-off between a sufficient level of transparency of the information and the time needed to gather it, and to consider this aspect while designing the system. Moreover, it is to be determined what the level of cognitive differentiation of the practitioners is, to avoid overwhelming the actors with too much information and minimize the time needed to process it, while still providing all the necessary insights.

Lastly, this research outlines that it might be worth it to include the practitioners in the design of the DSS and start building their perception of the system before they actually start using it. When all the actors, or the majority of them, trust the system, the discussion time is reduced and the decision-makers define a strategy quicker. Especially in contexts of public organizations, where, as Heikkila and Isett (2004) underline, discussions commonly take place between the practitioners to ensure that everybody agrees with the operational decisions, using a system the actors trust has the potential to largely reduce the discussions and thus the decision-making time. It is however paramount to consider that in this research, the quality of the solution provided by the DSS is not established, and thus it is not possible to determine if, in the actors' perspective, the DSS leads to an actual improvement in the decision quality. In reality, it might happen that, even if the actors have experience with the system and they have trust in it, they might think that in certain situations their own strategy is more efficient. Nonetheless, it surely is important for the practitioners to know the system in advance, how it works and how it processes the available information to maximize the support it can provide to the actors. This not only leads to higher perceived usefulness and perceived ease of use, but also smoother decision-making processes. Nevertheless, it appears from the results that the way the system is implemented (and especially the time it takes to run) plays a more important role in the decision on whether to employ the DSS compared to actors' past experience with it, especially for those who work in direct contact with the system.

The insights gained from the model as presented in this section, while obviously derived from the specific case study, might be applied to all the contexts inherently similar to the procedure of finding and arresting fugitives undertaken by the Dutch National Police, for instance, crisis management.

9.2. Reflection on the method

In Chapter 2, it is argued that an agent-based modeling approach is employed in this project, but without implementing a standard agent-based model. The reasons why it was decided to use this approach are also included in Chapter 2. In this section, a reflection on the used approach is included.

First, the agent-based model allows to model actors as characterized by properties and acting and re-acting to the inputs coming from other actors and the environment based on those properties. By using the agent-based modeling approach, it was possible to model the decision-making process based on the attributes of the agents, experiment with different values for these properties to define an overall heterogeneous population, and also to evaluate whether some properties of the agents have a critical impact on the outcomes. Moreover, standard agent-based models are used to model the adaptation and learning process of the agents over time, based on the input they get from the environment and from other agents. In this model, the evolvement of the agents over time is not investigated, but on the other hand, the focus is on the behavior of a heterogeneous population of agents, who are at different stages of the learning process (have more or less, positive or negative past experience) and act based on their personality, past experience and inputs coming from the environment. Nevertheless, even if no learning or adaptation is involved, using a simulation model instead of a set of excel sheets made it possible to simulate actors' behavior, which is not predetermined and is characterized by stochasticity. Furthermore, even if most of the results were expected, employing a simulation model was useful to verify that the hypotheses made with regard to actors' behavior and performance were actually true. After verifying these hypotheses, the gained insights can be applied to the design of DSS and can contribute to the state-of-the-knowledge regarding the use of such systems in environments characterized by time pressure, uncertainty, and dynamism. Additionally, the model results led to unexpected insights which can support the design process and indicate the contexts and the modalities in which the DSS can mostly be of help.

9.3. Limitations

9.3.1. Limitations on the research approach

As previously mentioned, the employment of a case study for this research comes with its limitations. Additionally, a lot of content the model is based on is defined by making use of the insights gained from the interviews. However, just a small sample was considered to gather information. Organizing more interviews or implementing a survey might have led to more specific information on the procedures of finding and arresting fugitives. This is especially true with regard to the quantitative data that has been gained from interviews and employed in the model. While the interviewed actors are highly involved in the procedures and have high experience, making use of a wider sample would have led to more precise insights. This represents a limitation that might have potentially impacted the results.

Moreover, the employment of a computational model leads to additional limitations. While the reason for using this approach has been argued for and all the other possible approaches were also characterized by many limitations, it is important to consider what using a simulation model implies in order to properly interpret the results.

First, a simulation model represents a simplification of reality (Kleijnen, 1995). This means that it fails to perfectly represent what happens in real life. For this reason, it is important to interpret the model results purely in qualitative terms, and not on the basis of the quantitative outcomes of the simulation (Bonabeau, 2002). The values of the duration of the decision-making time and communication time do not precisely represent what happens in the real procedures of finding and arresting fugitives; however, the difference in these values when the decision-maker is and when it is not assisted by the DSS can be considered to evaluate, in qualitative terms, the difference between these two situations.

Secondly, the results of the simulation model are very sensitive to the input parameters, following the principle ”garbage in, garbage out” (Kilkenny & Robinson, 2018). Given the small sample of actors interviewed, the outcomes of the model might have been influenced by these input parameters, whose level of accuracy is not known. This fact reinforces the need to only interpret the output data in qualitative terms. Moreover, some parts of the model are based on qualitative insights gained from literature and from interviews which have been transformed into quantitative input data (for instance, the values whose impact has been investigated through a sensitivity analysis in Section 6.5). This data could not be verified empirically due to a lack of knowledge in the field, and thus it must be noted that the results might be partially influenced by these inputs, whose level of accuracy is not clear.

Lastly, the literature review this project is based on is largely based on strategic, managerial, long-term decision-making processes. This is mainly due to the fact that the knowledge and research on operational decision-making processes is still very limited. For this reason, some insights coming from studies focusing on strategic decision-making processes had to be used to implement the simulation model and to model the behavior of the agents. The extent to which these insights are also applicable to contexts such as the one under investigation is however not clear.

9.3.2. Data and knowledge limitations

As previously stated, we implemented the simulation model based on the insights gained from the interviews and a literature research. However, there are some knowledge gaps and data limitations that partially affected the scope and the level of depth of the conceptualization of the model.

First, the model is based on various assumptions. While most of the assumptions are directly linked to literature and to the interviews, some of them could not be validated. For instance, it was not possible to empirically determine the time that it would take for the dispatchers to make decisions, since in reality, when they would take too long to formulate a strategy, they communicate the information on the case to the officers and rely on them to coordinate with each other.

Additionally, while many studies on the factors influencing the attitude towards a new technology could be found in literature, this research area is to be further developed. There are no universal models or frameworks that explain the relationship between the psychological and environmental factors affecting a user and their attitude towards the adoption of a new technology. The majority of the knowledge on the topic comes from isolated case studies and thus the statistical insights gained from those cannot be generalized to all kinds of research. The consequences of this lack of knowledge for this project are twofold. First, the attributes of the agents influencing the adoption of the DSS have been selected based on the results of the research and the case studies found in literature. It is not clear if there are more factors that play a role in this process and whether they have a low or high impact on the acceptance of the DSS. Secondly, the weights of these attributes in the definition of the perceived ease of use and perceived usefulness of the agents have been defined based on the same literature, which was used to determine whether some parameters have a higher weight than others, but the values used in the model could not be directly based on scientific evidence. The sensitivity analysis in Section 6.5 highlighted that some of these parameters have a higher correlation with the outcomes than others, but due to the lack of data, it was not possible to specify them further.

Another limitation refers to the lack of knowledge on the impact that the attitude of the officers towards the DSS has on the probability of agreement between dispatchers and police officers. In Section 7.3.6, it is shown that varying this impact leads to different distributions in terms of the communication time and the rate of adoption of the DSS by the police officers. Although the distributions are not extremely different, there still is a variation in the overall behavior of the agents. Due to the lack of data or knowledge on the topic, it was not possible to determine the real value of this impact, and thus, this represents a limitation for the analysis.

Finally, as previously stated, due to the lack of data on the fugitive behavior and on the content of the decision-making process of the dispatchers, it was decided not to model the environment and to leave it out of the scope of this research. However, if data was available regarding this topic, it would have been possible to more carefully delineate various aspects of the model, mainly being a more detailed conceptualization of:

- the decision-making process and the factors influencing the time needed to make a decision;
- the factors driving the decision (e.g. street properties) and thus more detailed information on when the DSS results to be especially useful;
- the factors influencing the probability of agreement between actors, and especially between dispatchers and police officers, to better determine the role that the use of the DSS plays in this;
- the changes in the environment that most deeply influence the decision-making process time;
- the probability that the DSS solution matches with the one determined by the dispatchers;
- in case of non-agreement with the DSS, the extent to which the two solutions differ, and the extent to which the DSS advice is applied;
- the probability that the officers agree with the DSS solution.

While this lack of knowledge has been dealt with by not modeling the environment and uniquely focusing on the psychological factors, more research is needed to identify the environmental factors that influence the decisions of the dispatchers and police officers and the behavior of the fugitives.

10 Conclusion

In this project, we investigated the effect of using a DSS to assist decision-making processes taking place in environments characterized by time pressure, uncertainty, and dynamism. A literature review indeed clarified that, while this research area is very explored, the effect of these systems in such contexts is not yet clear.

To conduct this analysis, we employed a case study that focuses on the procedures of intercepting fugitives undertaken by the Dutch National Police. This task is indeed characterized by high uncertainties with regards to the (dynamic) location of the criminals and by high time-pressure, aspects that make it very challenging for the control room to position Police units, and the dispatchers currently approach this task by relying on intuition and experience. By conducting interviews with practitioners directly involved in these procedures, we gained an understanding of how the system works. Currently, a decision support system is being developed to assist the dispatchers in the decision-making process, but it is not clear to what extent the DSS can actually be of help, how the DSS should be implemented to be most effective and what the attitude of the actors towards the system would be.

In order to answer these questions, we implemented a simulation model, based on the insights gained from the interviews and literature research. We ran several experiments, and the results have been collected to answer the main research question. The model mainly explores: the difference in the personal efficiency and productivity of the practitioners (decision-making time) when the decision-makers are and are not assisted by the DSS; the impact of different implementations of the DSS; the impact of involving the actors in the DSS design and in training with the system, and the impact of having a positive pat experience with the system; what would happen if all actors always trusted the system.

In this chapter, the research sub-questions and then the main research question are answered. Afterward, the societal and scientific contributions of this project are highlighted. Finally, recommendations for future research and for the design of the decision support system are included.

10.1. Answer to research sub-questions

Before an answer to the main research question is formulated, the four research sub-questions are discussed.

Sub-question 1: How do the current procedures of finding and arresting fugitives work?

Based on the insights gained in the interviews, knowledge on how the procedures of intercepting fugitive work was gained. In this procedure, the most critical task is identifying the best strategy to position the units, in order to optimize the chances to intercept the offender. Currently, this task is conducted by primarily the dispatchers and also the police officers in the cars, who rely on their own intuition and experience to define the best solutions and strategies. However, especially given the huge amount of information the dispatchers are provided with and the short amount of time they have to formulate a strategy, the dispatchers are not always able to suggest to the officers where to position. Moreover, not all the dispatchers are sufficiently expert to be aware of the best strategies, especially because they might lack experience with the procedures or knowledge of the area where the crime took place. The police officers, on the other hand, are usually more experienced but need to handle the coordination with both the control room and the other units at the same time, thus making it very complex for them to efficiently organize. For this reason, if the dispatchers were supported in this task, the procedure would result to be more efficient.

Sub-question 2: How can the personal efficiency and productivity of the practitioners in the procedures be measured?

Considering both the knowledge gathered from literature and the interviews, it resulted clear that in general, measuring performance in public organizations' contexts is very complex. Since it was decided not to model the environment, it is not possible to measure the outcome of the process (the extent to which the Police succeed in intercepting fugitives), but on the other hand, it is possible to focus on the process itself, and investigate the impact of the DSS on the personal efficiency and productivity of the practitioners. Personal efficiency refers to the time needed by the users to structure the problem or the number of alternatives evaluated by the user in a given time period (Dean Jr & Sharfman, 1993), while personal productivity refers to the time needed to make a decision or the amount of information, knowledge, wisdom, produced in a decision-making process (Kumar, 1999).

The interviews highlighted that, while the percentage of time the fugitives are intercepted definitely is an important aspect, the time that is needed to find them is also very critical since, the more time passes, the harder it gets to find the criminal. Decreasing the decision-time is, as mentioned by the practitioners, paramount to improving the organization's performance, which is linked to the main goals and values of the Police organization: arresting offenders and enhancing security (Moore & Braga, 2003). Thus, time is considered the most critical aspect of the procedures and in this case study, personal efficiency and productivity are translated into the time that the dispatchers need to define a strategy and the time they need to communicate the strategy to the officers, which altogether constitute the decision-making process time.

Finally, as Le Blanc and Kozar (1990) underline, to assess the effectiveness of decision support systems it is important not only to focus on the improvements that the use of a DSS led to but also to consider the extent to which the DSS is actually employed by the users. For this reason, the results of the performance of the procedures with and without the DSS assessed by the aforementioned indicators are analyzed in relation to the percentage of time the solution that comes from the DSS is actually employed to find the fugitive.

Sub-question 3: How can the procedures of finding and arresting fugitives, with and without the assistance of the decision support system, be translated into an agent-based model?

The simulation model is conceptualized as follows. Two types of actors are included: the dispatchers and the police officers. Both actors are characterized by their experience with the procedures, properties influencing their attitude towards the system, and their attitude towards each other. Moreover, the dispatchers are characterized by their knowledge of the area of the crime and by their role (whether they work on the phone or on the radio). The properties influencing their attitude towards the DSS and the relations between these properties are specified based on a literature review and are shown in Figure 6.2.

Based on the information the dispatchers have, their experience with the procedures and knowledge of the area of the crime, the decision-making process takes more or less time. The radio dispatcher is the one primarily in charge of defining a strategy but can be supported by the phone dispatcher in case of a lack of knowledge of the area or of experience with the procedures. After a decision is made, the strategy is communicated to the police officers that might or might not agree with it, also based on their experience and attitude towards dispatchers.

The model is implemented in two versions, with and without the DSS. In the version with the DSS, the dispatchers decide whether to use their own solution or to adopt the one coming from the DSS. They might decide to directly use the DSS solution if it would take too long for them to define a strategy on their own. They also decide whether or not to wait for the DSS to run, based on whether or not it is convenient for them in terms of eventual additional time spent and information gained. If they wait for the DSS to run, they then compare the solution coming from the DSS with the one defined by them, and if these two do not match, they consider whether they trust the system sufficiently to follow its advice. Then, they communicate the strategy to the police officers. In this case, the reaction of the police officers is influenced by their attitude towards the DSS.

The outcomes collected from the model, coherently with the answer given to sub-question 2, are: the decision-making process time, the communication time, the rate of adoption of the DSS solution by the dispatchers, and the rate of adoption of the DSS solution by the police officers.

Sub-question 4: What is the difference in the personal efficiency and productivity of the practitioners, when the decision-makers are and when the decision-makers are not assisted by the decision support system?

The results of the experiments conducted highlight that, on average, the decision-making process time increases with the use of the DSS. More specifically, when the run length is minimum (30 seconds) the increase is limited, but when the run length is equal to 1 or 2 minutes, the increase is very evident, thus leading to a decrease in the personal efficiency and productivity of the practitioners.

Depending on the information scenario, the DSS is more or less useful. If the dispatchers have information on the direction of the fugitives already at the beginning, the DSS is often adopted, and its use can lead to an improvement in the performance (depending on the run length of the algorithm and the time needed to process the information gained). On the other hand, when the dispatchers do not have this information at the beginning and gain it afterward, the DSS does not lead to high improvements in the performance. However, in the cases where the dispatchers get, during the decision-making process, some information on the direction of the fugitive that is different from what they previously had, leading to an increased time pressure and complexity of the decision, the DSS can offer more support.

Another situation in which the DSS is especially helpful is when the dispatchers are not very experienced with the procedures or do not have a deep knowledge of the area of the crime. Although this result seems to identify a scenario in which employing the system helps the practitioners, it is to be noted that, in the real procedures, the dispatchers would not wait for the system to run for one or two minutes, but would most probably rely on the police officers to define a strategy to intercept the fugitives. Thus, it is important to determine what the most efficient trade-off is between the run length and the accuracy of the solution. In general, a run length of 30 seconds can be considered adequate.

When the DSS shows the information on the optimal positions, the system is more frequently adopted. This is due to the fact that minimizing the time needed to gather and process information is a very critical aspect for the practitioners, more important than the level of transparency of the information displayed by the system. However, while it is clearly important to display the information on the optimal positions to minimize the processing time, it is not clear whether, for the Dutch National Police, getting the information on the escape routes and associated probabilities can be useful or counterproductive. One possible flexible strategy can be providing the dispatchers uniquely with the information on the optimal positions as a standard setting while including an option to visualize the information on the routes and associated probabilities in case of need.

In general, the results show that the rate of adoption by the dispatcher is not too high on average, while the net rate of adoption by the officers is. Furthermore, it is visible that trust in the system leads to higher adoption of the system, but also faster communication between dispatchers and officers, because if most agents trust the system or are very experienced with it, the discussions are reduced. On the other hand, for the dispatchers this effect is not visible. In fact, the dispatchers are in direct contact with the system, and thus, for them, other aspects (such as the run length of the algorithm) play a more crucial role in the decision.

10.2. Answer to research question

After answering the research sub-questions, the main research question is discussed. The research question for this project was defined as:

"What is the effect of using a decision support system on the personal efficiency and productivity of decision-making processes, in environments characterized by time pressure, uncertainty, and dynamism?"

Firstly, the model results outline that in situations characterized by time pressure, uncertainty, and dynamism, the use of a DSS does not always have the effect of making the process faster. This research indeed highlights that the use of a DSS can lead to longer decision-making processes, which is not desirable in contexts of time pressure. This largely depends on how the DSS is implemented, especially in relation to the level of expertise of the decision-makers and the time it would take for them to make a decision without a system. On the other hand, the DSS does have a positive effect on the process, by assisting the decision-makers who lack experience with the activities and processes at stake, and thus either would require a long time to make a decision, or would not be able to make a high-quality decision at all without the assistance of the system. Furthermore, in dynamic settings, when the changes in the environment lead to increased time pressure and complexity of the decision, the DSS can be very helpful and lead to improved performance.

Moreover, the results highlight that time is a very critical factor in these contexts and is far more relevant than the level of transparency of the information displayed. The DSS is more frequently employed when it takes less time for the decision-makers to gather and evaluate the information provided by it. This also suggests that it might be better to reduce the run length of the algorithm and to quicker display the information rather than to invest in showing more information to increase transparency. It is important to determine the trade-off between a sufficient level of transparency of the information and the time needed to gather it, and to consider this aspect while designing the system. Given the uncertainty and dynamism of these environments, the DSS does not always result to provide optimal support, and for this reason, flexibility is a very important property for such systems. Moreover, it is to be determined what the level of cognitive differentiation of the practitioners is, to avoid overwhelming the actors with too much information and minimize the time needed to process it, while still providing all the necessary insights.

Lastly, this research outlines that it might be worth it to include the practitioners in the design of the DSS and start building their perception of the system before they actually start using it. When all the actors, or the majority of them, trust the system, the discussion time is reduced and the decision-makers define a strategy quicker. Especially in contexts of public organizations, where, as Heikkila and Isett (2004) underline, discussions commonly take place between the practitioners to ensure that everybody agrees with the operational decisions, using a system the actors trust has the potential to largely reduce the discussions and thus the decision-making time. This could only lead to higher perceived usefulness and perceived ease of use, but also to smoother decision-making processes. Nevertheless, it appears from the results that the way the system is implemented (and especially the time it takes to run) plays a more important role in the decision on whether to employ the DSS compared to actors' past experience with it, especially for those who work in direct contact with the system.

10.3. Societal contribution

This research investigates the effect of using decision support systems in contexts characterized by time pressure, uncertainty, and dynamism, with a specific focus on the case study of the Dutch National Police. The results highlight that a DSS can assist decision-makers in these contexts, especially those lacking experience with the procedures at stake. However, for the DSS to provide support also to more experienced and faster decision-makers, the system is to be implemented in a way that it does not take too much time for the users to gain and process the information coming from the system. A trade-off between the run length of the algorithm and the accuracy of the results is to be determined in each specific case, to avoid deep increases in the decision-making process time. This research indeed highlights that the use of a DSS can lead to longer decision-making processes, which is not desirable in contexts of time pressure. Given the uncertainty and dynamism of these environments, the DSS does not always result to provide optimal support, and for this reason, flexibility is a very important property for such systems. For instance, while it is important to guarantee transparency, it is also important to take into consideration the level of cognitive differentiation of the user group. Moreover, the results show that having some past experience or training with the system can lead to quicker decision-making processes since it reduces the discussions between the actors, which are an inherent characteristic of decision-making processes in public organizations.

These insights can not only support the implementation of the DSS considered in the case study but also the one of all DSS employed in similar contexts, especially given the lack of knowledge on the effect of using DSS in these environments.

10.4. Scientific contribution

As mentioned in Section 3.4, the research on the effect of employing DSS in contexts of time pressure, uncertainty, and dynamism is still very limited. While many case studies have been carried out to investigate the effect of using a DSS in strategic long-term decision-making processes, there are not many studies focusing on operational decision-making processes. The results of this research support the advancement of this research field.

This study highlights that, also in operational decision-making processes, and more specifically in situations of time pressure, uncertainty, and dynamism (as emergency situations), the employment of a DSS can lead to an increase in the decision-making time. This is primarily due to the additional information the practitioners have to process when the DSS is in place. Depending on the way the system is implemented, this increase can be more or less evident. Thus, specific attention is to be paid to this aspect, given the fact that these processes are usually especially time-sensitive. Moreover, contrarily to what is commonly visible in strategic decision-making, the past experience of the actors with the systems is not as relevant as the time needed to gather and process information from it. This is especially true for the actors who work in direct contact with the system, highlighting the importance to analyze the context where such a system is employed, to understand how the system should be implemented, and identify the proper trade-off between a short run length and a sufficient level of detail of the information displayed. Additionally, this research contributes to understanding the role of DSS in dynamic decision-making processes. The results indeed underline that, when the changes in the environment lead to increased time pressure and complexity of the decision, the DSS can be very helpful and lead to improved performances. Furthermore, this study provides some insights into the research area focusing on the DSS design. The model results highlight that in rapid decision-making processes, providing the users with much information to guarantee a high level of transparency is not completely necessary. On the other hand, it is important to guarantee flexibility in the design and investigate the average level of cognitive differentiation of the user base.

Finally, this research shows how a simulation model, structured as an agent-based model, can be employed to explore the behavior of decision-makers and their interactions between each other and with the decision support system. An exploratory agent-based model can be implemented to support the investigation of the effects of using the DSS, and of different implementations of the system, in operational contexts. Making use of this approach makes it possible not only to model the behavior of the actors involved but also to understand what policies can better support the inclusion of a decision support system in a process where no such system was present beforehand.

10.5. Recommendations for future research

While conducting this study, several topics were identified that could be addressed in further research.

First, more research is needed on the decision-making processes taking place in environments characterized by time pressure, uncertainty, and dynamism. The behavior of users and their attitude towards DSSs in such contexts is not very clear. Thus, more knowledge is needed on the attributes influencing the perceived ease of use and the perceived usefulness of a decision support system. Moreover, more knowledge is needed in general on the attributes influencing the adoption of a new technology and the correlation between these attributes and the adoption of the technology itself.

Secondly, in order to better evaluate the role that a DSS has in contexts of time pressure, uncertainty, and dynamism, further research is needed that focuses on the decision-making process outcomes and on whether the DSS leads to an improvement in the quality of the outcomes. This means that an investigation is to be carried out that focuses on what the decision of the dispatchers and police officers is based on and the factors or changes in the environment that influence these decisions. Moreover, knowledge is needed on the behavior of the fugitives, so that, by also modeling the environment and the content of the decisions of the agents (the strategies implemented), it is possible to evaluate not only whether the use of the DSS improves the decision-making time, but also whether it improves the quality of the decisions. This can be evaluated by investigating how often the fugitives are actually intercepted, without and with the system. As an alternative, if knowledge cannot be gathered on what the decision of the dispatchers and police officers is based on and the factors or changes in the environment that influence these decisions, a simulation game with the practitioners could be implemented. More knowledge of the behavior of the fugitives is however paramount to conducting this analysis.

Finally, the model can be extended to determine the effect of the DSS over time, the direct effect of positive or negative experiences with the system over time, and how those affect the personal efficiency and productivity of the actors. This study focuses on the effect of using the DSS in the first stages of its implementation. However, it might be interesting to evaluate whether the behavior of the agents changes over time.

10.6. Recommendations for design

As previously mentioned, this research highlighted that the time needed to gather and evaluate information coming from the decision support system is a factor that not only influences the rate of adoption of the system, but also the duration of the decision-making process. For this reason, it is advised to work towards the minimization of the run length of the DSS algorithm. In the considered case study, 30 seconds can be considered an adequate run time.

Moreover, as the results highlighted, with regards to the information to be displayed, it is suggested to include the information on the optimal position of the units. This information is especially important because it minimizes the time needed to process the information provided by the DSS, thus better supporting the decision-makers. It is also suggested to further investigate the level of cognitive differentiation of the practitioners, to determine whether it is the case to include information on the escape routes and associated probabilities. One possible flexible strategy can be to provide the dispatchers uniquely with the information on the optimal positions as a standard setting while including an option to visualize the information on the routes and associated probabilities in case of need.

Lastly, it is advised to include the dispatchers and police officers in the design of the system or to organize training with it. It is important for the users not only to know the system so that it is easier to use but also to know how it works to build their trust in it. The results of this study indeed highlighted that increasing the trust in the system can minimize the discussions, thus leading to more efficient, faster decision-making processes.

Bibliography

Alavi, M., & Joachimsthaler, E. A. (1992). Revisiting dss implementation research: A meta-analysis of the literature and suggestions for researchers. *MIS quarterly*, 95–116.

Al-Rahmi, A. M., Ramin, A. K., Alamri, M. M., Al-Rahmi, W. M., Yahaya, N., Abualrejal, H., & Al-Maatouk, Q. (2019). Evaluating the intended use of decision support system (dss) via academic staff: An applying technology acceptance model (tam). *Int. J. Recent Technol. Eng*, *8*, 268–275.

Alshenqeeti, H. (2014). Interviewing as a data collection method: A critical review. *English linguistics research*, *3*(1), 39–45.

Angehrn, A. A., & Jelassi, T. (1994). Dss research and practice in perspective. *Decision Support Systems*, *12*(4-5), 267–275.

Bennett, A. (2004). Case study methods: Design, use, and comparative advantages. *Models, numbers, and cases: Methods for studying international relations*, 19–55.

Bharati, P., & Chaudhury, A. (2004). An empirical investigation of decision-making satisfaction in web-based decision support systems. *Decision support systems*, *37*(2), 187–197.

Bohanec, M. (2009). Decision making: A computer-science and information-technology viewpoint. *Interdisciplinary Description of Complex Systems: INDECS*, *7*(2), 22–37.

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the national academy of sciences*, *99*(suppl 3), 7280–7287.

Boyle, R., & Bonacich, P. (1970). The development of trust and mistrust in mixed-motive games. *Sociometry*, 123–139.

Carlsson, S. A., Skog, L.-M., & Tona, O. (2010). An is success evaluation of a dss in a police organization. *DSS*, 443–454.

Carver, L., & Turoff, M. (2007). Human-computer interaction: The human and computer as a team in emergency management information systems. *Communications of the ACM*, *50*(3), 33–38.

Chai, N. (2009). *Sustainability performance evaluation system in government: A balanced scorecard approach towards sustainable development*. Springer Science & Business Media.

Chan, S. H., Song, Q., Sarker, S., & Plumlee, R. D. (2017). Decision support system (dss) use and decision performance: Dss motivation and its antecedents. *Information & Management*, *54*(7), 934–947.

CityGIS. (2022). *New technologies for public safety*. Retrieved April 8, 2022, from https://www.citygis.nl/en/

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: A comparison of two theoretical models. *Management science*, *35*(8), 982–1003.

Dean Jr, J. W., & Sharfman, M. P. (1993). The relationship between procedural rationality and political behavior in strategic decision making. *Decision sciences*, *24*(6), 1069–1083.

Diana, M. (2014). Measuring performance in the public sector: Between necessity and difficulty. *Studies in Business & Economics*, *9*(2).

Djamasbi, S., Strong, D. M., & Dishaw, M. (2010). Affect and acceptance: Examining the effects of positive mood on the technology acceptance model. *Decision Support Systems*, *48*(2), 383–394.

Doney, P. M., & Cannon, J. P. (1997). An examination of the nature of trust in buyer–seller relationships. *Journal of marketing*, *61*(2), 35–51.

Dulcic, Z., Pavlic, D., & Silic, I. (2012). Evaluating the intended use of decision support system (dss) by applying technology acceptance model (tam) in business organizations in croatia. *Procedia-Social and Behavioral Sciences*, *58*, 1565–1575.

Fogli, D., & Guida, G. (2013). Knowledge-centered design of decision support systems for emergency management. *Decision Support Systems*, *55*(1), 336–347.

Forgionne, G. A. (1999). An ahp model of dss effectiveness. *European Journal of Information Systems*, *8*(2), 95–106.

Forgionne, G. A. (2000). Decision-making support system effectiveness: The process to outcome link. *Information Knowledge Systems Management*, *2*(2), 169–188.

Gönül, M. S., Önkal, D., & Lawrence, M. (2006). The effects of structural characteristics of explanations on use of a dss. *Decision support systems*, *42*(3), 1481–1493.

Government of Netherlands. (n.d.). *Organisation of the dutch police*. Retrieved April 8, 2022, from https://www.government.nl/topics/police/organisation-of-the-dutch-police

Heikkila, T., & Isett, K. R. (2004). Modeling operational decision making in public organizations: An integration of two institutional theories. *The American Review of Public Administration*, *34*(1), 3–19.

Hu, Y., Wang, D., Pang, K., Xu, G., & Guo, J. (2015). The effect of emotion and time pressure on risk decision-making. *Journal of Risk Research*, *18*(5), 637–650.

Hwang, M. I. (1994). Decision making under time pressure: A model for information systems research. *Information & Management*, *27*(4), 197–203.

Kamel, S. (2001). Using dss for crisis management. *Pitfalls and triumphs of information technology management* (pp. 292–304). IGI Global.

Keen, P. G. (1980). Decision support systems: A research perspective. *Decision support systems: Issues and challenges: Proceedings of an international task force meeting*, 23–44.

Kilkenny, M. F., & Robinson, K. M. (2018). Data quality:“garbage in–garbage out”.

Kim, J., Jin, B., & Swinney, J. L. (2009). The role of etail quality, e-satisfaction and e-trust in online loyalty development process. *Journal of retailing and Consumer services*, *16*(4), 239–247.

Kleijnen, J. P. (1995). Verification and validation of simulation models. *European journal of operational research*, *82*(1), 145–162.

Klein, G. A. (1993). A recognition-primed decision (rpd) model of rapid decision making. *Decision making in action: Models and methods*, *5*(4), 138–147.

Kowalski-Trakofler, K., Vaught, C., & Scharf, T. (2003). Judgment and decision making under stress: An overview for emergency managers. *International Journal of Emergency Management*, *1*(3), 278–289.

Kumar, R. L. (1999). Understanding dss value: An options perspective. *Omega*, *27*(3), 295–304.

Kwakkel, J. H. (2017). The exploratory modeling workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software*, *96*, 239–250.

Kwakkel, J. H., & van der Pas, J. W. G. (2011). Evaluation of infrastructure planning approaches: An analogy with medicine. *Futures*, *43*(9), 934–946.

Law, A., & Kelton, D. (1991). System, models, and simulation. *Simulation modeling & analysis*, 3–7.

Lawrence, M., Goodwin, P., & Fildes, R. (2002). Influence of user participation on dss use and decision accuracy. *Omega*, *30*(5), 381–392.

Lawrence, M., & Sim, W. (1999). Prototyping a financial dss. *Omega*, *27*(4), 445–450.

Le Blanc, L. A., & Kozar, K. A. (1990). An empirical investigation of the relationship between dss usage and system performance: A case study of a navigation support system. *MiS Quarterly*, 263–277.

Lei, Z., Shouju, R., & Zuzhao, L. (2000). Self-organization based dss framework. *Smc 2000 conference proceedings. 2000 ieee international conference on systems, man and cybernetics.'cybernetics evolving to systems, humans, organizations, and their complex interactions'(cat. no. 0*, *1*, 609–614.

Lipshitz, R., & Bar-Ilan, O. (1996). How problems are solved: Reconsidering the phase theorem. *Organizational Behavior and Human Decision Processes*, *65*(1), 48–60.

Loriette, S., Matta, N., Sediri, M., & Hugerot, A. (2019). Crisis clever system (ccs)–tracking experience of crisis management for decision support. *AI EDAM*, *33*(2), 188–205.

Lu, H.-P., Yu, H.-J., & Lu, S. S. (2001). The effects of cognitive style and model type on dss acceptance: An empirical study. *European journal of operational research*, *131*(3), 649–663.

Mohr, L. B. (1982). *The reliability of the case study as a source of information*. Institute of Public Policy Studies, University of Michigan.

Moore, M. H., & Braga, A. A. (2003). Measuring and improving police performance: The lessons of compstat and its progeny. *Policing: an international journal of police strategies & management*.

Neely, A. D., Adams, C., & Kennerley, M. (2002). *The performance prism: The scorecard for measuring and managing business success*. Prentice Hall Financial Times London.

Overheid.nl. (2022). *Nwb - wegen*. Retrieved April 6, 2022, from https://data.overheid.nl/en/dataset/14767-nwb---wegen

Perry, N. C., Wiggins, M. W., Childs, M., & Fogarty, G. (2012). Can reduced processing decision support interfaces improve the decision-making of less-experienced incident commanders? *Decision Support Systems*, *52*(2), 497–504.

Phillips-Wren, G., & Adya, M. (2020). Decision making under stress: The role of information overload, time pressure, complexity, and uncertainty. *Journal of Decision Systems*, 1–13.

Phillips-Wren, G., Jefferson, T., & McKniff, S. (2019). Cognitive bias and decision aid use under stressful conditions. *Journal of Decision Systems*, *28*(2), 162–184.

Prietula, M. J., Carley, K. M., & Gasser, L. (1998). *Simulating organizations: Computational models of institutions and groups*. Mit Press.

Project Mesa Team, A. (2016). *Mesa: Agent-based modeling in python3+*. Retrieved December 16, 2021, from https://mesa.readthedocs.io/en/master/#

Raghunathan, S. (1999). Impact of information quality and decision-maker quality on decision quality: A theoretical model and simulation analysis. *Decision support systems*, *26*(4), 275–286.

Rieger, T., & Manzey, D. (2020). Human performance consequences of automated decision aids: The impact of time pressure. *Human factors*, 0018720820965019.

Rigopoulos, G., Psarras, J., & Askounis, D. (2008). A tam model to evaluate user's attitude towards adoption of decision support systems. *Journal of applied sciences*, *8*(5), 899–902.

Salanova, M., Peiró, J. M., & Schaufeli, W. B. (2002). Self-efficacy specificity and burnout among information technology workers: An extension of the job demand-control model. *European journal of work and organizational psychology*, *11*(1), 1–25.

Saltelli, A. (2002). Sensitivity analysis for importance assessment. *Risk analysis*, *22*(3), 579–590.

Sargent, R. G. (1984). A tutorial on verification and validation of simulation models.

Savolainen, R., & Kari, J. (2006). User-defined relevance criteria in web searching. *Journal of Documentation*.

Scott-Morton, M. S., & Keen, P. G. (1978). Decision support systems: An organizational perspective. *Reading: Addison-Wesley*.

Sealy, W. I., & Feigh, K. M. (2020). Information modification for time-limited decision making. *2020 IEEE International Conference on Human-Machine Systems (ICHMS)*, 1–6.

Sharda, R., Barr, S. H., & McDonnell, J. C. (1988). Decision support system effectiveness: A review and an empirical test. *Management science*, *34*(2), 139–159.

Shibl, R., Lawley, M., & Debuse, J. (2013). Factors influencing decision support system acceptance. *Decision Support Systems*, *54*(2), 953–961.

Skinner, G., & Parrey, B. (2019). A literature review on effects of time pressure on decision making in a cyber security context. *Journal of Physics: Conference Series*, *1195*(1), 012014.

Speier-Pero, C. (2019). Using aggregated data under time pressure: A mechanism for coping with information overload. *Journal of Decision Systems*, *28*(2), 82–100.

Steiner, C., Nussbaumer, A., & Albert, D. (2015). A psychological framework modelling decision making in emergencies. *The European Conference on Information Systems Management*, 206.

Tang, J., Gao, H., Liu, H., & Das Sarma, A. (2012). Etrust: Understanding trust evolution in an online world. *Proceedings of the 18th ACM SIGKDD international conference on Knowledge discovery and data mining*, 253–261.

Thompson, S. M., Altay, N., Green III, W. G., & Lapetina, J. (2006). Improving disaster response efforts with decision support systems. *International Journal of Emergency Management*, *3*(4), 250.

Tsang, E. W. (2014). Generalizing from research findings: The merits of case studies. *International Journal of Management Reviews*, *16*(4), 369–383.

Van Dam, K. H., Nikolic, I., & Lukszo, Z. (2012). *Agent-based modelling of socio-technical systems* (Vol. 9). Springer Science & Business Media.

Van Rossum, G., & Drake, F. L. (2009). *Python 3 reference manual*. CreateSpace.

Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. *Management science*, *46*(2), 186–204.

Wilensky, U., & Rand, W. (2015). *An introduction to agent-based modeling: Modeling natural, social, and engineered complex systems with netlogo*. Mit Press.

Zarate, P. (1991). The process of designing a dss: A case study in planning management. *European journal of operational research*, *55*(3), 394–402.

Zinkhan, G. M., Joachimsthaler, E. A., & Kinnear, T. C. (1987). Individual differences and marketing decision support system usage and satisfaction. *Journal of Marketing Research*, *24*(2), 208–214.

A

Literature review approach

The literature research is conducted through two different databases (Scopus and Web of Science), making use of the following keywords: “decision making”, “time pressure”, “DSS”, “uncertainty”, “complexity”. Then, various rounds of backward snowballing are employed. The articles have been selected based on their relevance for this research. Figure A.1 shows the selection process.

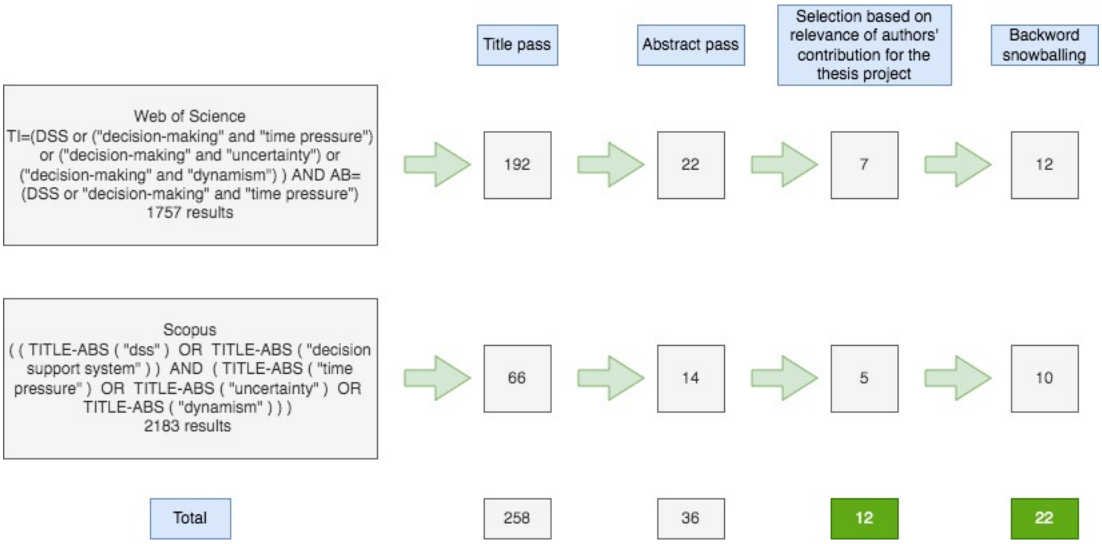


Figure A.1: The selection process.

Based on the selection criteria shown in Figure A.1, 34 papers have been chosen, 12 of which are obtained from the databases research and 22 from the subsequent backward snowballing. The selected literature is listed in Table A.1, where also the main contributions of each paper are specified.

Author(s)	**Year of publication**	**Main contribution(s)**
Alavi and Joachimsthaler	1992	Factors influencing the adoption of a new technology
Al-Rahmi et al.	2019	TAM and DSSs
Bohanec	2009	Decision-making
Boyle and Bonacich	1970	Factors influencing the adoption of a new technology
Carver and Turoff	2007	The role of DSSs in situations with time pressure, uncertainty and dynamism

Davis et al.	1989	TAM and DSSs; Factors influencing the adoption of a new technology
Doney and Cannon	1997	Factors influencing the adoption of a new technology
Dulcic et al.	2012	TAM and DSSs
Fogli and Guida	2013	The role of DSSs in situations with time pressure, uncertainty and dynamism
Forgionne	1999	DSSs; Decision-making; Decision-making under time pressure, uncertainty and dynamism; The role of DSSs in situations with time pressure, uncertainty and dynamism
Forgionne	2000	DSSs
Heikkila and Isett	2004	Institutional Model of Operational-Level Decision Making
Hu et al.	2015	Decision-making under time pressure, uncertainty and dynamism
Hwang	1994	Decision-making under time pressure, uncertainty and dynamism; The role of DSSs in situations with time pressure, uncertainty and dynamism
Keen	1980	DSSs
Kim et al.	2009	Factors influencing the adoption of a new technology
Klein	1993	RPD
Kowalski-Trakofler et al.	2003	Decision-making under time pressure, uncertainty and dynamism
Kumar	1999	DSSs
Lei et al.	2000	Decision-making; DSSs
Loriette et al.	2019	The role of DSSs in situations with time pressure, uncertainty and dynamism
Lu et al.	2001	TAM and DSSs
Phillips-Wren and Adya	2020	Decision making under time pressure, uncertainty and dynamism; The role of DSSs in situations with time pressure, uncertainty and dynamism
Phillips-Wren et al.	2019	The role of DSSs in situations with time pressure, uncertainty and dynamism
Rieger and Manzey	2020	Decision-making under time pressure, uncertainty and dynamism; The role of DSSs in situations with time pressure, uncertainty and dynamism
Rigopoulos et al.	2008	TAM and DSSs
Scott-Morton and Keen	1978	DSSs
Sealy and Feigh	2020	The role of DSSs in situations with time pressure, uncertainty and dynamism
Shibl et al.	2013	Factors influencing the adoption of a new technology
Skinner and Parrey	2019	Decision-making; DSSs; Decision-making under time pressure, uncertainty and dynamism; The role of DSS in situations with time pressure, uncertainty and dynamism
Speier-Pero	2019	Decision-making under time pressure, uncertainty and dynamism
Steiner et al.	2015	The role of DSSs in situations with time pressure, uncertainty and dynamism; TAM and DSS
Venkatesh and Davis	2000	TAM and DSSs; Factors influencing the adoption of a new technology
Zinkhan et al.	1987	Factors influencing the adoption of a new technology

Table A.1: Overview of selected literature.

B

Factors influencing the adoption of a new technology

Factor	References
Perceived usefulness	Davis et al. (1989) and Shibl et al. (2013)
Perceived ease of use	Davis et al. (1989) and Shibl et al. (2013)
Output quality	Venkatesh and Davis (2000)
Experience with the system	Alavi and Joachimsthaler (1992), Shibl et al. (2013), Venkatesh and Davis (2000), and Zinkhan et al. (1987)
Experience with the procedures	Alavi and Joachimsthaler (1992), Shibl et al. (2013), and Zinkhan et al. (1987)
Training	Alavi and Joachimsthaler (1992) and Shibl et al. (2013)
User involvement in the design	Alavi and Joachimsthaler (1992) and Shibl et al. (2013)
Personal involvement and interest in the system	Zinkhan et al. (1987)
Cognitive differentiation	Zinkhan et al. (1987)
Risk aversion	Alavi and Joachimsthaler (1992) and Zinkhan et al. (1987)
Reputation of the system	Doney and Cannon (1997)
Past interactions with the system	Boyle and Bonacich (1970)
Interface design	Kim et al. (2009)

Table B.1: Overview of factors influencing the acceptance of a new technology.

C
Agents' attributes

Attribute	Description	Type	Influenced by	Values
experience_ procedures	Level of experience with the procedures	Float	Random from normal distribution (avg 0.5)	[0,1]
areas_known	The areas that the dispatcher knows	List	Random for each area, based on probability_knowledge_ areas [Assumption C1]	[a], [a, b], [a, c, d, e], [b, e], etc.
role	The role the dispatcher has	String	One to each of the two dispatchers initialized.	"radio", "phone"
percentage_ positive_ experience_ DSS	% positive past experience with the system (in the output)	Float	Random	[0,1]
percentage_ positive_ experience_ DSS_peers	Reputation of the system (% positive experience that the peers had with the system)	Float	Random	[0,1]
user_personal_ involvement	User personal involvement (interest) in the DSS	Float	Random	[0,1]
perceived_ output_quality	The extent to which the dispatcher perceives the output of the DSS as accurate.	Float	0.4*percentage_ positive_ experience_ DSS_peers + 0.2*percentage_ positive_ experience_DSS + 0.4 * user_ personal_ involvement	[0,1]
risk_aversion	The extent to which the dispatcher is willing to take risks (0: high; 1: low).	Float	Random from normal distribution (average 0.6)	[0,1]
cognitive_ differentiation	The ability of the dispatcher to consider multiple concepts when making a decision	Float	Random from normal distribution (average 0.5) + experience_procedures/4	[0,1]
training_with_ DSS	The extent to which the dispatcher was trained to use the DSS	Float	Random between 0, 0.5 and 1.	0, 0.5, 1

involvement_in_DSS_design	The extent to which the dispatcher was involved in the design of the DSS	Float	Random between 0, 0.5 and 1.	0, 0.5, 1
experience_DSS	The level of experience with the DSS	Float	Random(0, 0.5) + 0.25*training_with_dss + 0.25*involvement_in_DSS_design	[0,1]
perceived_ intuitive_ design	The extent to which the dispatcher finds the design of the DSS intuitive	Float	Random(0, 0.4) + 0.1*training_with_dss + 0.1*involvement_in_DSS_design + 0.4*experience_DSS	[0,1]
perceived_ease _of_use	The extent to which the dispatcher finds the system easy to use	Float	0.1*involvement_in _DSS_design + 0.1*training_with_dss + 0.3*experience_DSS + 0.2*perceived_intuitive _design + 0.2*experience_procedures + 0.1*cognitive_differentiation	[0,1]
perceived_ usefulness	The extent to which the dispatcher finds the system useful	Float	0.5*perceived_output_quality + 0.1*risk_aversion + 0.1*cognitive_differentiation + 0.3*perceived_ease_of_use	[0,1]
authority	The level of authority they have with police officers	Float	Random(0,0.5) + 0.5*experience_procedures	[0,1]

Table C.1: Dispatchers' attributes.

Attribute	Description	Type	Influenced by	Values
experience_ procedures	Level of experience with the procedures	Float	Random from normal distribution (avg 0.7) [Assumption A3]	[0,1]
percentage_ positive_ experience_DSS	% positive past experience with the system (in the output)	Float	Random	[0,1]
percentage_ positive_ experience_ DSS_peers	Reputation of the system (% positive experience that the peers had with the system)	Float	Random	[0,1]
user_ personal_ involvement	User personal involvement (interest) in the DSS	Float	Random	[0,1]
perceived_ output_ quality	The extent to which the dispatcher perceives the output of the DSS as accurate.	Float	0.4*percentage_ positive_experience_ DSS_peers + 0.2*percentage_ positive_experience _DSS + 0.4 * user_ personal_ involvement	[0,1]
training_with _DSS	The extent to which the dispatcher was trained to use the DSS	Float	Random between 0, 0.5 and 1.	0, 0.5, 1
involvement_in_ DSS_design	The extent to which the dispatcher was involved in the design of the DSS	Float	Random between 0, 0.5 and 1.	0, 0.5, 1
experience_DSS	The level of experience with the DSS	Float	Random(0, 0.5) + 0.25*training_with_dss + 0.25*involvement_in_DSS_ design	[0,1]
perceived_ease _of_use	The extent to which the dispatcher finds the system easy to use	Float	0.2*involvement _in_DSS_design + 0.2*experience_DSS + 0.2*training_with_DSS + 0.4*experience_procedures	[0,1]
perceived_ usefulness	The extent to which the dispatcher finds the system useful	Float	0.7*perceived_ output_quality + 0.3 * perceived_ ease_of_use	[0,1]
attitude_towards _dispatchers	The attitude they have towards dispatchers, being 1 very bad and 0 very good.	Float	Random(0,0.5) + 0.5*experience_ procedures	[0,1]

Table C.2: Officers' attributes.

D
Verification

D.1. Tick test

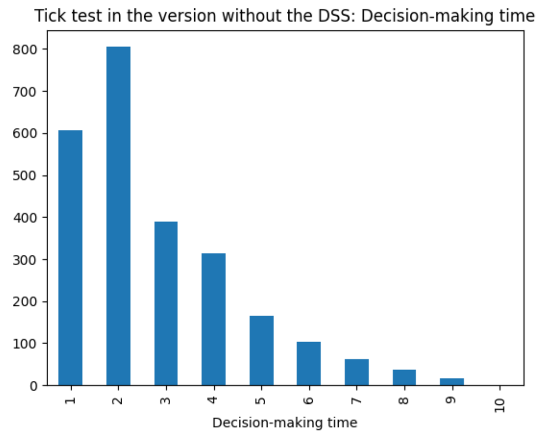


Figure D.1: Tick test for the version without the DSS.

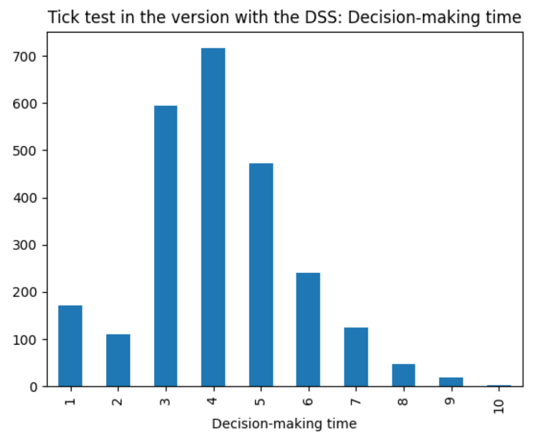


Figure D.2: Tick test for the version with the DSS.

D.2. Reproducibility and variability tests

The reproducibility and variability tests are meant to verify that the simulation provides the same results with the same seeds and different results with different seeds. To run these tests, the model is implemented in a separated version where seeds are specified. Both tests are run in both versions of the model, with and without the DSS. In the reproducibility test, the same seed is employed fifteen times and the results highlight that the same results are visible in all of the runs, for all outcomes. The results of the reproducibility test can be found in Tables D.1 and D.2.

On the other hand, in the variability test, three different seeds are used, each of them fifteen times, to verify that different outcomes are obtained when varying the seed. The results show that varying the seed, the decision-making time and the communication time vary accordingly to the seed employed. In the version with the DSS, also the rates of adoption of the DSS by the dispatchers and the police officers vary according to the seed. The results of the variability test can be found in Tables D.3 and D.4.

Decision-making time	**Communication time**	**Seed**
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0

Table D.1: Results of the reproducibility test in the version without the DSS.

Decision-making time	**Communication time**	**DSS adoption**	**Officers DSS adoption**	**Seed**
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0

Table D.2: Results of the reproducibility test in the version with the DSS.

Decision-making time	**Communication time**	**Seed**
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	5	0
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	1
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2
1	1	2

Table D.3: Results of the variability test in the version without the DSS.

Decision-making time	Communication time	DSS adoption	Officers DSS adoption	Seed
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	5	1	0.75	0
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	1
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2
3	1	1	1	2

Table D.4: Results of the variability test in the version with the DSS.

D.3. Sensitivity analysis

The sensitivity analysis is conducted by making use of the EMA workbench library in Python, which supports exploratory modeling. This library can be utilized to ”develop interfaces to existing simulation models, define computational experiments to conduct with those models, analyze the results of these experiments, and store the results” (Kwakkel, 2017).

The analysis includes one hundred experiments, each of which is repeated one thousand times. In this study, the input values for each experiment are defined by changing the default values of the input parameters making use of Latin Hypercube Sampling (LHS), which ensures uniform sampling across the uncertainty ranges for each of the input parameters. Table D.5 provides an overview of the applied uncertainty ranges in this investigation.

Parameter	**Ranges**	**Default value**
weight_area_component_probability_DSS_use	0.1, 0.5	0.3
weight_percentage_positive_experience_DSS_peers_perceived_output_quality	0.05, 0.4	0.2
weight_percentage_positive_experience_DSS_perceived_output_quality	0.05, 0.5	0.4
weight_involvement_in_DSS_design_experience_DSS	0.05, 0.4	0.25
weight_dispatchers_experience_procedures_cognitive_differentiation	0.05, 0.55	0.25
weight_dispatchers_involvement_in_DSS_design_perceived_intuitive_design	0, 0.3	0.1
weight_dispatchers_experience_DSS_perceived_intuitive_design	0.05, 0.5	0.4
weight_dispatchers_cognitive_differentiation_perceived_ease_of_use	0.05, 0.15	0.1
weight_dispatchers_experience_procedures_perceived_ease_of_use	0.05, 0.2	0.2
weight_dispatchers_perceived_intuitive_design_perceived_ease_of_use	0.05, 0.2	0.2
weight_dispatchers_experience_DSS_perceived_ease_of_use	0.05, 0.25	0.3
weight_dispatchers_involvement_in_DSS_design_perceived_ease_of_use	0.05, 0.1	0.1
weight_dispatchers_perceived_ease_of_use_perceived_usefulness	0.05, 0.4	0.3
weight_dispatchers_cognitive_differentiation_perceived_usefulness	0.05, 0.25	0.1
weight_dispatchers_risk_aversion_perceived_usefulness	0.05, 0.25	0.1
weight_dispatchers_experience_procedures_authority	0.3, 0.7	0.5
weight_officers_involvement_in_DSS_design_perceived_ease_of_use	0.05, 0.25	0.15
weight_officers_training_with_DSS_perceived_ease_of_use	0.05, 0.25	0.15
weight_officers_experience_procedures_perceived_ease_of_use	0.05, 0.5	0.4
weight_officers_perceived_output_quality_perceived_usefulness	0.5, 0.9	0.7
weight_officers_experience_procedures_attitude_towards_dispatchers	0.3, 0.7	0.5

Table D.5: Overview of the uncertainty ranges for each parameter.

A feature scoring analysis is conducted to evaluate the impact of the input parameters on the output ones and the results are shown in Figure D.3. As it is clear in the graph, among the parameters under analysis, a couple of them have an impact on some outputs that is higher than the others. These are the weight that the experience with the procedures of the officers has in the definition of their attitude towards dispatchers and the weight that the experience with the procedures of the officers has in the definition of their perceived ease of use. These two parameters especially have a high effect on the communication time.

The parameter with the highest impact on the decision-making time is the weight_area_component_probability_DSS_use parameter (0.073). The weights of the level of positive experience of the actors

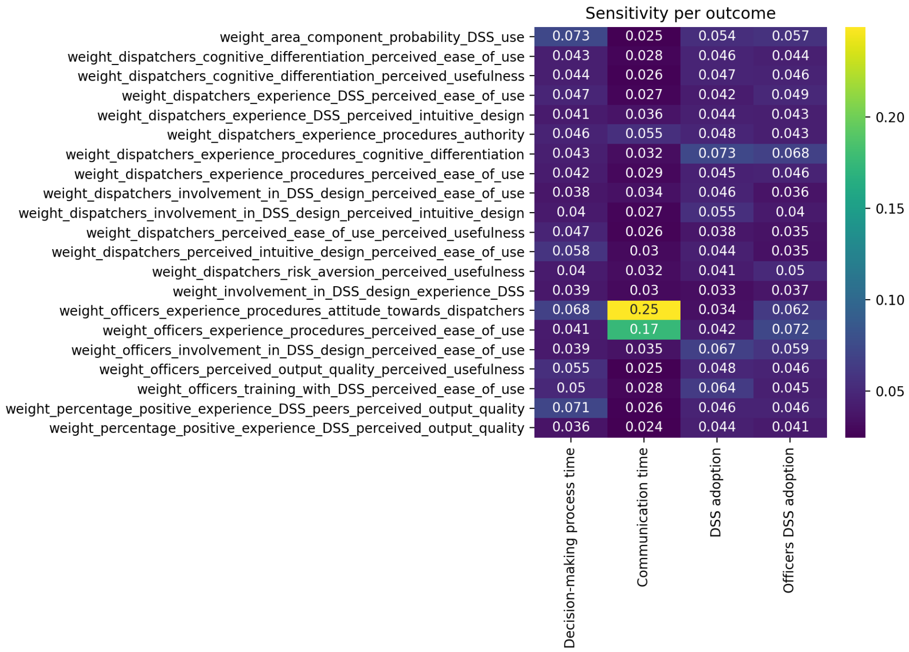


Figure D.3: Sensitivity analysis: correlation between input and output variables.

on their perceived output quality of the DSS and the weight that the experience with the procedures of the officers has in the definition of their attitude towards dispatchers have a secondary but still relevant correlation with the decision-making time (0.071 and 0.068 respectively).

On the other hand, the two parameters with the highest impact on the communication time are the weight of the experience with the procedures of the police officers in the definition of their attitude towards dispatchers and the weight of the experience with the procedures of the police officers in the definition of their perceived of use of the DSS (correlation = 0.25 and 0.17 respectively). These values have a very high correlation with this outcome compared to the other parameters, and thus it is important to take this into consideration while discussing the results. The parameter with the third highest correlation is the weight of the dispatchers' experience with the procedures on their level of authority with the officers (0.055).

With regards to the rate of adoption of the DSS by the dispatchers, it can be noticed that the input parameter with the highest impact is the weight of dispatchers' experience with the procedures on their cognitive differentiation (correlation = 0.073). The weight of the involvement of the officers in the design of the DSS in the definition of their perceived ease of use of the DSS and the weight of the level of officers' training with the system on their perceived ease of use follow closely (correlation = 0.067 and 0.064 respectively).

Finally, with regards to the rate of adoption of the DSS solution by the officers, the weight of the experience with the procedures of the police officers in the definition of their perceived ease of use of the DSS is the parameter with the highest correlation (0.072). The weight of dispatchers' experience with the procedures on their cognitive differentiation and the weight that the experience with the procedures of the officers has in the definition of their attitude towards dispatchers, have the second and third highest correlations (0.068 and 0.062 respectively).

E

Experiments implementation

E.1. Base case: current procedures without DSS

In the base case, the procedures without the DSS are simulated. In the base case, no levers are defined, since none of the parameters or the attributes of the agents are controllable. By making use of the EMA workbench, 100 scenarios are defined based on the following uncertainties:

- Knowledge of the area of the crime of the radio dispatcher (Yes or No);
- Knowledge of the area of the crime of the phone dispatcher (Yes or No);
- Experience with the procedures of the radio dispatcher (varied from 0 to 1);
- Experience with the procedures of the phone dispatcher(varied from 0 to 1);
- Information scenario (either having all the information on the direction of the fugitive at the beginning and then getting no more, or getting this information afterward, sooner or later during the decision-making process, or having some information at the beginning and then getting, sooner or later, new information in contrast with the one gained in the beginning).

We chose these parameters chose because of their impact on the decision-making and communication processes. Each scenario is run over 1000 repetitions for them to be sufficiently generalizable. Since in this version of the model, the DSS is not used, the only outcomes collected are the average decision-making time over all the repetitions and the average communication time over all the repetitions.

E.2. Experiment 1: varying the run-length of the algorithm and the components of the DSS

The first experiment is set up so that the levers are the run length of the algorithm and the components of the DSS. Based on these levers, twelve policies are experimented, as shown in Table E.1.

Moreover, by making use of the EMA workbench, 100 scenarios are defined based on the following uncertainties:

- Knowledge of the area of the crime of the radio dispatcher (Yes or No);
- Knowledge of the area of the crime of the phone dispatcher (Yes or No);
- Experience with the procedures of the radio dispatcher (varied from 0 to 1);
- Experience with the procedures of the phone dispatcher(varied from 0 to 1);
- Past experience with the DSS of both dispatchers and police officers (varied from 0 to 0.5);
- Cognitive differentiation of the radio dispatcher (varied from 0 to 1);
- Cognitive differentiation of the phone dispatcher (varied from 0 to 1);

Policy	Run length	Components DSS
1	1	['routes']
2	1	['routes', 'probabilities']
3	1	['routes', 'probabilities', 'positions']
4	1	['positions']
5	2	['routes']
6	2	['routes', 'probabilities']
7	2	['routes', 'probabilities', 'positions']
8	2	['positions']
9	4	['routes']
10	4	['routes', 'probabilities']
11	4	['routes', 'probabilities', 'positions']
12	4	['positions']

Table E.1: Values of run length and DSS components for each policy.

- Information scenario (either having all the information on the direction of the fugitive at the beginning and then getting no more, or getting this information afterward, sooner or later during the decision-making process, or having some information at the beginning and then getting, sooner or later, new information in contrast with the one gained in the beginning).

We chose these parameters because of their effect not only on the definitions of the other properties of the agents but also on the decision-making process itself, since they play a role in the decision on whether to adopt the solution advised by the DSS.

As a result, 1200 experiments are run (12 policies * 100 scenarios). Each experiment is repeated 100 times to reach a proper level of generalization. For each experiment, the collected outputs are:

- The average decision-making time over all the repetitions positioning the units);
- The average communication time over all the repetitions;
- The average percentage of times the solution advised by the DSS is adopted by the dispatchers over all the repetitions;
- The average percentage of police officers that decide to apply the solution advised by the DSS over all the repetitions.

E.3. Experiment 2: varying the involvement of the agents in the design and training with the DSS and the percentage of positive past experiences with the system

The second experiment is set up similarly to the first one, but here, the level of involvement of the agents in the design of the DSS and of training to use the system and the percentage of positive past experiences with the system are considered as a lever. The inclusion_training parameter determines both the inclusion_in_DSS_design and the training_with_DSS parameters of the dispatchers and the police officers. This parameter is chosen as a lever because it is the only parameter that determines the perceived ease of use and perceived usefulness of the DSS and is controllable. The positive_experience parameter, on the other hand, determines both the percentage of positive past experience of the agents and of the agents' peers with the system. Thus, two levers are considered here, and a total of 9 policies are defined, as listed in Table E.2.

Similarly as in the first experiment, by making use of the EMA workbench, 100 scenarios are defined based on the following uncertainties:

- Knowledge of the area of the crime of the radio dispatcher (Yes or No);
- Knowledge of the area of the crime of the phone dispatcher (Yes or No);
- Experience with the procedures of the radio dispatcher (varied from 0 to 1);

Policy	Positive past experience	Involvement
1	0	0
2	0	0.5
3	0	1
4	0.5	0
5	0.5	0.5
6	0.5	1
7	1	0
8	1	0.5
9	1	1

Table E.2: Values of the involvement of the agents and the percentage of positive past experience with the DSS for each policy.

- Experience with the procedures of the phone dispatcher (varied from 0 to 1);
- Experience with the DSS of both dispatchers and police officers (varied from 0 to 0.5);
- Cognitive differentiation of the radio dispatcher (varied from 0 to 1);
- Cognitive differentiation of the phone dispatcher (varied from 0 to 1);
- Information scenario (either having all the information on the direction of the fugitive at the beginning and then getting no more, or getting this information afterward, sooner or later during the decision-making process, or having some information at the beginning and then getting, sooner or later, new information in contrast with the one gained in the beginning).

As a result, 900 experiments are run (9 policies * 100 scenarios). Each experiment is repeated 1000 times to reach a proper level of generalization. For each experiment, the same outputs as in the first experiment are collected.

In this experiment, as in all the following ones, the run length of the DSS algorithm is set as 2 (60 seconds) and the DSS shows all the possible components. the routes, the probabilities, and the optimal positions. This is considered the standard implementation of the DSS.

E.4. Experiment 3: investigating what happens if all the agents always trust the system

The third experiment is set up similarly to the previous ones, but here, no lever is defined. In this experiment, the agents behave as in the normal narrative but when they are evaluating whether to trust the system (and thus to apply the DSS solution), they do not actually make a choice but directly trust it.

The same uncertainties considered in the previous experiment are also implemented here. As a result, 100 experiments are run (1 policy * 100 scenarios). Each experiment is repeated 1000 times to reach a proper level of generalization. For each experiment, the same outcomes as in the previous experiments are collected.

E.5. Experiment 4: varying the matching_probability distribution

The fourth experiment is meant to understand the impact that using different distributions to define the matching_probability has on the outcomes. As a standard setting, this probability is varied based on a uniform distribution ranging between -0.1 and 0.1. However, this distribution is not defined based on empirical data and thus, this experimentation is meant to verify the impact that using different distributions has on the outcomes.

The experiment has one lever, which determines the distribution to experiment with, and four policies are consequently defined based on the four options for this lever:

- uniform distribution ranging between -0.1 and 0.1 (*uniform1*);
- uniform distribution ranging between -0.2 and 0.2 (*uniform2*);

- normal distribution with average = 0, standard deviation = 0.05, lower bound = -0.1 and upper bound = 0.1 (*normal1*);
- normal distribution with average = 0, standard deviation = 0.15, lower bound = -0.3 and upper bound = 0.3 (*normal2*).

The same uncertainties as the previous experiments are defined and as a result, 400 experiments are run (4 policy * 100 scenarios). Each experiment is repeated 1000 times to reach a proper level of generalization. For each experiment, the same outcomes as in the previous experiments are collected.

E.6. Experiment 5: varying the impact of the attitude of the officers towards the DSS on the probability of agreement between dispatchers and police officers

The fifth experiment is meant to understand the consequences of using different distributions in the definition of the impact of the attitude of the officers towards the DSS on the probability of agreement between dispatchers and police officers. In fact, as mentioned in Chapter 6, the probability of agreement varies based on the officers' perceived ease of use and perceived usefulness of the DSS. This variation is however not defined based on empirical data and thus, this experimentation is meant to verify the impact of using different distributions on the outcomes.

The experiment has one lever, which determines the distribution (variation) to experiment with, and three policies are consequently defined based on the three options for this lever:

- a variation of 5% and 10% (variation variable is equal to *0.1*);
- a variation of 10% and 20% (variation variable is equal to *0.2*);
- a variation of 25% and 50% (variation variable is equal to *0.5*).

The same uncertainties as the previous experiments are defined and as a result, 300 experiments are run (3 policy * 100 scenarios). Each experiment is repeated 1000 times to reach a proper level of generalization. For each experiment, the only outcomes collected are the communication time and the net rate of adoption of the DSS by the police officers, since the probability of agreement between dispatchers and police officers just impacts the second part of the procedures (the communication phase).

F

Results: base case

An analysis is conducted to identify the relation between the input and output parameters. Firstly, a feature scoring analysis shows that the experience of the dispatchers with the procedures has a higher correlation with the decision-making and communication time compared to their knowledge of the area, as shown in Figure F.1. The information scenario has, anyways, the strongest correlation with the outcomes (0.069 and 0.066).

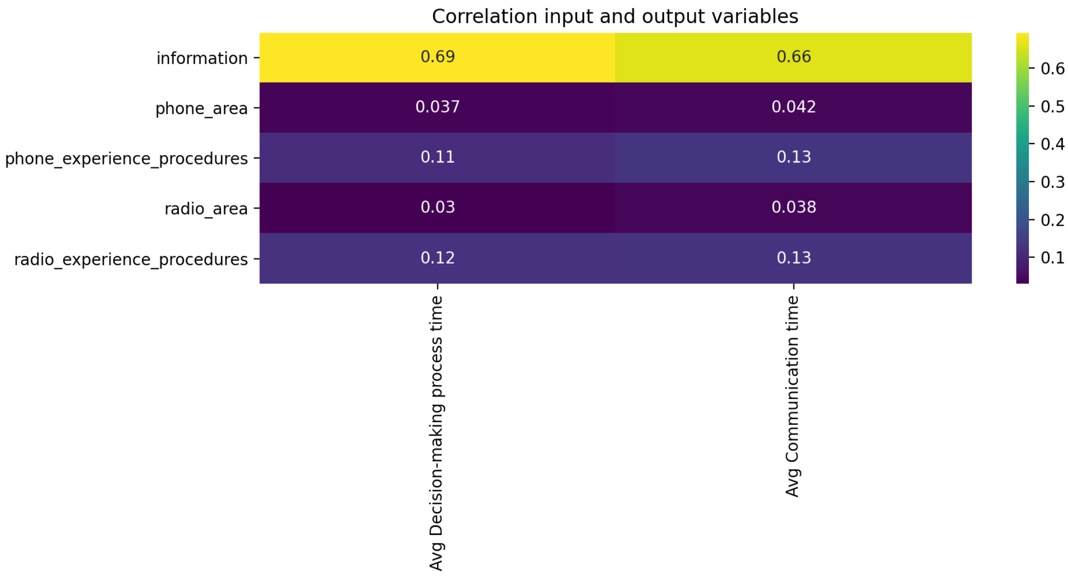


Figure F.1: Correlation between input and output parameters in the Base Case, based on the different information scenarios.

To further investigate the correlation between the input and output parameters, the relations between the decision-making time and the experience of the two dispatchers are more carefully investigated. In Figure F.2 the results are shown. While a direct correlation is not visible, these graphs clearly underline that, for each scenario, either the average decision-making time is around 2 ticks, or 3.5 or 4. Given the results shown in Figures 7.3 and F.1, it is clear that the decision-making time is highly influenced by the information scenario.

Finally, the relation between the decision-making time and the communication time is investigated. Also in this case, there does not seem to be any direct relation between the two parameters, as highlighted in Figure F.3. On the other hand, the influence of the information scenario is evident.

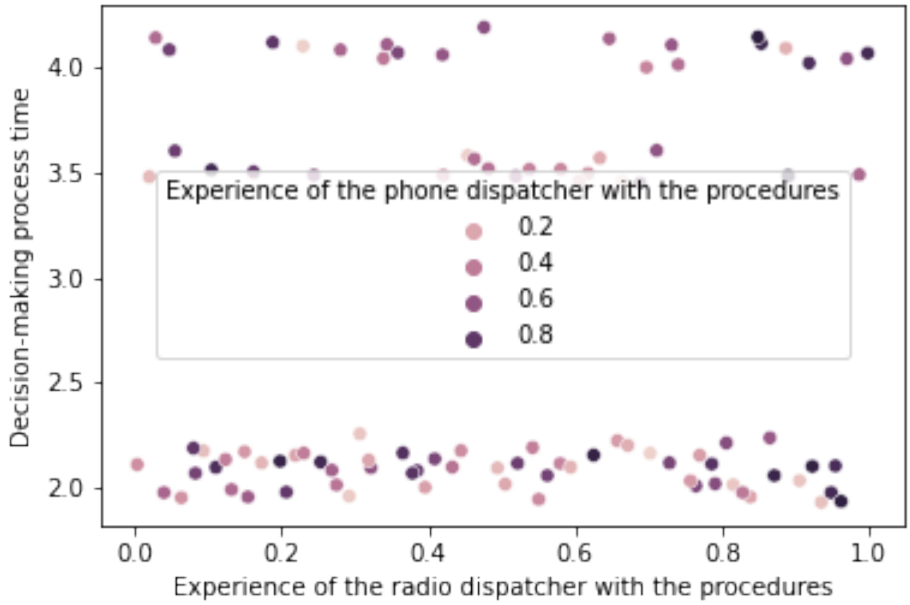


Figure F.2: Decision-making process time in relation to the experience of the radio and phone dispatchers in the Base Case.

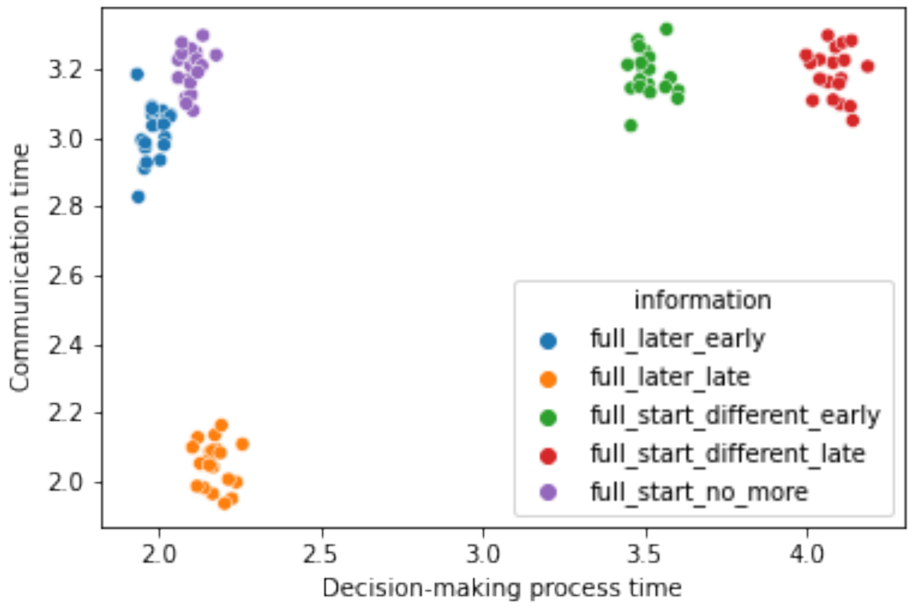


Figure F.3: Relation between the decision-making process and communication time in the Base Case.

G
Results: Experiment 1

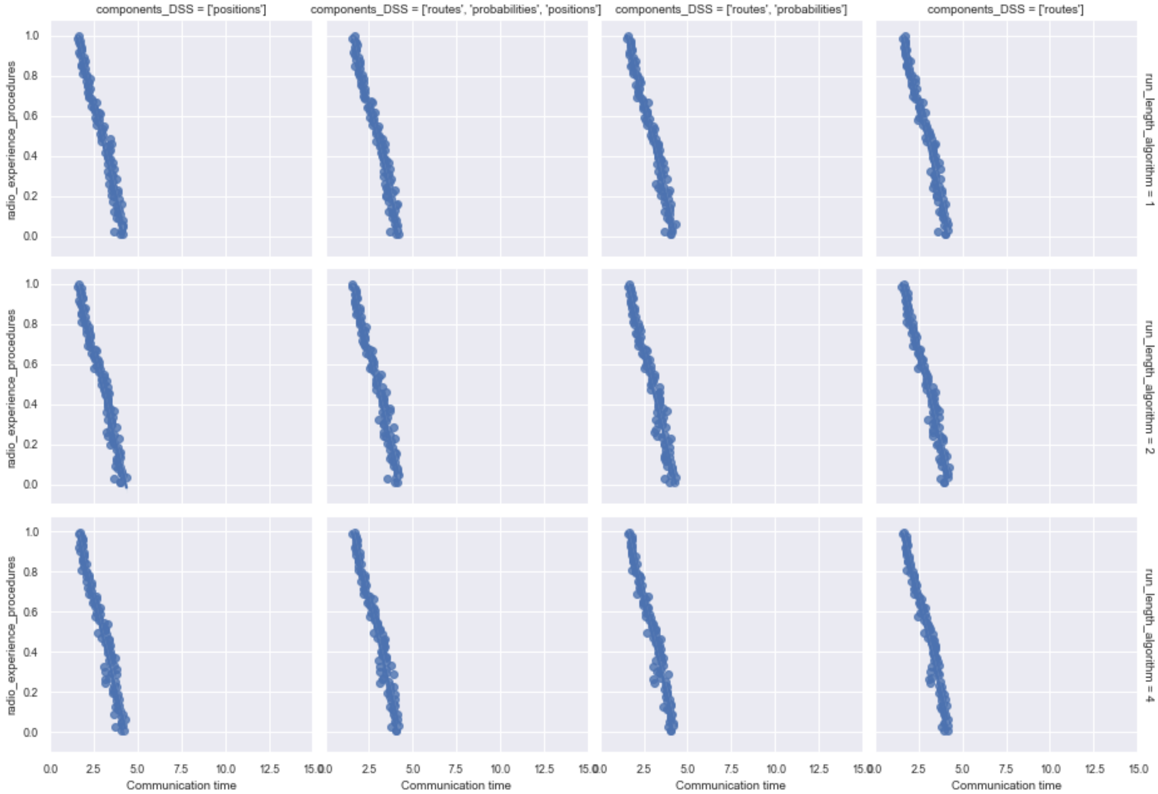


Figure G.1: Relation between the communication time and experience of the radio dispatchers with the procedures based on the different policies in Experiment 1.

Run length	Components DSS	Avg decision-making time (min)	Avg communication time (min)	Avg DSS adoption (%)	Avg net officers DSS adoption (%)
2	['routes', 'probabilities', 'positions']	1,975	1,462	0,425	0,881
2	['positions']	1,948	1,457	0,411	0,881
1	['routes', 'probabilities', 'positions']	1,652	1,462	0,462	0,887
4	['routes']	2,519	1,473	0,277	0,877
4	['positions']	2,353	1,468	0,307	0,878
2	['routes']	2,238	1,460	0,377	0,880
4	['routes', 'probabilities']	2,573	1,473	0,285	0,877
1	['positions']	1,643	1,457	0,459	0,887
1	['routes', 'probabilities']	1,972	1,460	0,425	0,880
4	['routes', 'probabilities', 'positions']	2,455	1,463	0,334	0,877
2	['routes', 'probabilities']	2,254	1,468	0,381	0,877
1	['routes']	1,971	1,459	0,422	0,881

Table G.1: Averages of the outcomes per policy in Experiment 1.

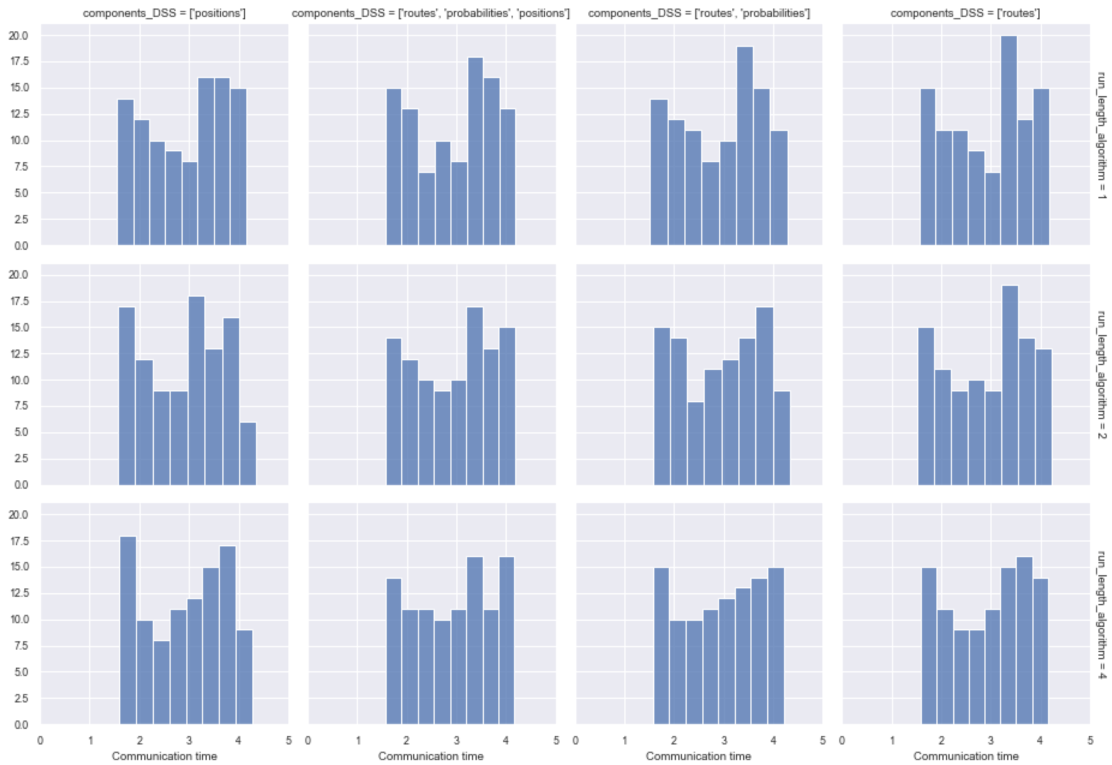


Figure G.2: The distribution of the communication time based on the different policies in Experiment 1.

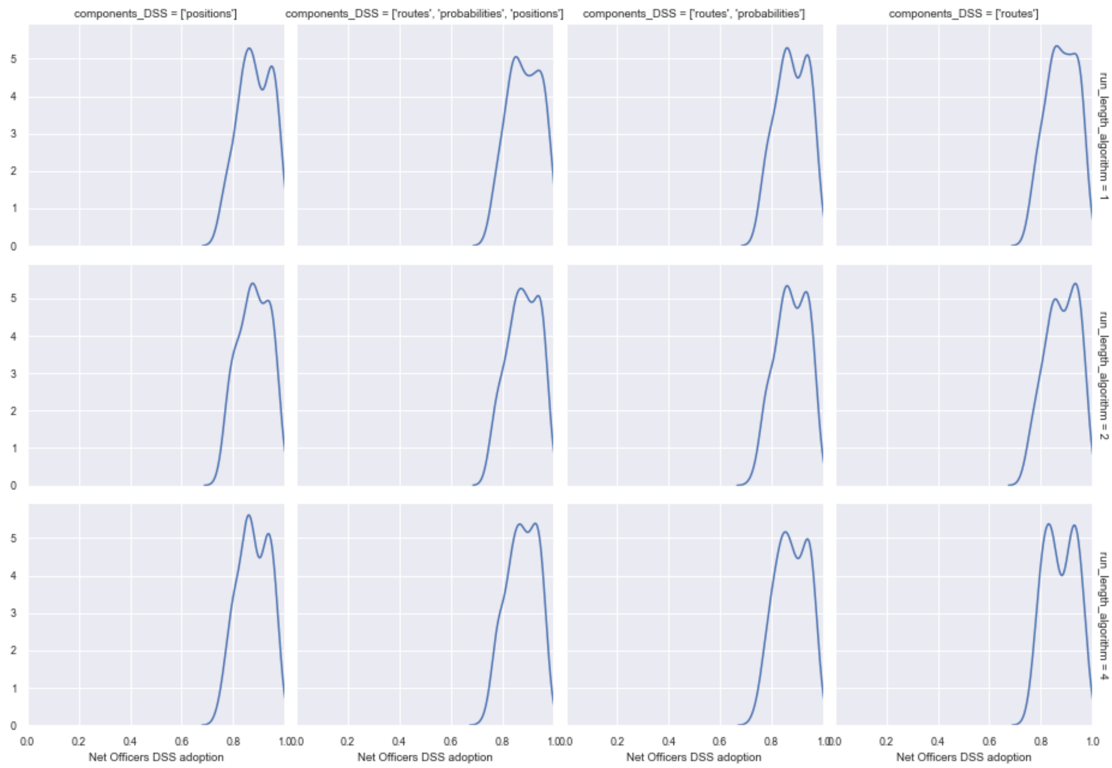


Figure G.3: The distribution of the net rate of adoption of the solution advised by the DSS by the police officers based on the different policies in Experiment 1.

H Results: Experiment 2

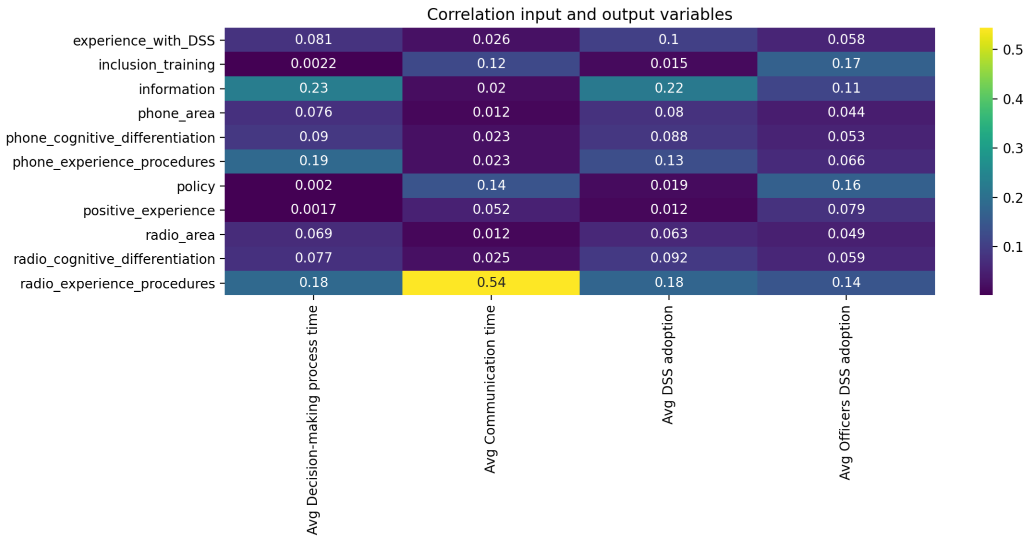


Figure H.1: Correlation between input and output parameters in Experiment 2.

Inclusion	Positive past experience	Avg decision-making time (min)	Avg communication time (min)	Avg DSS adoption (%)	Avg net officers DSS adoption (%)
0,5	0	1,977	1,765	0,410	0,745
1	1	1,978	1,206	0,414	0,987
0	0,5	1,975	1,707	0,411	0,775
0,5	1	1,976	1,267	0,413	0,962
0	0	1,974	2,014	0,411	0,597
0	1	1,978	1,417	0,413	0,903
1	0	1,971	1,504	0,410	0,868
0,5	0,5	1,975	1,457	0,411	0,887
1	0,5	1,977	1,294	0,411	0,952

Table H.1: Averages of the outcomes per policy in Experiment 2.

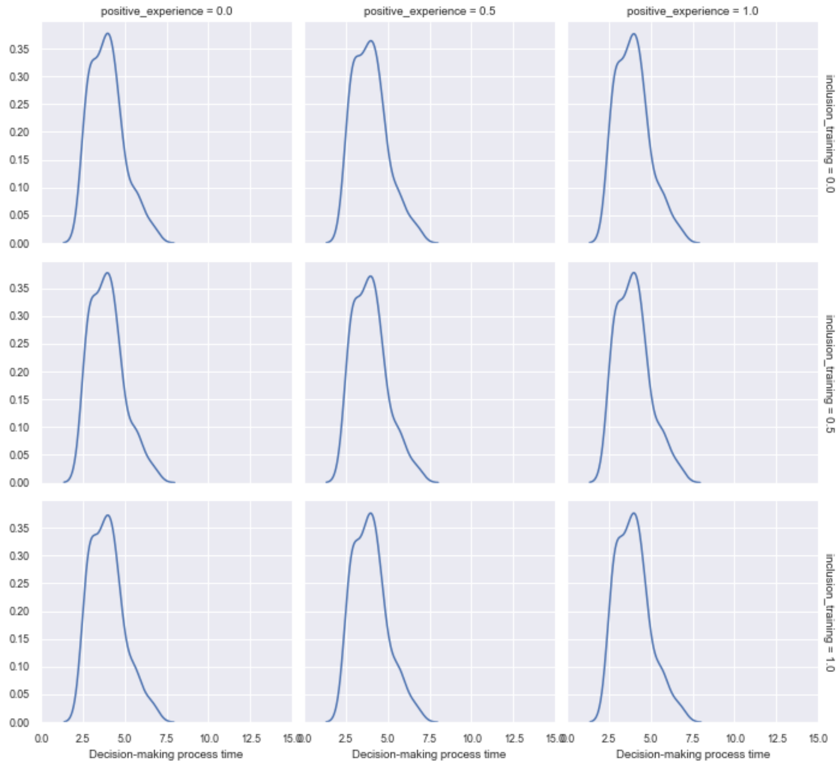


Figure H.2: The distribution of the decision-making time based on the different policies in Experiment 2.

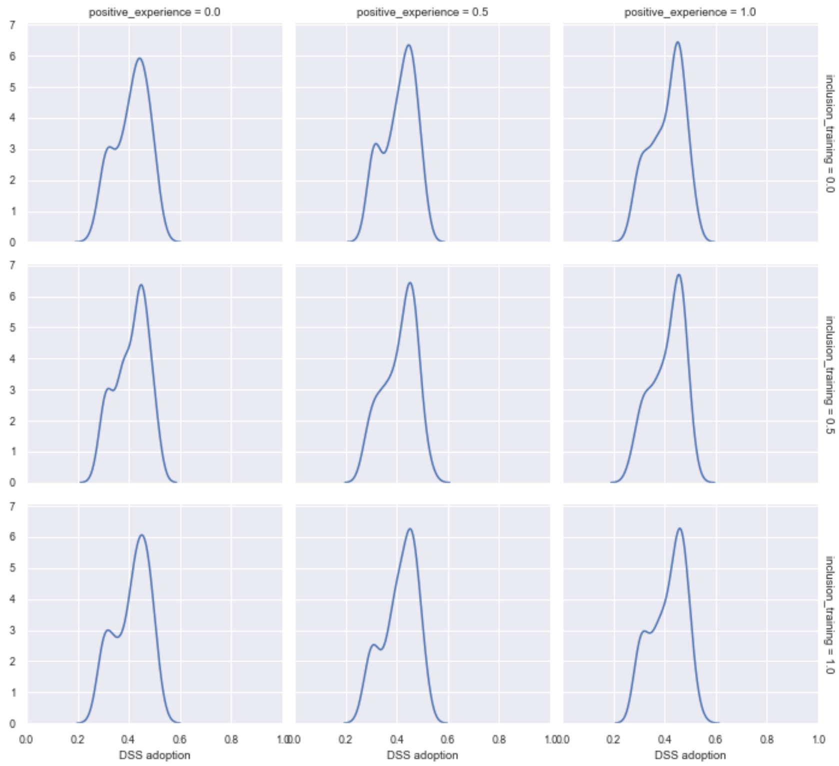
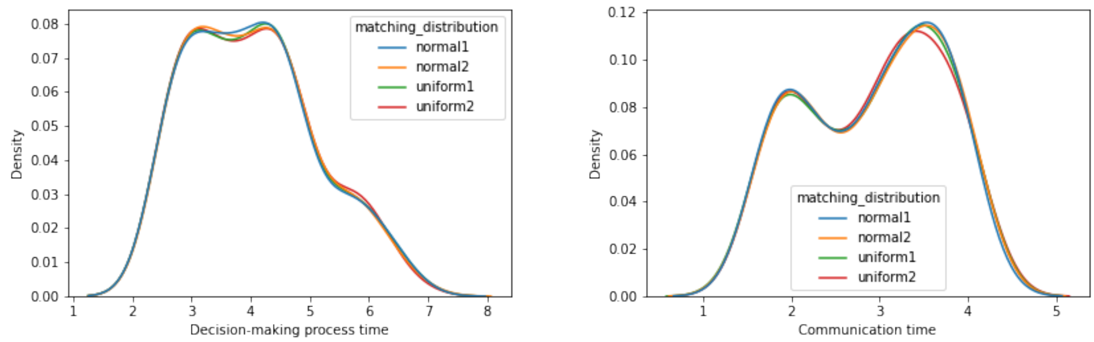


Figure H.3: The distribution of the rate of adoption of the solution advised by the DSS by the dispatchers based on the different policies in Experiment 2.

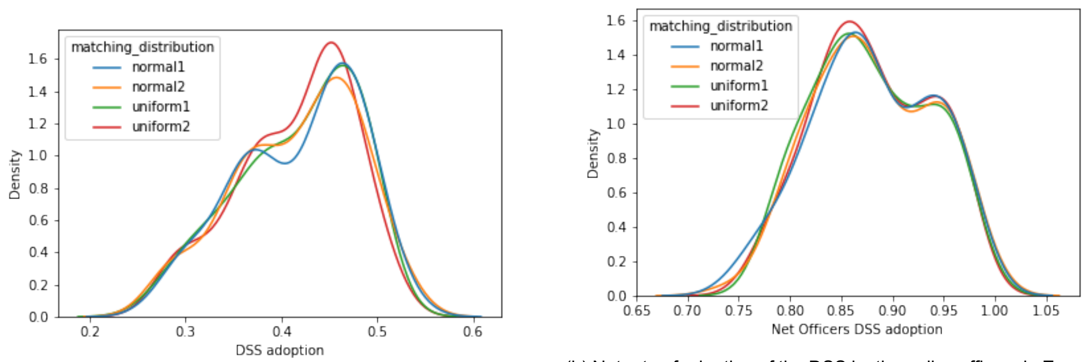
Results: Experiment 4



(a) Decision-making process time in Experiment 4.

(b) Communication time in Experiment 4.

Figure I.1: Decision-making process time and communication time in Experiment 4.



(a) Rate of adoption of the DSS by the dispatchers in Experiment 4.

(b) Net rate of adoption of the DSS by the police officers in Experiment 4.

Figure I.2: Rate of adoption of the DSS by the dispatchers and the police officers in Experiment 4.

J
Results: Experiment 5

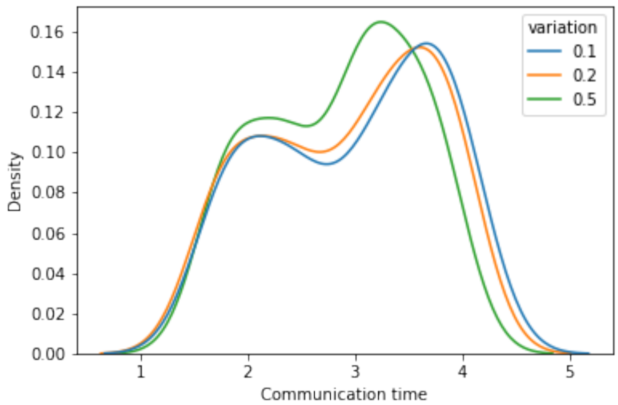


Figure J.1: Communication time in Experiment 5.

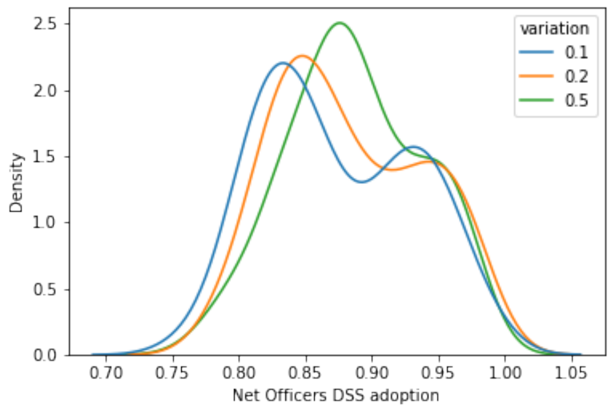


Figure J.2: Net rate of adoption of the DSS by the police officers in Experiment 5.