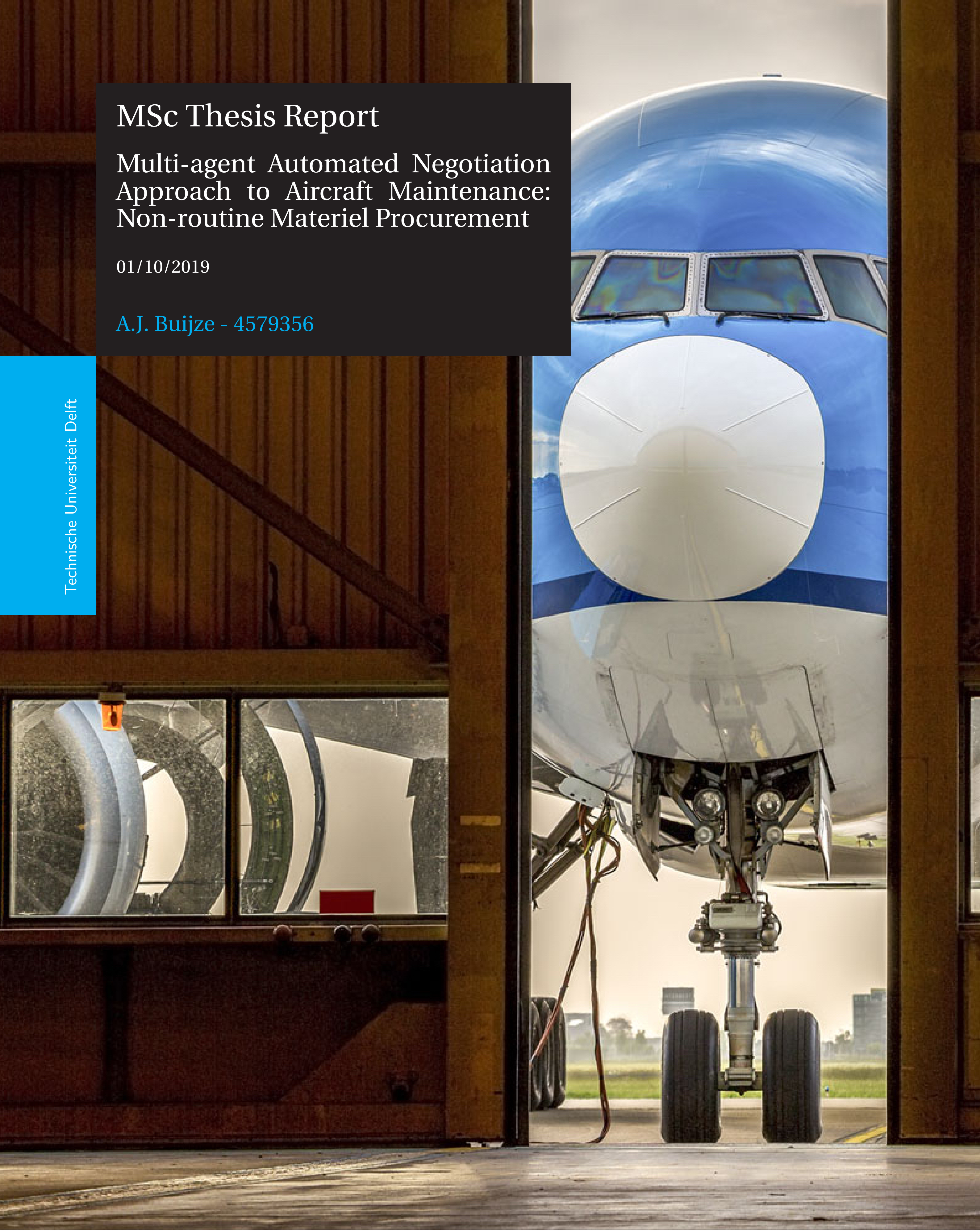

MSc Thesis Report

Multi-agent Automated Negotiation Approach to Aircraft Maintenance: Non-routine Materiel Procurement

01/10/2019

A.J. Buijze - 4579356

Technische Universiteit Delft

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MSC THESIS REPORT

Multi-agent Automated Negotiation Approach to Aircraft Maintenance: Non-routine Materiel Procurement

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01/10/2019

Preface

Dear reader,

This document reports on the research that has been performed in fulfillment of the degree of Master of Science, Aerospace Engineering at the Technical University of Delft. The main body of work is reported on in the Thesis Paper that is included in this document. The remainder of chapters serve as addition to the paper and may be considered in order to obtain a better understanding of certain parts of the research.

The process of designing, performing and reporting on the research has been challenging and instructive as most of the work is beyond the state-of-the-art, meaning that it had to be created from scratch. This has resulted in novel methodology concerning its field of application.

Concluding this MSc Thesis project does also conclude a chapter of my personal life. After finishing a BSc at the University of Applied Sciences in Amsterdam, I decided to start a pre-master and thereafter Master program at the TU Delft. These last three years have been very challenging and have contributed to personal skills that will be valuable for future steps in my career. I would like to thank everyone who has supported me throughout these three years.

Regarding this MSc project, I would like to thank Dr. Alexei Sharpanskykh and Dr.ir. Wim Verhagen for their supervisory roles in this project that combines two fields of research: Agent-based Modelling and Aircraft Maintenance. Thank you for your availability, constructive feedback and views on the project. I would like to thank Corina Enache, Anna Aris and Roos Scholten, who formed the team of anthropologists at KLM. They have shown interest in the research and provided me with great ideas and views on the project and the contribution to practice.

I would like to thank my parents, sister and all other family members for their never-ending support and interest. A special thanks to my girlfriend Robyn who has spend the most time with me throughout the TU Delft journey and has supported me at every step along the way. Her endless support, belief and love has motivated me at times where I needed it.

Finally, to all I have met, spend time and worked with along the way: it was a great run, thank you guys and girls. Let's meet again in the future.

Arjen Buijze
September 2019

Contents

Nomenclature

ABM	Agent-based Modelling and Simulation
AOG	Aircraft on Ground
AUP	Average Unit Price
CI	Central Inventory
CNP	Contract Net Protocol
DMB	Duty Manager Base
DS	Delivery Service
DT	Delivery Time
E&M	Engineering & Maintenance
ER	Exceeded Rounds
GS	Global State
IHX	Inventory Hangar X
IHY	Inventory Hangar Y
KLM	KLM Royal Dutch Airlines - Koninklijke Luchtvaart Maatschappij
KPI	Key Performance Indicator
MAS	Manager Action State
MBS	Manager Belief State
MOS	Manager Observation State
MQ	Material Quantity
MRO	Maintenance, Repair and Overhaul
OS	Official Supplier
QC	Quantity Check
SC	Scenario
SO	Supplier Out
SsAS	Supplier s Action State
SsBS	Supplier s Belief State
SsOS	Supplier s Observation State
TD	Timely Delivery
TFD	Time to Final Delivery
TFO	Timely First Order
TPS	Third Party Supplier
TQR	Total Quantity Received
UP	Unit Price
USW	Utilitarian Social Welfare

List of Tables

List of Figures

List of Notations

Notation	Description
c_{comp}	Computational cost
c_{tot}	Number of messages send
H_0	Null hypothesis
i	Variable to indicate a negotiation issue
$I_s^i(0)$	The initial value of negotiation issue i of supplier s
$I_s^i(t)$	Offer from supplier s concerning negotiation issue i at time point t
$L_{ur_n}^s$	The length of negotiation n between manager and supplier s in negotiation with urgency ur
L^s	Number of rounds elapsed in current negotiation for supplier s
m	Amount of historic time series taken into account for Moving Average
max_m^i	Maximum acceptable value of negotiation issue i of manager agent
max_s^i	Maximum acceptable value of negotiation issue i of supplier agent s
min_m^i	Minimum acceptable value of negotiation issue i of manager agent
min_s^i	Minimum acceptable value of negotiation issue i of supplier agent s
n	Variable to indicate the negotiation
NA	Number of supplier agents in negotiation
n_{tot}	Number of rounds required to finish negotiations
p	Value used for significance level
p_x^y	Probability
$P_s(t)$	Performance of supplier s
Q_m	Quantity of material required by manager
$Q_{os}(t)$	Number of materials ordered at supplier s
$Q_s(t)$	Quantity of material in stock of supplier s at time point t
$ru(t)$	Reservation utility of the manager at time point t
s	Variable to indicate supplier
$s_{os}(t)$	Supplier that has received material order at time point t
t_{sim}	Elapsed time in simulation execution
$U_m(t)$	The overall utility of the manager gained from negotiation
ur	Urgency level
$U_s^m(t)$	Utility of manager based on proposal of supplier s at time point t
$U_s(t)$	Utility of supplier s at time point t
$V_m(I_s^i(t))$	Value of valuation function from manager based on offer I from supplier s concerning negotiation issue i
V_{min}^i	Minimum valuation of negotiation issue i
$V_s(I_s^i(t))$	Value of valuation function of supplier s based on offer I concerning negotiation issue i
w_m^i	Weight of negotiation issue i for manager
w_s^i	Weight of negotiation issue i for supplier s
X	Set of negotiation attributes
$\bar{X}$	Sample mean
$\alpha_s^i(t)$	Offer (generalized) of negotiation issue i of supplier agent s at time point t
κ_s^i	Generalized initial offer of supplier s for issue i
$\tau_{ur_{n+1}}^s$	Estimated number of negotiation rounds for supplier s needed for next negotiation with urgency ur
τ^s	Estimated required number of rounds to reach agreement of supplier s
$\eta(t)$	Amount of suppliers in negotiation at time point t
ω	Manager's willingness to lower reservation utility
$\Delta I(0)$	Percental variable indicating the adjustment of the initial offer
ΔP	Percental variable indicating the adjustment in supplier performance and trust
ΔX	Sample mean confidence interval
θ	Population mean
σ	Standard deviation

Table 1: List of notations

Thesis Paper

Thesis Paper is included starting from the next page.

Multi-agent Automated Negotiation Approach to Aircraft Maintenance: Non-routine Materiel Procurement

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Abstract

In aircraft maintenance, performance of routine maintenance tasks is prone to generate additional non-routine tasks. These non-routine tasks relate to solving an unexpected issue and have specific requirements in terms of materiel, tools and manpower. In existing research regarding optimization of aircraft maintenance environments and schedules, these requirements are assumed to be in place or not considered at all. In real-life, the required resources may not be in place and retrieving them is subject to human interactions and decision-making, potentially resulting in delays in the maintenance schedule. This research proposes a novel methodology to address this problem by developing a multi-agent automated negotiation model capable of simulating negotiations related to the procurement of required aircraft materials in order to perform non-routine tasks. The proposed model explores its applicability by incorporating several negotiation strategies, adaptive parameters and negotiation circumstances, e.g. urgency. The main research question is: *In the context of non-routine aircraft maintenance materiel availability, to what extent can multi-agent automated negotiation be applied to explore effective agent strategies for various negotiation circumstances regarding the procurement of aircraft components and expendables?* The proposed methodology has shown to be very suitable for modelling negotiation circumstances as evaluation of the model's performance has resulted in understanding and recommendations to policy makers concerning what strategy to apply in which circumstance. Variations of circumstances have lead to expected findings, e.g. increasing urgency results in a sooner delivery of materials, whereas in other situations the model's KPIs are unaffected by parameter variations, unexpectedly.

Keywords: Agent-based Modelling, Resource Availability, Multi-attribute Extended Contract Net Protocol

1. Introduction

1.1. Context and Problem

Aircraft maintenance accounts for 10% to 20% of an airline's operational costs, depending on the size, age and utilization of the aircraft fleet [1]. Long-term scheduling of maintenance activities may result in cost savings while unexpected maintenance events disrupt this planning, resulting in an increase of cost levels [2]. Managing such disruptions involves human decision-making and interactions [3]. According to Samaranayake and Kiridena [4], 50% of hangar maintenance work involves performing non-routine tasks that emerge from performance of routine inspections or tasks. The requirements for non-routine task performance in terms of parts, supplies and time may vary depending on the event, potentially resulting in costly delays if not directly available [1, 5]. According to interviews conducted with aircraft maintenance technicians [6], the lack of tooling and part availability prevent them from performing maintenance tasks.

In existing research regarding optimization of maintenance environments, availability of materials required for non-routine tasks and human involvement related to retrieving the required materials are not considered. These gaps are considered in this research by applying Agent-based Modelling (ABM) techniques to the problem. Three main advantages of ABM over traditional modelling techniques, e.g. top-down, non-linear dynamic systems described by differential equations, are that the ABM approach captures emergent phenomena, provides a natural environment for researching certain systems and is flexible [7]. Whereas traditional methods require assuming average behaviour of individuals, ABM's bottom-up approach allows for local phenomena to be understood and measured on a global level. ABM is a suitable tool for modelling human and individual behaviour on a local level represented by agents and agent reasoning. ABM is effective in simulating agent interactions, e.g. negotiations, while agents autonomously make decisions. ABM techniques are used in this research to propose a novel methodology to simulate negotiations associated with the procurement of aircraft maintenance materials required to perform non-routine tasks.

As this research addresses availability of non-routine materials and human interactions involved in the procurement of these materials, which has not been considered before in aircraft maintenance research, a specific case study is used to describe the operational context and the negotiations in the hangar maintenance environment and procurement process. Elements from the case are used in the proposed methodology in order to resemble the real-life procurement process.

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1.2. Case Study

This case study, provided by a major European Maintenance, Repair and Overhaul (MRO) provider, is comprised from multiple historic events related to unavailability of materials required to perform non-routine tasks. The case concerns the finding of damaged seat covers during a scheduled inspection that require replacement. After consulting multiple sources of information, the mechanic finds a central material inventory location that has the material in stock. The mechanic alarms the hangar manager that the central inventory must be contacted in order to retrieve the material. The hangar manager uses its personal knowledge and experience to assess alternative material suppliers, but eventually initiates negotiations with the central inventory in order to retrieve the material before the end of the day. By calling the inventory representative, the hangar manager negotiates over the required material. Eventually, the hangar manager retrieves the required materials and has them delivered at an agreed moment in time.

1.3. State of the Art and Beyond

Taking the influence of aircraft maintenance operations on airline cost levels into consideration, several studies have attempted to minimize cost levels by: optimizing maintenance schedules [4, 8, 9, 10, 11, 12], including maintenance events in aircraft routing problems [13], predicting operational factors that may cause unscheduled maintenance [14] or optimizing decision-making in case of unscheduled events [1, 15, 16]. Maintenance optimization problems are considered as mathematical models and the focus is primarily on mathematical analysis and techniques [17]. In all studies discussed above, resources, e.g. spare parts, related to non-routine events are not included.

Spare part models are normally excluded from maintenance optimization models, because these focus on inventory control, according to Dekker [17]. Research concerning inventory control mainly focuses on forecasting spare part demand and consequently on developing inventory control mechanisms to fulfill the demand [18]. Inventory control research does include spare part demand for unplanned maintenance activities, but usually resorts to safety stock, i.e. buffers, for covering this demand [19, 20]. It fails to cover the situation in which materials or parts are required that are not included in the inventory. Moreover, according to Sahay [20], there is never a day or hour that mechanics demand a certain part that is unavailable in the warehouse. As described by the case study, this statement does not resemble real operational maintenance. This research contributes to the field of aircraft maintenance by:

- Addressing an operational aircraft maintenance problem that emerges in real operational maintenance activities, namely resource unavailability and consequently retrieving these resources.
- Addressing a gap between inventory control and aircraft maintenance scheduling activities, by dealing with materials required for non-routine maintenance activities.
- Including human interactions and decision-making in the process of procurement of aircraft maintenance materials.

Automated negotiation within the context of multi-agent systems is a fast growing field of research [21]. Several studies have been performed on single-issue, multi-issue, bilateral and multilateral negotiations with complete or incomplete information. Fields of applications include supply chain management and business processes. One study [22] has introduced a bargaining protocol for automated multilateral buyer-seller negotiations for supply chain management between one buyer and multiple sellers, which uses effective valuation and utility functions. Other work has addressed multilateral negotiations using alternating offer protocols [23]. In developing novel protocols for multilateral multi-issue automated negotiations, studies normally attempt to reach Pareto optimal or Nash equilibrium solutions [24, 25, 26, 27, 28, 29]. Reaching such solutions is considered computationally expensive and hard to achieve in trade-off situations [21].

ABM has been applied to deal with aircraft maintenance problems before. Most approaches are concerned with maintenance scheduling problems that are solved by using multi-agent negotiation techniques to request rescheduling of repair slots or maintenance personnel [12, 30]. This research contributes to the field of ABM and automated negotiation by:

- Developing a methodology for supply chain buyer-seller negotiations that resembles real-life negotiations.
- Introducing an approach that explores the applicability and effectiveness of multilateral multi-attribute negotiations leading to understanding and recommendations to practice, rather than attempting to reach optimal solutions.
- Extending automated negotiation applications to aircraft maintenance material procurement.

1.4. Objective and Structure

Considering the contributions discussed above, the objective of this research is to apply ABM techniques to explore its effectiveness of simulating the aircraft maintenance domain with respect to the specific problem of acquiring materials required to perform non-routine maintenance tasks. To achieve this, the following main question is formulated for this research: *In the context of non-routine aircraft maintenance materiel availability, to what extent can multi-agent automated negotiation be applied to explore effective agent strategies for various negotiation circumstances regarding the procurement of aircraft components and expendables?* The main objective is to ascertain relationships between local agent negotiation strategies and global performance of the system in different negotiation circumstances, e.g. level of urgency, by proposing a novel methodology to simulate negotiations in aircraft maintenance environments.

This paper is organized as follows. An overview of ABM and automated negotiation methodology and its building blocks are provided in Section 2. The proposed methodology is discussed in Section 3. A description of the experiments and methods used for assessing results is discussed in Section 4. The results are discussed in Section 5. A discussion on the interpretation of results, proposed methodology and recommendations is provided in Section 6. Conclusions are given in Section 7.

2. Methodology Approach: Overview

Figure 1 shows the methodological steps that are required in order to fully specify the model that will be used to answer the main research question. The methodological steps are divided into ABM specification (2.1) and negotiation specification (2.2).

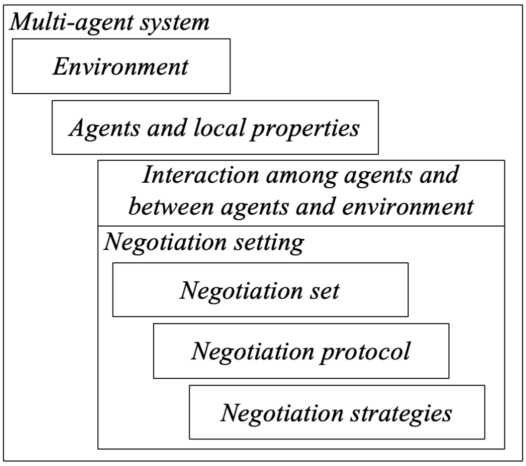


Figure 1: Overview of methodological steps for specification of multi-agent automated negotiation model

2.1. Agent-based Modelling

Specifying an agent-based model comprised of multiple agents, i.e. multi-agent system, requires three elements. The model environment is the virtual world in which agents act, which is an aircraft maintenance hangar. Whereas the physical surroundings of the hangar are not modelled, elements of the hangar related to the negotiations, e.g. materials from inventories, can be observed by agents and influence their behaviour.

A specification of agents and their local properties describe the type of actors within the environment and local behaviour they exhibit. The case describes one hangar manager and one supplier involved in the negotiation over aircraft material procurement. In order to resemble a real-life aircraft maintenance environment, the hangar manager will be represented as a buyer agent of materials as well as negotiation manager. The seller is represented by one supplier in the case, but this is extended to five different types of suppliers. The model is adoptable to simulate negotiations with less, more or other suppliers.

Interactions between agents and between agents and their environment specify how interactions take place in terms of communication, coordination or negotiation. The hangar manager should be able to interact simultaneously with multiple suppliers as this would also be possible in real-life. Personal reservation values, negotiation strategies and proposals are not openly available and suppliers are not allowed to communicate with other suppliers. The interactions, i.e. negotiation in this case, are specified by the negotiation setting.

2.2. Negotiation Setting

Agents in a multi-agent system may be able to negotiate over certain predefined topics. The purpose of negotiation is to reach an agreement when facing conflicting goals and preferences among participants [21]. The negotiation setting should comprise three main elements: the negotiation set, protocol and strategies used by participants (Figure 1). The negotiation set describes all possible deals an agent can make, which may comprise multiple attributes.

In this research, the negotiation set is described by the scenario that is simulated. Two scenarios for aircraft material procurement are considered, namely procurement of aircraft components and expendables. The negotiation attributes differ between the scenarios in order to simulate the difference between the procurement of the two types of aircraft material. Negotiations involving multiple attributes, i.e. multi-attribute, lead to an exponential growth of possible deals. In multi-attribute negotiations, three common methods of negotiating over issues are the package-deal, sequential or simultaneous procedures [21]. With simultaneous procedures, agents negotiate on all attributes simultaneously. Sequential negotiations imply that each attribute is handled sequentially and their handling order is covered by the negotiation agenda. The package-deal procedure implies that a proposal from an agent assigns a value to each attribute and the proposal is accepted or rejected for the package of attributes, negotiation over individual attributes is not allowed. The package-deal procedure is adopted in this research because this resembles the case the closest as a supplier would propose a deal for material comprising multiple negotiation issues. Whereas it would be possible for the hangar manager to appeal the value of an issue in real-life, it is assumed that the manager is not allowed to in this research.

The negotiation protocol describes how the negotiation will proceed, it defines the proposals or bids agents are allowed to make. The protocol also defines rules of negotiation, such as a rule that prevents a certain deal may not be proposed more than once. Also, the protocol entails when an agreement has been reached or has failed. Several protocols have been developed over the years to simulate real-life many-to-one negotiations. For multilateral negotiations, the most common developed protocols are: alternating offer protocols [31], auction protocols [32], contract net protocols (CNP) [33] and bargaining protocols [34]. Recently, Aydoğan et al. [23] defined two alternating offer protocols, namely Stacked Alternating Offers Protocol (SAOP) and Alternating Multiple Offers Protocol (AMOP) to simulate multilateral turn-taking negotiations. A multi-agent bargaining protocol based on an extended CNP called *ECNPro* was introduced in Wong and Fang [22] to simulate supply chain negotiations between one buyer and multiple sellers which are modelled as multiple simultaneous bilateral negotiations.

The way the real-life negotiation is performed is considered as the main motivation for the selection of a protocol here. The methodology that is proposed in the following sections uses a buyer-seller representation but introduces a CNP extension to simulate aircraft maintenance material retrieval negotiations, as discussed by the case. The classic CNP [33] is extended to allow for multi-attribute many-to-one simultaneous negotiation between one manager, i.e. the hangar manager, and multiple material suppliers. The proposed protocol adopts elements from Wong and Fang [22], e.g. proposal scoring functions and supplier performance elements. However, as Wong and Fang [22] treat multilateral bargaining as multiple simultaneous bilateral negotiations, this research allows the manager to simultaneously negotiate with multiple suppliers, excluding bargaining elements. Other mechanisms such as auctions or bargaining could also be applied but are not used in this case. In further research, these mechanisms can be applied in the model to assess their effectiveness and results.

Agents' negotiation strategies define what proposals will be made over time. The chosen strategy by an agent and knowledge of behaviour of other agents are not visible for other participants. The negotiation strategies are usually formed by the goal to maximize agent utility. In this research, the manager can apply one of three different strategies, chosen at the start of the negotiation. The different strategies are designed to represent three different types of managers: greedy, patient and balanced managers. The proposals made by suppliers are evaluated based on functions adopted from Wong and Fang [22]. Because the purpose of this research is not to find optimal solutions, the suppliers apply a bidding heuristic that is resource-dependent. Their offer strategy is dependent on the level of urgency, an estimated required number of rounds that is needed to reach an agreement, the number of elapsed rounds and an estimated number of suppliers in negotiation.

Besides the elements mentioned above, the proposed methodology also exhibits four adaptive elements to adapt agent strategies and resemble adaptive human behaviour. In the following sections, it is elaborated how the methodological steps are applied to specify the model.

3. Proposed Methodology

In this section the application of ABM (3.1) and automated negotiation methodological steps, i.e. negotiation setting (3.2), protocol (3.3) and strategies (3.4), are discussed consecutively. Adaptive elements of the model are also explained (3.5).

3.1. Environment, Agents and Interactions

As mentioned in the previous section, the model's environment is an aircraft maintenance hangar. The level of urgency, competition, inventory storage places and materials themselves are modelled as environment. Agents may observe their environment, but the global environment is not observable for agents.

The five suppliers that are available for the procurement of materials, assuming that these are present in the proximity of the hangar, are defined as representative agents of:

1. **Inventory Hangar X:** represents an agent representative for the warehouse inventory of the hangar where the routine inspection or task is performed that results in the non-routine task.
2. **Inventory Hangar Y:** represents an agent representative of the warehouse inventory of the hangar that is located near Hangar X, assuming multiple hangars are located close to each other.
3. **Central Inventory:** represents an agent representative of the inventory of materiel that can be accessed by multiple buyers, e.g. a spare part pool.
4. **Third Party Supplier:** represents an agent representative of an external supplier that provides certified material but is not directly controlled by the OEM of the material.
5. **Official Supplier:** represents an agent representative of the official supplier, usually the OEM of the material.

3.2. Negotiation Set

3.2.1. Scenarios

The case is extended to explore effective agent strategies for the procurement of two types of aircraft materials. The first type, scenario 1 (SC1), is representative of the procurement of aircraft components. The procurement of aircraft components, i.e. rotables and repairables, is normally associated with relatively high costs and thus requires careful order placement. To simulate the procurement of these components, negotiation comprises three attributes: unit price, delivery time and delivery service. These attributes are negotiable with the suppliers because usually different unit prices, delivery times and service is associated with other (types of) suppliers. It is assumed that these are the primary negotiation attributes used in a real-life case. The methodology proposed in this research does have potential for extension to more or other attributes to increase complexity. When an agreement is reached between the hangar manager and supplier, the manager may place an order at the supplier for any amount of components at the cost of the agreed attributes, as long as the order quantity does not exceed the supplier's stock level. The manager has this choice because in the pursuance of materials, the manager might require just a few materials to reach the required amount. The space of possible outcomes is extensive as any outcome that does not exceed any reservation value or material stock level of the suppliers is possible.

The second scenario (SC2) simulates the procurement of aircraft expendables. These aircraft materials are usually associated with relatively low procurement costs as repairing these parts is more expensive than replacement, e.g. seat covers. Procurement is usually done periodically and in larger batches than aircraft components. To simulate the procurement of these parts, the quantity of material associated with an order becomes one of the attributes to explore its effect on the outcomes of negotiation. Because aircraft expendables are usually ordered in larger batches, suppliers may be willing to discount other attributes when procuring larger volumes. To increase ability to compare the two scenarios, it is assumed that discounts on any attributes are not applicable here. The model does allow for extension to include volume discounts. For comparison reasons, the reservation values for the unit price, delivery times and delivery service attributes remain the same as in SC1, even though aircraft expendables are usually associated with lower procurement costs. As with SC1, the space of possible outcomes is bounded by supplier stock levels and agent reservation values.

The unit price, delivery time and material quantity attributes can take any value in the set of natural numbers $\mathbb{N}$ and the delivery service attribute is a binary value, where 0 represents material pick-up and 1 represents material delivery performed by the supplier. Within both scenarios, elements of level of urgency and competition are included to simulate variations of negotiation circumstances.

3.2.2. Urgency

Urgency (ur) is introduced in the simulations to resemble time critical requests for aircraft materials from the hangar manager towards the suppliers. It is assumed that the level of urgency is determined by the hangar manager's environment, but it is observed and transmitted by the hangar manager. A high urgency ($ur = 1$) represents a time-critical situation in which materials are required as soon as possible, e.g. Aircraft on Ground (AOG) or safety critical material. Medium urgency ($ur = 2$) is related to a less time-critical situation and the low urgency level ($ur = 3$) represents the situation that materials are not required within a particular time frame, e.g. periodically ordering. Negotiation strategies from supplier agents are adjusted depending on the level of urgency of the material request. It should be noted that the outcome space is not subject to the level of urgency that is simulated.

3.2.3. Competition

To include and simulate the element of competition (CO), the supplier stock levels changes over time. In this respect, it is simulated that the materials are provided to other buyers. This is assumed to be a representation of how competition between buyers results in a drop in stock levels. The model does allow for further extension of more sophisticated ways of including competitive elements such as introducing multiple buying agents or including preferences of suppliers to provide materials to specific buyers. In this research the five suppliers' initial stock levels $Q_s(0)$ are fixed and equal to $50, 100, 150, 200$ and 200, respectively. It should be noted that the initial stock level values are assumed based on the characteristics of the supplier agents. The proposed methodology does allow for more extensive and realistic stock level constructions, e.g. backordering, but this is not included in this research. When further researching the influence of competition on the procurement of materials, prioritizing preference of suppliers to provide materials to certain buyers would yield interesting insights, but this is excluded here. Three levels of competition are considered:

- **CO 0:** no competition involved, supplier stock levels are constant over time and equal to the initial stock level $Q_s(0)$.
- **CO 5:** the stock level available at each supplier decreases with 5% per simulated half hour (Figure 2).
- **CO 10:** the stock level available at each supplier decreases with 10% per simulated half hour.

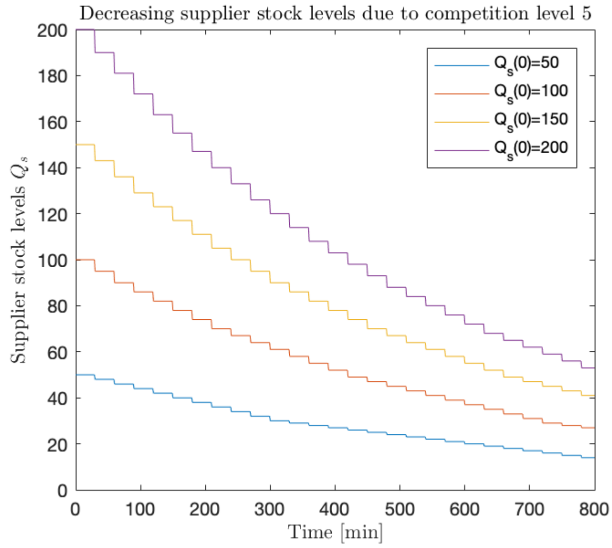


Figure 2: Supplier stock levels with competition 5

The space of possible outcomes is subject to the level of competition as re-stock of materials is not included in the model. As stock levels decrease over time, the space of possible outcomes shrinks while being subject to the same boundaries as before, i.e. without competition.

3.3. Automated Negotiation Protocol

In the CNP extension proposed in this section, proposals from suppliers to the manager may be rejected or accepted. In the protocol used in this research (Figure 3), negotiation is initiated by the manager by requesting information from available suppliers concerning the stock level of a particular material. Based on a probability p_x^y related to the supplier's performance $P_s(t)$, i.e. a measure to indicate the manager's trust in the supplier, the supplier responds by either informing the manager that the request is not understood, refused or understood. If the request is not understood, probability p_m determines whether if the supplier receives a new request for quantity, or is excluded from further negotiation. When understood, the supplier communicates its stock level to the manager, who will request the particular supplier to propose a deal. With probability p_2, the supplier will either refuse or accept the request to propose a package-deal. The manager will reject the proposal if the supplier has exceeded the maximum allowed number of bidding rounds, i.e. deadline, if the proposal exceeds a manager reservation value on either of the attributes or if the utility gained by the manager fails to exceed its reservation utility threshold. If either of the latter two is true and the maximum allowed number of rounds has not been exceeded, then the proposal is refused but the supplier is requested to propose a new bid. In cases other than the ones described above, the proposal is accepted by the manager.

A probability related to supplier performance determines whether if the agreed deal is read back or cancelled by the supplier. In the first case, the manager may place an order at the supplier. Order placement is dependent on the scenario and acceptance strategy, i.e. manager type, that is selected at the start of the negotiation.

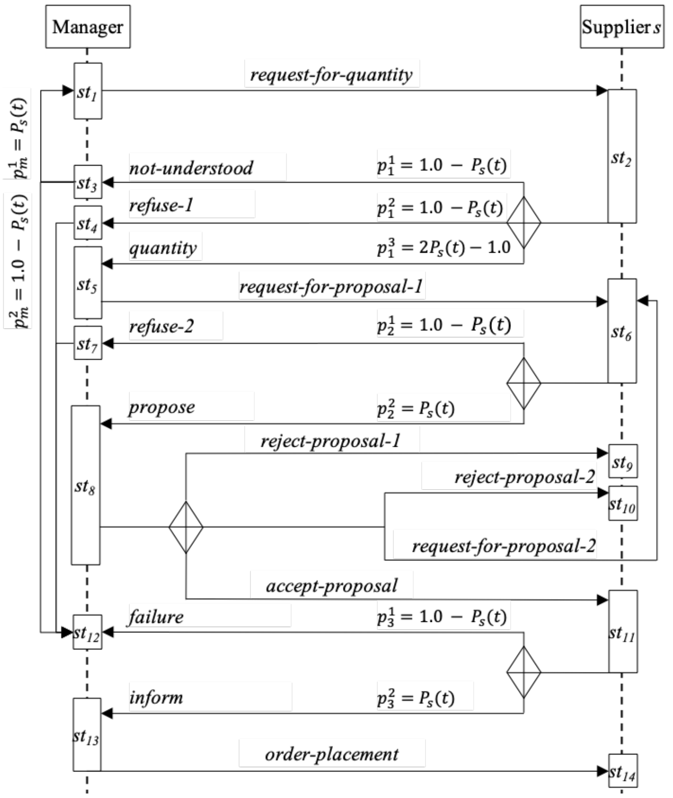


Figure 3: Extended CNP with probabilities for responses

3.4. Negotiation Strategies

3.4.1. Manager Agent

Three separate acceptance strategies (AS) are used to represent three different types of hangar managers:

1. **Greedy:** a greedy manager will accept any proposal that is considered acceptable and will place an order immediately after an agreement is reached with any supplier.
2. **Patient:** a patient manager will postpone proposal acceptance and order placement until all suppliers have submitted a proposal or agreed to a deal. In ascending order, the hangar manager will place orders at suppliers that result in the highest utility.
3. **Balanced:** a balanced manager represents a combination of greedy and patient behaviour. The balanced manager will accept any deal that is considered acceptable, but will postpone order placement or agreement confirmation until an agreement is reached or failed with every supplier. In ascending order, the hangar manager will place orders at suppliers that result in the highest utility.

Proposals from suppliers are evaluated by the manager using the valuation function below (Equation 1, [22]). Because of the different ranges used for negotiation attributes, e.g. discrete variable price and binary variable of delivery service, the package-deal proposal must be generalized according to the manager's reservation values in order to assess the value of the proposal and consequently the utility gained from the proposal. In other words, each attribute value must be valued in a range $V_m(I_s^i(t)) \in [0.1, 1.0]$.

$$V_m(I_s^i(t)) = \begin{cases} V^i_{min} + (1 - V^i_{min})\Big(\frac{I_s^i(t) - min_m^i}{max_m^i - min_m^i}\Big) \\ V^i_{min} + (1 - V^i_{min})\Big(\frac{max_m^i - I_s^i(t)}{max_m^i - min_m^i}\Big) \end{cases} \tag{1}$$

$V_m(I_s^i(t))$ represents the valuation for the manager based on a proposal of supplier s concerning issue i at time point t, V^i_{min} equals the minimum valuation of negotiation issue i, $I_s^i(t)$ represents the current offer of supplier s concerning negotiation issue i and max_m^i and min_m^i are the maximum and minimum acceptable values for the manager concerning negotiation issue i. The reservation values associated with any of the negotiation attributes is assumed to give a representation of actual reservation values performed by the hangar manager. The top function in Equation 1 is applied to issues where a increasing value represents a benefit to the manager, i.e. delivery service and material quantity. The latter function is applied to issues where a decreasing value represents a benefit to the manager, i.e. unit price and delivery time. When the valuation of a proposal is evaluated for all negotiation issues using Equation 1, the utility gained from the particular proposal by the manager is evaluated using Equation 2 [22].

$$U_s^m(t) = P_s(t)\Big(\sum_{i=1}^{X} w_m^i \times V_m(I_s^i(t))\Big) \tag{2}$$

Where $U_s^m(t)$ represents the manager utility gained when accepting the proposal from supplier s, $P_s(t)$ represents the performance related to supplier s, $w_m^i \in [0, 1]$ is the weight of negotiation issue i for the manager and $V_m(I_s^i(t))$ is obtained from Equation 1. Equation 2 uses the valuation from each of the attributes and multiplies it with the weight representing the importance of each attribute to the manager. The weights are assumed in order to resemble actual prioritization of importance of attributes to the manager. Adjusting the weights will most likely lead to different results, but this is subject for further research. The calculation from Equation 2 yields the true utility gained by the manager regarding the proposal made by the supplier. Supplier performance is used to depreciate the utility related to the trust from the manager in the supplier. At the start of the first negotiation the performance of each supplier is equal, but this parameter is adaptive as will be discussed in Section 3.5.4. The initial reservation utility is equal for all manager AS, meaning that any proposal that fails to exceed the reservation utility value will be rejected by the manager. Based on the accepted proposals, the manager will place orders or confirm agreements for SC1 and SC2, respectively. The overall manager utility is evaluated after order placement using Equations 3 [22] and 4.

$$\text{Scenario 1: } U_m(t) = \frac{\sum_{s=1}^{S} U_s^m(t) \times Q_{os}(t)}{\sum_{s=1}^{S} Q_{os}(t)} \tag{3}$$

$$\text{Scenario 2: } U_m(t) = \frac{\sum_{s=1}^{S} U_s^m(t)}{\sum_{s=1}^{S} s_{os}(t)} \tag{4}$$

Where $U_m(t)$ is the overall manager utility gained from the collection of orders for materials, $U_s^m(t)$ equals the utility gained from the supplier's proposal, $Q_{os}(t)$ represents the quantity of materials ordered at supplier s and $\sum_{s=1}^{S} s_{os}(t)$ represents the sum of suppliers that have received an order. For SC1 the overall manager utility is calculated as a weighted average utility per quantity of material by multiplying utility gained from a proposal by a supplier with the order quantity associated with the supplier. This is divided by the total utility from all suppliers whom have received an order by the total quantity that has been ordered, to get to a value of overall manager utility as a measure of successful negotiation. With SC2, a similar formula is used to calculate overall manager utility, however as material quantity that is ordered is part of the proposal and thus part of $U_s^m(t)$, $U_m(t)$ is calculated by summing the utility gained from each supplier by the manager and consequently dividing this by the amount of suppliers whom have received an order. The manager's AS determines what proposal is accepted and how it is evaluated, in the following section the way a proposal is formed is explained.

3.4.2. Supplier Agents

The offer of supplier s at time point t follows a resource-dependent offer strategy deduced from classic bidding heuristics [21] and is determined by Equations 5 and 6.

$$\alpha_s^i(t) = \kappa_s^i + (1 - \kappa_s^i) \exp -\left(\frac{\tau^s \times NA}{(L^s)^2}\right) \tag{5}$$

$$\text{with } \kappa_s^i = \frac{I_s^i(0) - min_s^i}{max_s^i - min_s^i} \tag{6}$$

Where κ_s^i is the generalized initial offer from supplier s concerning issue i, $I_s^i(0)$ is the initial offer from supplier s concerning issue i, max_s^i and min_s^i are the maximum and minimum acceptable values of issue i for supplier s.

In Equation 5, $\alpha_s^i(t)$ is the generalized offer for negotiation issue i of supplier s at time point t, τ^s is the estimated required number of negotiation rounds needed to reach an agreement, NA is the number of supplier agents in negotiation and L^s is the number of rounds elapsed in the current negotiation for supplier s. With this resource-dependent offer strategy, time and number of agents in negotiation influence the value of the offer for each attribute. The supplier assumes the value of NA because actual information concerning the involved number of suppliers is not available to them. An interesting extension to the current model would be to allow suppliers to obtain actual information from negotiations such as NA, but this is excluded here. The values of the parameters in Equation 5 are assumed based on the level of urgency and are presented in Table 1. The influence of these parameters on the offer $\alpha_s^i(t)$ is depicted in Figure 4. Alterations concerning the parameter values would yield other proposals and thus results. This resource-dependent offer strategy results in less pressure to approach reservation values if more suppliers are participating in negotiations. On the other hand, pressure increases if the number of rounds that have elapsed increase.

The value of $\alpha_s^i(t)$ determines the value of each negotiation attribute i for the proposal using Equation 7. The notation in Equation 7 matches Equations 5 and 6 and $I_s^i(t)$ is also represented in Equation 1. The top function in Equation 7 is applied

urgency level	τ^s	NA
High ($ur = 1$)	1	1
Medium ($ur = 2$)	3	2
Low ($ur = 3$)	5	3

Table 1: urgency levels and related offer parameters

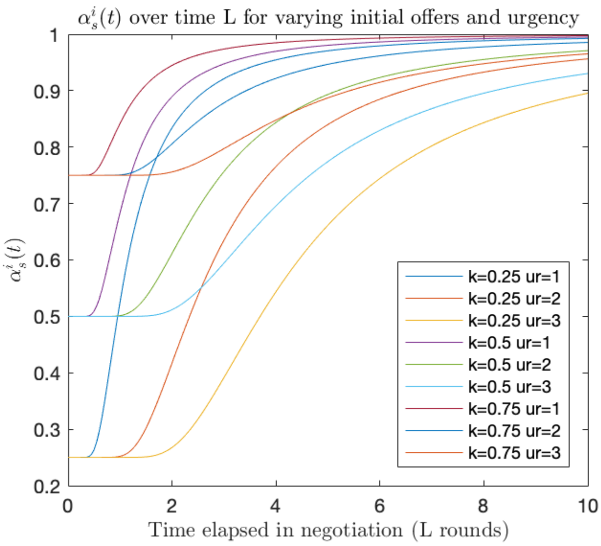


Figure 4: α offer strategy related to urgency ur and initial offer κ_s^i

to negotiation issues where the value increases when the pressure increases, i.e. delivery service and material quantity, the latter function is applied to negotiation issues where the value decreases when the pressure increases, i.e. unit price and delivery time. The value of each attribute $I_s^i(t)$ is proposed to the manager and to calculate the supplier's valuation and utility. The supplier valuation and utility is determined in the same way as the manager's (Equation 1), only the supplier performance is not applied in the supplier utility function. The top function in Equation 1 is applied to negotiation issues where an increased value is associated with benefit for the supplier, i.e. unit price, delivery time and quantity, and the latter function is applied to negotiation issues where an increased value is associated with cost for the supplier, i.e. delivery service. When no order is placed at a particular supplier, then the utility gained by that supplier equals zero. In an attempt to increase personal utilities of the self-interested agents and resemble adaptive human behaviour, adaptability techniques are applied to manager and supplier strategies.

$$I_s^i(t) = \begin{cases} min_s^i + \alpha_s^i(t)(max_s^i - min_s^i) \\ min_s^i + (1 - \alpha_s^i(t))(max_s^i - min_s^i) \end{cases} \tag{7}$$

3.5. Adaptability

The four adaptive elements related to agent strategies are discussed in this section. These are: adaptive reservation utility (3.5.1), adaptive τ (3.5.2), initial offer (3.5.3) and supplier performance (3.5.4).

3.5.1. Adaptive Manager Reservation Utility ru

The manager's reservation utility *ru* is a threshold that a particular proposal must exceed in order to be considered as acceptable. At the start of a negotiation, $ru(0)$ is equal for all AS, but as suppliers are withdrawn or excluded from further negotiations, the manager lowers its $ru(t)$ in order to increase chances of reaching an agreement with any of the remaining suppliers, following Equation 8. This adaptability is included in the model to resemble behaviour from the hangar manager to lower demands in order to reach an agreement, as in this case, a worse deal, i.e. resulting in a lower utility, is more preferable than no deal.

$$ru(t) = ru(0) - \frac{(\eta(0) - \eta(t))}{\omega} \tag{8}$$

Where $ru(t)$ equals the reservation utility at time point t, $\eta(0)$ equals the amount of suppliers in negotiation at t=0, $\eta(t)$ equals the amount of suppliers that are still participating in the negotiation at time point t and ω represents the manager's willingness to lower its reservation utility. The variable ω is used to represent willingness and flexibility of the manager, which may resemble a certain type hangar manager. The model allows for more complex representations of adaptive reservation utility, e.g. non-linear, but that is subject for future studies.

3.5.2. Adaptive τ^s Related to Urgency ur

As described in section 3.4.2, the estimated required number of negotiations rounds τ^s is dependent on the urgency *ur* of the material request. The value of τ^s influences the value of $\alpha^i_s(t)$. The parameter used in a current negotiation $\tau^s_{ur_n}$ is adapted for the next negotiation instance $\tau^s_{ur_{n+1}}$ based on *Moving Averages* (Equation 9).

$$\tau^s_{ur_{n+1}} = \frac{1}{m}\sum_{k=0}^{m-1} L^s_{ur_{n-k}} \tag{9}$$

Where $\tau^s_{ur_{n+1}}$, rounded to the nearest integer, equals the estimated number of required negotiation rounds for supplier s for the next negotiation, m represents the amount of historic time series that are considered for forecasting of $\tau^s_{ur_{n+1}}$ and $L^s_{ur_{n-k}}$ represents the number of rounds that have elapsed in negotiation $n-k$ between supplier s and the manager.

The value of m determines how reactive the value of τ is. In this research it is related to the level or urgency *ur*. The value of m equals $1, 3$ or 5 for $ur = 1, 2$ or 3, respectively. In the case of $ur = 1$ and $m = 1$, high urgency causes each supplier to create a belief that the amount of negotiation rounds elapsed in last negotiation with $ur = 1$ is needed again to reach an agreement in the current negotiation. For example, in negotiation n with $ur = 1$, only 1 bidding round has elapsed to reach an agreement, then for the next negotiation $n + 1$ with $ur = 1$, the supplier believes that only 1 round is needed, which influences its bidding strategy (Figure 4). For $m = 1$, τ is very reactive, i.e. takes the last value of τ, and for $m = 5$, τ is less reactive because five historic negotiations are used to forecast the required number of negotiations rounds for the next negotiation with urgency *ur*.

The Moving Average method is a relatively simple way of including adaptive τ in the model, but it is not the main topic of this research. In further research, extensions or more sophisticated methods can yield interesting results regarding relations between supplier adaptability to time critical situations and the reached agreements with the manager.

3.5.3. Adaptive Initial Offer $I^i_s(0)$

In an attempt to increase the utility of the self-interested suppliers, the initial offer $I^i_s(0)$ is adaptive. If a supplier s receives an order in negotiation n, then for the next negotiation $n + 1$ it adapts its initial offer for all issues in an attempt to reach a more beneficial deal, i.e. greater utility. If an agreement with a supplier is not reached, then for the next negotiation the initial offer is decreased with respect to the supplier's utility in an attempt to be more appealing to the manager, hoping to reach an agreement in the next negotiation. The initial offer is adapted based on a fixed percentage $\Delta I(0)$ (Equation 10 and 11). This method of including adaptive initial offers is assumed to resemble a way of increasing utilities of self-interested agents. More extensive research would be required to establish precisely how suppliers in the aircraft maintenance industry adopt their initial offers, but as this type of information is not available to this research, this relatively simple method is applied.

$$\text{Reached agreement in } n\text{: } I^i_{s_{n+1}} = I^i_{s_n}(0) \times (1 + \Delta I(0)) \tag{10}$$

$$\text{Failed agreement in } n\text{: } I^i_{s_{n+1}} = I^i_{s_n}(0) \times (1 - \Delta I(0)) \tag{11}$$

3.5.4. Adaptive Supplier Performance $P_s(t)$

As explained before, supplier performance is representative of the trust the manager has in a particular supplier and is capable of negatively influencing the utility gained from a proposal of supplier s by the manager (recall Equation 2). If an agreement is reached with supplier s during negotiation n, then the performance of the supplier $P_s(t)$ is increased with ΔP percent (Equation 12) resulting in an increased or maintained trust, i.e. $P_s(t) = 1.0$. If an agreement has failed then $P_s(t)$ decreases with ΔP percent (Equation 13) resulting in decreased trust in supplier s for the next negotiation. $P_s(t)$ ranges from 0 to 1, because overvaluation of supplier offers is not applied here, thus $P_s(t)$ can only be used to devalue the utility gained by the manager. Also, the values of $P_s(t)$ are used to determine probabilities of responses for suppliers in the negotiation protocol, thus range from 0 to 1 to use in the probabilities as well (Recall Figure 3). This is one way of representing manager trust in the model and it is assumed to resemble real-life trust adaptation, however the model allows for more elaborate methods to be used to, for example, include supplier specific methods as trust in a particular supplier may exhibit adaptive behaviour different than other suppliers. Along with the above mentioned adaptive parameters, the supplier stock levels are also adaptive in order to capture the element of competition (Recall Section 3.2.3).

$$\text{Reached agreement in } n\text{: } P_{s_{n+1}}(t) = P_{s_n}(0) \times (1 + \Delta P) \tag{12}$$

$$\text{Failed agreement in } n\text{: } P_{s_{n+1}}(t) = P_{s_n}(0) \times (1 - \Delta P) \tag{13}$$

4. Experiments

This section explains how the experiments are carried out and evaluated in order to assess the effectiveness of agent strategies in various negotiation circumstances and the methodology's applicability to the aircraft maintenance problem. Section 4.1 describes the various simulations that are performed. The KPIs are described in Section 4.2. A few initial values and methods of statistical evaluation are discussed in Section 4.3.

4.1. Simulation Sets

4.1.1. Simulation Set A

In simulation set A the model is simulated with variations applied to the simulated scenario (SC), manager acceptance strategy (AS), urgency level (*ur*) and competition (CO) (Table 2). Three different simulation sets are performed and their results are compared to the relevant baseline produced by another set. In simulation set A1, SC and AS is varied to assess how the model reacts to changes in acceptance strategies and scenarios while maintaining one level of urgency ($ur = 2$) and competition (CO=0). The results from simulation set A1 operate as baseline for simulation set A2 and A3 in which variations to *ur* and CO are made.

Sim	*SC*	*AS*	*ur*	*CO*	ω	ΔI	ΔP
A1	1/2	1/2/3	2	0	15	5	5
A2	1/2	1/2/3	1/3	0	15	5	5
A3	1/2	1	1	5/10	15	5	5

Table 2: Simulation set A

For simulation set A2, the greedy AS has been subject to an increase in urgency from 2 to 1, to simulate a more urgent request for materials. Patient and balanced AS would be more logical to apply to less urgent situations, thus the urgency has been decreased from 2 to 3 to simulate situations where the materials are not required as soon as possible. The results from simulation set A2 are compared to results from simulation set A1, with the same AS but an urgency level of 2.

In simulation set A3, the effect of competition is evaluated by introducing it to specific combinations of SC and AS. When competition is present, a greedy AS and high urgency level would be a logical strategy to apply instead of patient or balanced AS, thus in this simulation only the greedy AS is considered with urgency level 1 and a variation of CO levels 5 and 10. Results from these simulations are compared to the results from simulation A2 with greedy AS, urgency level 1 and CO=0.

4.1.2. Simulation Set B

For simulation set B only one combination of SC, AS, *ur* and CO is selected to assess the effects of ω, ΔI and ΔP on the outcomes of negotiation (Table 9). The combination of SC-AS-*ur*-CO: 2-1-1-10 has been selected because this situation resembles the case study materials with the most pressure: a request for aircraft expendables with high urgency. The competition level of 10 is used because this is the most pressing situation that is modelled. In this particular situation the adaptability of the model has been varied to assess its effect on performance.

Sim	*SC*	*AS*	*ur*	*CO*	ω	ΔI	ΔP
B1	2	1	1	10	10/20	5	5
B2	2	1	1	10	15	10/15	5
B3	2	1	1	10	15	5	10/15

Table 3: Simulation set B

In simulation B1, the manager willingness ω has been varied from 10 to 20 to simulate the situations in which a manager would be less or more willing to lower its reservation utility as suppliers are withdrawn or excluded from negotiations (Figure 5). In simulation B2 and B3, the percentage related to initial offer and supplier performance adaptation has been varied to 10 and 15 percent to assess their effect on the outcomes of negotiation. The results obtained from simulations B1, B2 and B3 are compared to the results from simulation A3's SC-AS-*ur*-CO-ω-ΔI-ΔP: 2-1-1-10-10-5-5 simulation.

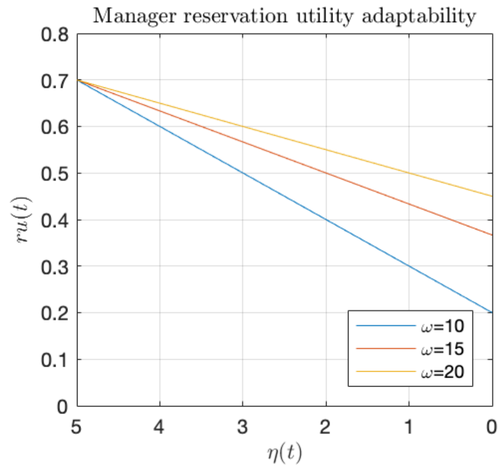


Figure 5: Manager's reservation utility as a function of ω with $\eta(0) = 5$

4.2. Performance Indicators

Adaptations in local properties and strategies are measured on a global level using performance indicators. The results from all simulations are evaluated by the same five KPIs:

- **Utilitarian Social Welfare (USW):** measure to indicate the benefit for all agents regarding the outcome of the negotiation by summing the individual utilities of all agents at the end of negotiation.
- **Time to Final Delivery (TFD):** measure to indicate the time that elapses from the start of negotiation until all ordered materials have arrived at the hangar. Relevant because a manager would like to receive the materials as soon as possible during an urgent request.
- **Average Unit Price (AUP):** measure to indicate the average unit price for the materials that are retrieved. A relevant measure because a hangar manager would prefer to minimize costs while a supplier would like to maximize revenue.
- **Total Quantity Retrieved (TQR):** measure to indicate the amount of materials retrieved during negotiations. In this

research the hangar manager requires to retrieve 200 units of material.

- **Quantity Check (QC):** verification measure whether if the required amount of materials are retrieved, i.e. 1 if yes, 0 if no.

Whereas more performance indicators are included in the model, e.g. total costs of procurement, together with a few verification measures to make sure that no orders are placed at suppliers whom are out of negotiation, only these five KPIs are considered here.

4.3. Simulation Plan

The method from Ross [35] was adopted to determine how many results should be generated in order to make statements on statistical significance. For each KPI an acceptable standard deviation has been assumed, equalling 0.06, 20, 5, 10 and 0.06, respectively for the five KPIs. For each simulation, twenty simulations with five runs each are performed in order to incorporate the adaptive elements throughout the runs, leading to 100 results per simulation. The sample standard deviation S from each of the KPIs when divided by the square root of the number of runs has not exceeded the chosen acceptable standard deviation, which makes the sample mean an estimate of the population mean. Besides, a sample was drawn from the simulations to assess the stability of the coefficient of variation for the KPIs in relation to the performed number of runs. Only for two of the fifteen sample combinations of simulation and KPI, the coefficient of variation has not yet stabilized with the performed number of runs.

In Table 4, the manager reservation values for the negotiation attributes are presented along with the weights assigned to each attribute. These values are constant through the simulations and are assumed to represent case-related real-life values a hangar manager would maintain. Changing the initial values of the manager would very likely yield different results but a sensitivity analysis on these values is not included in this research. A similar representation of the supplier reservation values, together with values for their initial offers are omitted here, but these are subject to the same assumption. Heterogeneity of suppliers is guaranteed by applying different values for material stock levels as well as different reservation values for negotiation issues. The deadline for proposing a deal is set at the maximum of ten bidding rounds for each individual supplier.

Attribute	max^i_m	min^i_m	w^i_m (SC1)	w^i_m (SC2)
Unit Price (UP)	400	0	0.45	0.3
Delivery Time (DT)	500	10	0.45	0.3
Delivery Service (DS)	1	0	0.1	0.1
Material Quantity (MQ)	200	10	n/a	0.3

Table 4: Manager reservation values and weights for negotiation attributes

At the start of negotiation the supplier performance $P_s(0)$ equals 0.95 for all suppliers, but this is subject to adaptability as discussed before. This assumed value is equal for all suppliers in order to prevent bias from the start of negotiation in terms of trust in suppliers. For comparison reasons, the initial reservation utility $ru(0)$ for the manager equals 0.7 for all manager AS.

In the next section the results from the simulations conducted in simulation sets A and B are evaluated using the sample mean $\bar{X}$, sample standard deviation S, i.e. an estimate of standard deviation σ, and $\bar{X} \pm \Delta X$, a 95% confidence interval estimate of the population mean θ [35]. For each of the simulation sets, a null hypothesis H_0 is formulated. The specific null hypothesis is rejected for a KPI in every simulation at the 0.05 significance level, otherwise the null hypothesis is retained [36]:

A1: The tested KPI is unaffected by a variation of AS within simulated SC.
A2: The tested KPI is unaffected by a variation of the level of urgency *ur*, when maintaining AS within simulated SC.
A3: The tested KPI is unaffected by a variation of the level of competition CO, when maintaining AS and urgency levels within simulated SC.
B1: The tested KPI is unaffected by a variation of manager's willingness ω, when maintaining SC, AS, *ur*, CO, ΔI and ΔP.
B2: The tested KPI is unaffected by a variation of adaptability of initial offer ΔI, when maintaining SC, AS, *ur*, CO, ω and ΔP.
B3: The tested KPI is unaffected by a variation of adaptability of supplier performance ΔP, when maintaining SC, AS, *ur*, CO, ω and ΔI.

A null hypothesis is rejected if statistical significance is found, meaning that their exists a relation between the local behaviour or circumstance and global performance. Normality of the results for all simulations has been evaluated using the Kolmogorov-Smirnov test and it has shown that all results do not match a normal distribution. Statistical evaluation has been performed using the Mann-Whitney U test, i.e. Wilcoxon rank test, for all KPIs, except the Quantity Check. This binary variable has been evaluated using the Chi-Squared test when the observed count of 0 and 1 exceeded ten, otherwise the Fisher-exact Test was applied.

5. Results

The sections below present and briefly discuss results obtained from experiments discussed in the previous sections. Results of simulations A1 (5.1), A2 (5.2), A3 (5.3) and B (5.4) are presented consecutively. Section 5.5 discusses trade-offs between KPIs as a result of applied strategies and negotiation circumstances.

5.1. Simulation A1

The results from simulation set A1 operate as baseline results for comparison to the results from the other simulations, but also give insights concerning application of the various manager AS (Table 5). A box plot of the simulation results for A1 is included to visually represent the spread of results (Figure 6), QC is not included because of its binary nature.

		1-1-2-0	1-2-2-0	1-3-2-0	2-1-2-0	2-2-2-0	2-3-2-0
USW	$\bar{X}$	1.496	1.453	1.536	1.570	1.434	1.505
	S	0.146	0.167	0.097	0.200	0.126	0.181
	ΔX	0.029	0.033	0.019	0.039	0.025	0.035
TFD	$\bar{X}$	383.7	555.3	489.1	366.9	550.1	471.0
	S	118.0	154.7	146.3	54.4	114.9	112.9
	ΔX	23.1	30.3	28.7	10.7	22.5	22.1
AUP	$\bar{X}$	54.03	48.74	48.94	110.78	121.99	123.04
	S	20.54	26.00	15.17	25.76	19.83	19.11
	ΔX	4.03	5.10	2.97	5.05	3.89	3.75
TQR	$\bar{X}$	196.0	189.5	195.0	233.7	269.6	253.5
	S	13.63	23.88	15.08	47.95	65.60	42.09
	ΔX	2.67	4.68	2.96	9.40	12.86	8.25
QC	$\bar{X}$	0.920	0.810	0.900	0.830	0.938	0.970
	S	0.273	0.394	0.302	0.378	0.243	0.171
	ΔX	0.053	0.077	0.059	0.074	0.048	0.034

Table 5: Statistical results from simulation A1

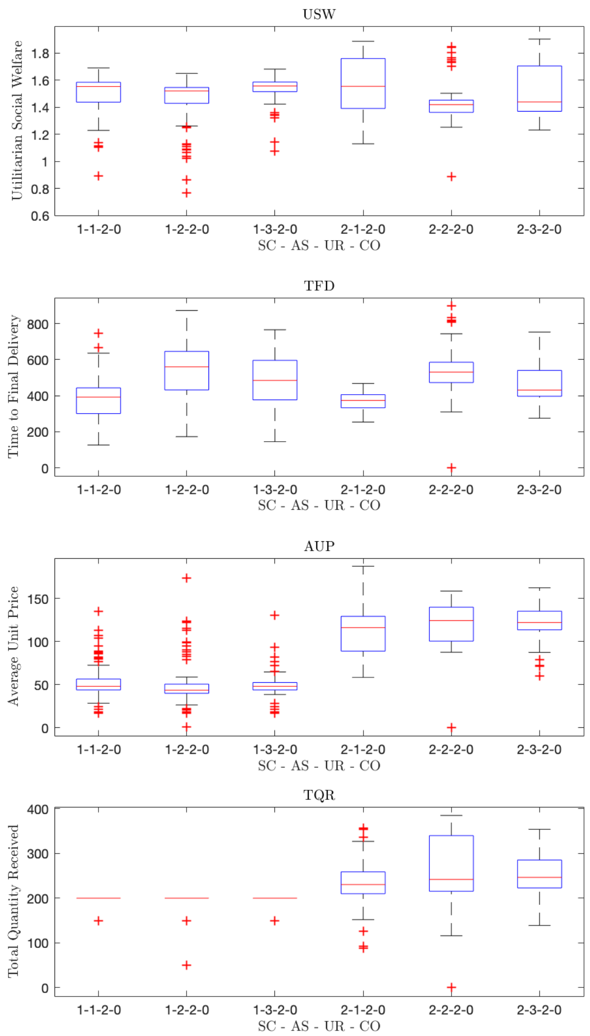


Figure 6: Box plots of results from simulation A1

Statistical tests have been performed on the TFD, AUP and TQR KPIs for this simulation set to assess if statistically significant results are obtained in varying manager AS. The results of the statistical test are presented in Table 6. The null hypothesis is rejected in comparisons highlighted green. The TFD shows statistically significant differences across all simulations. With AUP and TQR when comparing the greedy AS with balanced AS, the null hypothesis is retained, meaning that the change in AS does not statistically significant affect these KPIs for SC1. For SC1, the null hypothesis is retained for the TQR when comparing patient AS and balanced AS. The change from patient to balanced AS for SC2 does not lead to statistically significant results for AUP and TQR, thus H_0 is retained here. The results obtained from this set as presented in Table 5 are compared to results from set A2.

	TFD		AUP		TQR	
Compared results	p	H_0	p	H_0	p	H_0
1-1-2-0 vs 1-2-2-0	0.000	rejected	0.000	rejected	0.022	rejected
1-1-2-0 vs 1-3-2-0	0.000	rejected	0.317	retained	0.624	retained
1-2-2-0 vs 1-3-2-0	0.005	rejected	0.006	rejected	0.069	retained
2-1-2-0 vs 2-2-2-0	0.000	rejected	0.007	rejected	0.013	rejected
2-1-2-0 vs 2-3-2-0	0.000	rejected	0.002	rejected	0.003	rejected
2-2-2-0 vs 2-3-2-0	0.000	rejected	0.424	retained	0.781	retained

Table 6: Hypothesis test results from A1

5.2. *Simulation A2*

In simulation set A2 a variation in the level of urgency is introduced to explore the effects on results relating to specific AS. For the greedy AS the *ur* has been increased, i.e. $ur = 1$, and for patient and balanced strategy has been lowered, i.e. $ur = 3$. The results of each variation is compared to the results from simulation A1 with the same SC and AS. The results are presented in Table 7. The cells highlighted green relate to statistically significant differences based on applicable statistical tests.

		1-1-1-0	1-2-3-0	1-3-3-0	2-1-1-0	2-2-3-0	2-3-3-0
USW	$\bar{X}$	1.453	1.487	1.543	1.489	1.445	1.524
	S	0.169	0.131	0.149	0.165	0.177	0.209
	ΔX	0.033	0.026	0.029	0.032	0.035	0.041
	p	0.003	0.058	0.005	0.031	0.449	0.674
TFD	$\bar{X}$	373.4	524.3	507.6	322.0	599.5	489.4
	S	74.9	165.0	156.4	31.2	141.9	114.3
	ΔX	14.7	32.4	30.6	6.1	27.8	22.4
	p	0.190	0.227	0.387	0.000	0.000	0.070
AUP	$\bar{X}$	59.20	47.13	52.73	112.61	111.96	118.39
	S	25.11	17.34	19.85	21.75	28.96	21.56
	ΔX	4.92	3.40	3.89	4.26	5.68	4.23
	p	0.390	0.654	0.264	0.779	0.076	0.129
TQR	$\bar{X}$	199.5	192.0	196.0	254.9	226.3	239.2
	S	5.00	22.16	13.63	47.28	62.27	44.65
	ΔX	0.98	4.34	2.67	9.27	12.21	8.75
	p	0.017	0.348	0.624	0.005	0.000	0.008
QC	$\bar{X}$	0.990	0.860	0.920	0.960	0.750	0.850
	S	0.100	0.349	0.273	0.197	0.435	0.359
	ΔX	0.020	0.068	0.053	0.039	0.085	0.070
	p	0.035	0.203	0.806	0.005	0.000	0.000

Table 7: Statistical results from simulation A2

For both SC increasing the level or urgency from 2 to 1 results in statistically significant decreased values of USW. The TFD and AUP drop when urgency is increased but only statistically significant for the TFD in the 2-1-1-0 simulation. Both simulations with $ur = 1$ show statistically significant increases compared to their baseline from A1 when considering TQR and QC. This means that in both simulations increasing the urgency leads to an increase of retrieved materials, which would be preferable in a high urgent situation.

Whereas decreasing the urgency level for the patient AS in SC1 has not resulted in statistically significant results, performing the same variation to SC2 has resulted in statistically significant results. The TFD increases, TQR decreases and QC decreases statistically significant when the urgency level is decreased.

Decreasing the urgency level for the balanced AS shows an increase of all KPIs sample means when comparing them to the baseline from 1-3-2-0 (Table 5). However, only for the USW the null hypothesis is rejected. Considering SC2, the TQR and QC statistically significantly decrease. As with the patient AS, this is probably caused by creating more opportunities for suppliers to refuse to bid as more bidding rounds elapse (Recall Figure 3).

		1-1-1-5	1-1-1-10	2-1-1-5	2-1-1-10
USW	$\bar{X}$	1.505	1.478	1.584	1.588
	S	0.090	0.113	0.234	0.541
	ΔX	0.018	0.022	0.046	0.106
	p	0.580	0.917	0.017	0.015
TFD	$\bar{X}$	367.7	358.8	321.4	315.2
	S	64.9	81.3	37.6	105.7
	ΔX	12.7	15.9	7.4	20.7
	p	0.467	0.017	0.767	0.537
AUP	$\bar{X}$	57.24	67.97	116.19	88.16
	S	12.35	18.01	20.49	42.46
	ΔX	2.42	3.53	4.02	8.32
	p	0.004	0.000	0.186	0.000
TQR	$\bar{X}$	200.0	198.9	255.9	189.5
	S	0.00	8.43	43.73	74.16
	ΔX	0.00	1.65	8.57	14.54
	p	0.322	0.180	0.862	0.000
QC	$\bar{X}$	1.000	0.960	0.970	0.600
	S	0.000	0.197	0.171	0.492
	ΔX	0.000	0.039	0.034	0.097
	p	0.315	0.369	0.610	0.000

Table 8: Statistical results from simulation A3

5.3. Simulation A3

In simulation A3 competition is introduced to relevant scenarios. CO levels 5 and 10 are applied to the greedy AS for SC1 and SC2. The results from these simulations are compared to the results from A2 with the greedy AS and $ur = 1$ where no competition was included, i.e. CO = 0. Results are presented in Table 8. The null hypothesis is rejected for particular KPIs and simulations in cases where cells are highlighted green. Increasing CO results in a decrease in TFD, statistically significant in case of CO level 10 for SC1. The AUP decreases statistically significantly when the CO level equals 5, but increases statistically significant when CO level equals 10. Interestingly, increasing the level of CO for SC1 with the greedy AS does not result in a statistically significant decrease of TQR and QC, whereas one would expect a decrease due to the method of including competition in the model. Here H_0 is retained meaning that the introduction of competition does not affect the TQR and QC for greedy AS in SC1.

The introduction of competition to SC2 shows different results compared to the competition level introduction in SC1. Compared to the 2-1-1-0 simulation results (Table 7), the 2-1-1-5 and 2-1-1-10 scenarios both show a statistically significant increase in USW. The AUP statistically significantly decreases when the competition level is increased to 10, just as the TQR and QC. Striking is the difference in TQR and QC between competition levels 5 and 10. Whereas with 95% confidence the TQR's population mean is between 247 and 264, the mean for CO level 10 is between 175 and 204.

5.4. Simulation B

This simulation set assesses if the negotiation results are affected by variations to adaptive parameters: ω, ΔI and ΔP. The baseline for the results of simulation set B are the results from simulation 2-1-1-10 (Table 8) and are also displayed in Table 9 highlighted in grey. Decreasing the manager's willingness ω from 15 to 20 in simulation B1 does not result in statistically significant differences, thus H_0 is retained. However, increasing ω to 10 (Figure 5) does show a statistically significant increase in USW, TFD, TQR and QC. These KPIs are affected by a increase in the willingness of the hangar manager, thus H_0 is rejected for these KPIs in simulation B1.

Increasing the percentage of initial offer adaptation in simulation B2 shows that when ΔI is increased to 10% the USW and TFD statistically significantly decrease, thus the null hypothesis is rejected for these KPIs. Interestingly, the same results are not obtained when ΔI is increased to 15%. QC also decreases statistically significant when ΔI equals 10. When increasing ΔI to 15% the TQR increases statistically significant. It is worth noting that the 15-10-5 simulation results in a decrease of all KPI's sample mean and the increment of ΔI to 15% results in an increase of the sample mean of all KPIs.

			B1		B2		B3	
		15-5-5	20-5-5	10-5-5	15-10-5	15-15-5	15-5-10	15-5-15
USW	$\bar{X}$	1.588	1.472	1.775	1.447	1.569	1.655	1.536
	S	0.541	0.327	0.566	0.349	0.403	0.423	0.287
	ΔX	0.106	0.064	0.111	0.068	0.079	0.083	0.056
	p		0.157	0.003	0.027	0.369	0.114	0.651
TFD	$\bar{X}$	315.2	293.8	366.5	284.3	327.2	298.9	287.7
	S	105.7	89.3	95.5	107.7	69.5	93.2	98.6
	ΔX	20.7	17.5	18.7	21.1	13.6	18.3	19.3
	p		0.584	0.000	0.046	0.077	0.978	0.082
AUP	$\bar{X}$	88.16	80.20	100.68	77.40	92.34	76.16	78.20
	S	42.46	43.47	33.43	47.80	34.62	42.43	43.27
	ΔX	8.32	8.52	6.55	9.37	6.79	8.32	8.48
	p		0.123	0.099	0.100	0.835	0.028	0.058
TQR	$\bar{X}$	189.5	180.1	223.7	177.8	217.5	183.7	176.1
	S	74.16	81.34	66.06	83.72	66.17	77.47	74.37
	ΔX	14.54	15.94	12.95	16.41	12.97	15.19	14.58
	p		0.176	0.003	0.417	0.016	0.460	0.088
QC	$\bar{X}$	0.600	0.510	0.700	0.460	0.670	0.520	0.450
	S	0.492	0.502	0.461	0.501	0.473	0.502	0.500
	ΔX	0.097	0.098	0.090	0.098	0.093	0.098	0.098
	p		0.066	0.041	0.004	0.153	0.103	0.002

Table 9: Statistical results from simulation set B

When considering the results from simulation B3 in which the supplier performance adaptability has been increased, it can be observed that for the USW, TFD and TQR KPIs the null hypothesis is retained. The AUP does show a statistically significant decrease for the simulation in which ΔP equals 10. The AUP also decreases when ΔP equals 15 compared to the baseline from 15-5-5 but as $p = 0.088$, H_0 is retained. From the results in Table 9 it can be observed that the TQR and QC decrease when the adaptability of supplier performance is increased, i.e. QC decreases statistically significantly when $\Delta P = 15$. Figure 7 shows box plots for the simulation results from simulation set B.

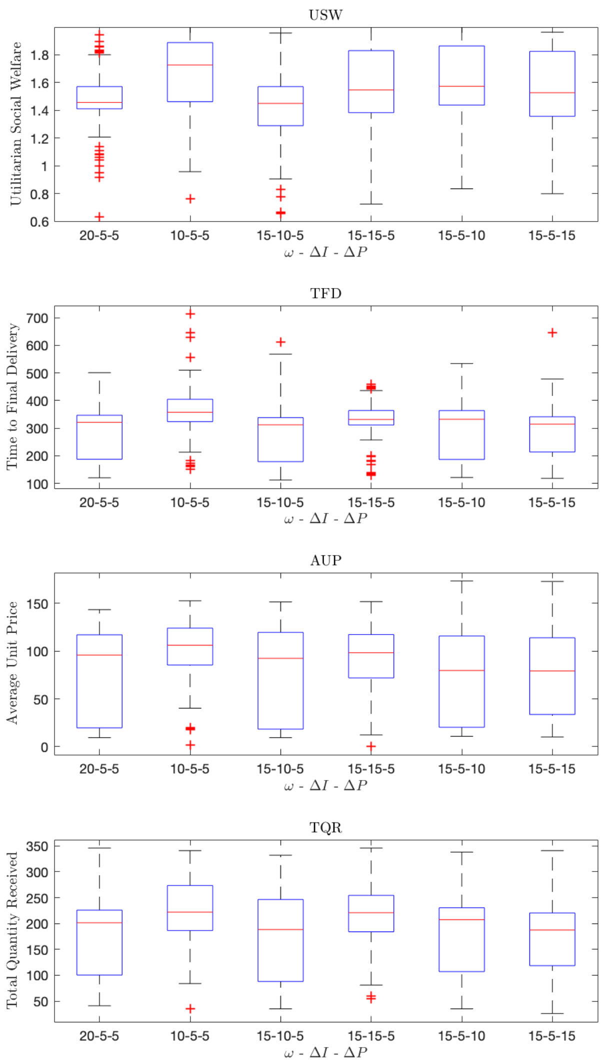


Figure 7: Box plots of results from simulation B

5.5. Trade-offs and Relative Results

In Figures 8 and 9 below, two trade-offs are displayed by the sample means of four KPIs from all performed simulations. One can observe the results from the trade-off that is made between TFD and AUP when simulating a specific scenario that is subject to the chosen AS, level of *ur* and CO. Figure 9 displays a similar trade-off, but then between TQR and QC.

When considering Figure 8, four interesting clusters can be identified in terms of results from the simulations for TFD and

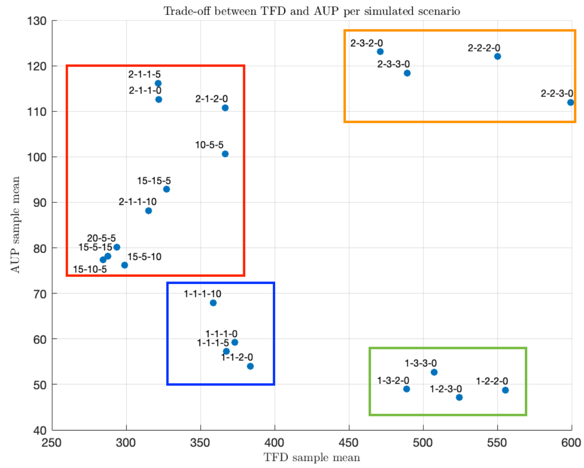


Figure 8: Tradeoff between TFD and AUP

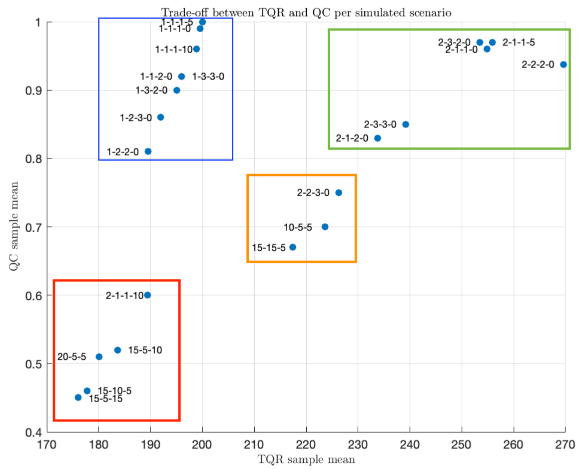


Figure 9: Tradeoff between TQR and QC

AUP KPIs. The cluster represented by the red frame are simulations that result in relatively high AUP and low TFD. These simulations are only SC2 simulations with high urgency and competition. The blue frame is a cluster of simulations that lead to relatively low AUP and low TFD, ideal for high to medium urgency request while attempting to minimize costs. The orange framed cluster are simulations with balanced and patient AS for SC2 with relatively high AUP and high TFD. The combination between high AUP and high TFD is not very desirable for the hangar manager in any situation. Lastly, the green frame represents a cluster of SC1 simulations with patient and balanced AS with relatively low AUP and high TFD. These situations could be desirable when facing low urgency while attempting to minimize costs.

Figure 9 shows the relative results from the simulations in terms of TQR and QC. The red framed cluster shows simulations that result in relatively low TQR and low QC. These simulations are all SC2 simulations with the greedy AS while facing competition. The blue frame clusters the results from

SC1 simulations with various AS, *ur* and CO levels. None of these simulations exceeds the required number of 200 materials, but is associated with a high QC. The orange framed cluster shows results from simulations that result in an mean TQR just over 200 and a QC of around 0.7. Interestingly, the 10-5-5 and 15-5-5 simulations are located in this cluster while variations to these simulations are all located in the red cluster. Lastly, the green cluster represent SC2 simulations that on average exceed the required 200 materials by at least 30, while also achieving a relatively high value of QC. When policy makers attempt to retrieve more materials than required, e.g. safety stock, adopting the strategies from these simulations would be effective, assuming the circumstances are similar and assumptions are valid.

6. Discussion

This discussion starts with an interpretation of the results presented in the previous section (6.1). A reflection on the proposed methodology is given in Section 6.2. Recommendations are presented in Section 6.3. Lastly, opportunities for future work are discussed (6.4).

6.1. Interpretation of Results

The results presented in the previous sections show that the presented methodology and model can simulate different circumstances of negotiation that lead to statistically significant results. When concerning the procurement of aircraft components under the circumstances simulated by simulation set A1, the results can be interpreted as a guideline to determine which AS is effective when pursuing a certain goal. For instance, if a manager has the goal to achieve the quickest delivery time of aircraft components, it should adopt the greedy AS because it is statistically significant shorter than with another AS. On the other hand, if the manager aims to minimize AUP, it would be the most effective to adopt a patient AS as its results are statistically significant lower than with the greedy and balanced AS. If a hangar manager wants to achieve the highest TQR or QC, it should adopt the greedy AS. Unexpectedly, the greedy AS results in the highest values of these KPIs where one would expect a patient or balanced AS to result in higher TQR and QC.

When interpreting the results from SC2 in simulation A1, procurement of aircraft expendables, similar statements can be made. Again the greedy AS shows to be the most effective when attempting to retrieve the required materials as quickly as possible. In contrast to SC1, applying the greedy AS will also result in the lowest AUP, unexpectedly. However, if a manager wants to retrieve the highest QC or TQR, it would be best to adopt a patient or balanced AS. To synthesize, simulation set A1 has shown that adopting a particular AS, while under the same circumstances in terms of urgency and competition, can lead to improved or deteriorated results when attempting to achieve a certain goal.

Simulation set A2 has been performed to assess the model's sensitivity to the introduction of urgency to certain AS. For both SCs, it is shown that increasing the level of urgency while maintaining a greedy AS will result in increased values of TQR and QC. For the aircraft expendables scenario, i.e. SC2, it is shown that this increase in urgency will result in a quicker delivery of the required materials, which is very desirable in a time critical situation. SC1 has shown to be less reactive to a decrease in urgency as only the USW of the balanced AS has shown a statistically significant increase, meaning that on average the summed utilities of all agents has increased.

For aircraft expendables, a decrease in the level of urgency when applying the patient or balanced AS has resulted in a statistically significant decrease of TQR and QC. Thus in the case that no time critical situation is present, it would be best to act as if urgency is higher in order to retrieve more materials when adopting one of these AS.

Simulation set A3 showed the model's reactivity in terms of the KPIs when incorporating competition to the procurement of aircraft components and expendables. The results have shown that the introduction to CO level 5 does not really affect results when simulating the greedy AS with high urgency. For both SC1 and SC2, only one KPI has shown statistically significant changes, AUP and USW respectively. This means that the other KPIs are unaffected by CO level 5, i.e. H_0 is retained, which is unexpected and positive for the manager. When CO is increased to 10, the TFD and AUP show statistically significant changes for SC1, resulting in a shorter TFD and higher AUP. Concerning the TQR and QC in this respect, H_0 is retained, meaning that the KPIs are not affected by this level of competition. This is worth noting because competition levels affect supplier stock levels, meaning that the model may be considered as robust when concerning TQR and QC for SC1 with CO level 10.

CO level 10 has shown statistically significant differences for four out of five KPIs, only for TFD the null hypothesis is retained. The increase in USW, decreases in AUP, TQR and QC mean that for all agents the final solution is better and the average unit price has dropped for the manager. However, in an average of only 60% of the simulations the required material quantity was retrieved. This means, in contrary to the results concerning SC1, the TQR and QC are statistically significantly affected in SC2 because of the decrease of supplier stock levels.

Simulation set B has been performed to assess the sensitivity of a few negotiation parameters. In B1, variations to the manager willingness ω has shown interesting results. A less willing manager, i.e. $\omega = 20$, has not shown statistically significant results, whereas a more willing manager has lead to the rejection of the null hypothesis. A more willing manager has lead to an increase in USW, TFD, TQR and QC. At the cost of a longer TFD, the manager thus retrieves more materials and exceeds the required number of materials more often. This could be an effective manager strategy when attempting to retrieve more materials when urgency is not the most important theme, but further studies concerning this expectation are not performed here.

Simulation B2 has shown that the increase of initial offer adaptation to 10% leads to statistically significant decreases of USW, TFD and QC. Interestingly, this means that if the offer adaptation is increased, this leads to a quicker delivery of materials but the required quantity is less often retrieved by the manager. This can be considered as a trade-off in time critical situations. Increasing ΔI to 15% has not show the same reactivity as 10% as this change only leads to a statistically significant increase in TQR. This would be beneficial to the manager because more materials are retrieved while other KPIs remain unaffected.

Simulation B3 has assessed the influence of ΔP on KPI results. In both variations, the increase of ΔP has only lead to one statistically significant difference when compared to the baseline in which $\Delta P = 5$. This means that the model is quite robust as the KPIs remain relatively unaffected while also considering that the value of P_s affects the probability that suppliers will refuse to share their material quantity, propose a deal or de-commit an agreement (Figure 3).

6.2. Reflection on Proposed Methodology

The proposed ABM and automated negotiation methodology has shown to be capable of simulating human elements and interactions in the process of procurement of aircraft materials. In this respect, an advantage of the methodology is that it allows for further inclusion of human behaviour and reasoning. Currently included human elements are adaptive features and agent strategies that represent human behaviour, along with the possibility to refuse bidding or end negotiation with a supplier. The methodology allows for more complex human reasoning concerning what action to take in the negotiation by allowing observation of other suppliers and their proposals, but this would require a substantial elaboration of the current model. Another strong point is that the methodology allows for extension that may resemble real-life events. Urgency and competition are already included, but the model could be adjusted specifically to simulate a particular real-life situation. The automated negotiation protocol that is proposed is believed to be very suitable to represent the buyer-seller environment for aircraft maintenance, however it would be interesting how the model behaves if other protocols are applied. The used protocol has shown to be reactive to particular simulations, where it has also shown robustness for other situations subject to competition as discussed in the previous section. Overall, the proposed methodology has shown that it is capable of simulating the procurement of aircraft components and expendables with the inclusion of urgency and competition elements.

The proposed methodology also exhibits some disadvantages, for instance that most initial values and strategies are based on assumptions related to the case study. The model and methodology requires validation to real-life data in order to judge if it is capable to simulate real-life events. Also, the model is, as established, reactive in most negotiation situations, meaning that changing the value of one or more parameters could alter the results completely. In other words, in a future attempt to maximize negotiation solutions for any agent, extensive parameter tuning would be required. Another possibility would be to apply game-theoretic methods for exploring dominant and best strategies for agents, in attempts to find optimal outcomes which could allow to predict future outcomes. Another weak point is the relatively simple representation of urgency and competition in the model. The relatively simple methods have shown to affect results, but do not necessarily represent real-life urgency or competition events. More sophisticated ways of including urgency or competition in the model would allow further exploration of the model's capabilities. This is also valid for the methods applied in the adaptability of the model, these could be more complex, e.g. relating specific adaptations to individual agents. In this research, adaptive parameters are equal to all agents.

6.3. Recommendations

Considering the interpretations of results, it is possible to recommend policy makers to explore the effects of negotiation strategies in real-life. Table 10 below suggests the recommended negotiation strategies for particular negotiation circumstances.

Material	*ur*	Goal	Recommended AS
Components	1	Max TQR	Greedy
	2	Min TFD	Greedy
	2	Min AUP	Patient
	2	Max TQR	Greedy / Balanced
	3	Min AUP	Patient
	3	Max TQR	Balanced
Expendables	1	Min TFD, Max TQR	Greedy
	2	Min TFD, Min AUP	Greedy
	2	Max TQR	Patient / Balanced
	3	Min AUP	Patient
	3	Max TQR	Balanced

Table 10: Recommended AS for specific situations, all for CO= 0

The strategies in Table 10 are recommended in particular situations of urgency when pursuing a specific goal. For situations subject to competition, it would be recommended to apply the greedy AS, as this is the only AS simulated in these situations. It is recommended to policy makers to recognize particular situations and then apply the strategies associated with their goal and situation.

It is also recommended to further evolve the methodology proposed in this research to simulate other (aircraft maintenance) applications. The methodology can also be applied to the procurement of aircraft maintenance equipment and be used to simulate other negotiations that take place in the aircraft maintenance domain, e.g. scheduling problems and resource allocations. Outside the aircraft maintenance domain, the proposed methodology can be adopted to simulate other instances of buyer-seller negotiations with one buyer and multiple suppliers. It is recommended to apply the methodology to these problems and assess its capabilities there.

6.4. Opportunities for future work

Concerning further work, it is recommended to validate the proposed model to a real-life data set showing historic agreements between suppliers and a hangar manager. Extension of the methodology would yield possibilities to study cases of restock of materials at suppliers while facing competition. As mentioned, the methodology allows for extensions with more (homogeneous) or other suppliers and even multiple buyers. It is recommended to apply required extensions to simulate particular cases from inside and outside the aircraft maintenance domain.

Future work can also be performed within the existing model, such as finding the optimal manager strategy and value of ω to achieve the desired performance from the manager's perspective. Within the current methodology other methods may be applied to alter supplier responses in interactions with the manager. In the current model, the probabilities are equally calculated for each supplier, but this may be adapted in order to better resemble specific suppliers.

Applying the proposed methodology to other existing fields of supply chain optimization would hopefully yield novel insights in negotiations involved in these processes.

7. Conclusion

This research is novel in applying multi-agent automated negotiation methodology to an aircraft maintenance problem regarding non-routine material availability. Recall the main research question: *In the context of non-routine aircraft maintenance materiel availability, to what extent can multi-agent automated negotiation be applied to explore effective agent strategies for various negotiation circumstances regarding the procurement of aircraft components and expendables?*

As established in the previous section, the research has been successful in establishing relations between local agent negotiation strategies and global performance, resulting in recommendations to practice to apply certain strategies when facing certain circumstances. It is therefore concluded that the automated negotiation method proposed in this research is very suitable to simulate non-routine material procurement negotiations and has shown its applicability when exploring particular negotiation strategies for the aircraft maintenance environment.

The methodology has potential to be adapted to include other or more suppliers, other or more advanced negotiation strategies and more parameters to enhance complex negotiations or increase realism. This research has shown that the effectiveness of aircraft maintenance procurement negotiations is subject to circumstances of the negotiation, e.g. competition and urgency, and the negotiation strategies chosen by involved parties, e.g. manager type.

References

[1] N. Papakostas, P. Papachatzakis, V. Xanthakis, D. Mourtzis, G. Chryssolouris, An approach to operational aircraft maintenance planning, Decision Support Systems 48 (2010) 604–612.

[2] H. A. Kinnison, T. Siddiqui, Aviation maintenance management, 2012.

[3] N. Kohl, A. Larsen, J. Larsen, A. Ross, S. Tiourine, Airline disruption managementperspectives, experiences and outlook, Journal of Air Transport Management 13 (2007) 149–162.

[4] P. Samaranayake, S. Kiridena, Aircraft maintenance planning and scheduling: an integrated framework, Journal of Quality in Maintenance Engineering 18 (2012) 432–453.

[5] P. Belobaba, A. Odoni, C. Barnhart, The global airline industry, John Wiley Sons, 2016.

[6] M. R. Endsley, M. M. Robertson, Situation awareness in aircraft maintenance teams, International Journal of Industrial Ergonomics 26 (2000) 301–325.

[7] A. T. Crooks, A. J. Heppenstall, Introduction to agent-based modelling, Springer, 2012.

[8] Z. Yang, G. Yang, Optimization of aircraft maintenance plan based on genetic algorithm, Physics Procedia 33 (2012) 580–586.

[9] J. Sheng, D. Prescott, A coloured petri net framework for modelling aircraft fleet maintenance, Reliability Engineering System Safety 189 (2019) 67–88.

[10] Y. Liu, T. Wang, H. Zhang, V. Cheutet, G. Shen, The design and simulation of an autonomous system for aircraft maintenance scheduling, Computers Industrial Engineering (2019) 106041.

[11] Y. Qin, Z. Wang, F. T. Chan, S. Chung, T. Qu, A mathematical model and algorithms for the aircraft hangar maintenance scheduling problem, Applied Mathematical Modelling 67 (2019) 491–509.

[12] A. Stranjak, P. S. Dutta, M. Ebden, A. Rogers, P. Vytelingum, A multi-agent simulation system for prediction and scheduling of aero engine overhaul, in: Proceedings of the 7th international joint conference on Autonomous agents and multiagent systems: industrial track, International Foundation for Autonomous Agents and Multiagent Systems, 2008, pp. 81–88.

[13] N. Safaei, A. K. Jardine, Aircraft routing with generalized maintenance constraints, Omega 80 (2018) 111–122.

[14] W. J. Verhagen, L. W. De Boer, Predictive maintenance for aircraft components using proportional hazard models, Journal of Industrial Information Integration 12 (2018) 23–30.

[15] V. S. V. Dhanisetty, W. J. C. Verhagen, R. Curran, Multi-criteria weighted decision making for operational maintenance processes, Journal of Air Transport Management 68 (2018) 152–164.

[16] P. Callewaert, W. J. C. Verhagen, R. Curran, Integrating maintenance work progress monitoring into aircraft maintenance planning decision support, Transportation Research Procedia 29 (2018) 58–69.

[17] R. Dekker, Applications of maintenance optimization models: a review and analysis, Reliability engineering system safety 51 (1996) 229–240.

[18] S. Zhu, W. v. Jaarsveld, R. Dekker, Spare parts inventory control based on maintenance planning, Reliability Engineering System Safety 193 (2019) 106600.

[19] R. J. Basten, J. K. Ryan, The value of maintenance delay flexibility for improved spare parts inventory management, European Journal of Operational Research 278 (2019) 646–657.

[20] A. Sahay, 3 - Aircraft maintenance paradigm, Woodhead Publishing, 2012.

[21] S. Fatima, S. Kraus, M. Wooldridge, Principles of automated negotiation, Cambridge University Press, 2014.

[22] T. Wong, F. Fang, A multi-agent protocol for multilateral negotiations in supply chain management, International Journal of Production Research 48 (2010) 271–299.

[23] R. Aydoğan, D. Festen, K. V. Hindriks, C. M. Jonker, Alternating offers protocols for multilateral negotiation, Springer, 2017.

[24] C. M. Jonker, V. Robu, J. Treur, An agent architecture for multi-attribute negotiation using incomplete preference information, Autonomous Agents and Multi-Agent Systems 15 (2007) 221–252.

[25] C. Jonker, V. Robu, Automated multi-attribute negotiation with efficient use of incomplete preference information (2004) 1054–1061.

[26] G. Lai, C. Li, K. Sycara, J. Giampapa, Literature review on multi-attribute negotiations, Robotics Inst., Carnegie Mellon Univ., Pittsburgh, PA, Tech. Rep. CMU-RI-TR-04-66 (2004).

[27] G. Lai, K. Sycara, A generic framework for automated multi-attribute negotiation, Group Decision and Negotiation 18 (2009) 169.

[28] G. Lai, K. Sycara, C. Li, A decentralized model for automated multi-attribute negotiations with incomplete information and general utility functions, Multiagent and Grid Systems 4 (2008) 45–65.

[29] R. Zheng, T. Dai, K. Sycara, N. Chakraborty, Automated multilateral negotiation on multiple issues with private information, INFORMS Journal on Computing 28 (2016) 612–628.

[30] Q. Feng, S. Li, B. Sun, A multi-agent based intelligent configuration method for aircraft fleet maintenance personnel, Chinese Journal of Aeronautics 27 (2014) 280–290.

[31] M. J. Osborne, A. Rubinstein, Bargaining and markets, Academic press, 1990.

[32] V. Krishna, Auction theory academic press, San Diego, USA (2002).
[33] R. G. Smith, The contract net protocol: High-level communication and control in a distributed problem solver, IEEE Transactions on computers (1980) 1104–1113.
[34] M. Andersson, T. Sandholm, Leveled Commitment Contracting among Myopic Individually Rational Agents, volume 26, 1998.
[35] S. M. Ross, Simulation, 4th edition edition, 2006.
[36] H. J. Seltman, Experimental design and analysis, Online at: http://www. stat. cmu. edu/, hseltman/309/Book/Book. pdf (2012).

List of Model Assumptions

- **Competition**
  The method of representation of competition is assumed to resemble the effect competition has on supplier stock levels.
- **Complete Information**
  Suppliers do not possess or are able to retrieve information regarding other suppliers. Information concerning reservation values are private and communication between supplier is not possible.
- **Manager Types**
  The manager types are reflected by different proposal acceptance strategies and are assumed to reflect three different types of human behaviour a manager can have when negotiating over aircraft materials. The three types of managers that are used in this research are assumed to be the three main types of managers, while other types may also exist in real life.
- **Model Adaptability**
  The adaptive elements included in the model are assumed to represent real adaptive measures taken by the agents to increase their own utility.
- **Negotiation Attributes**
  The negotiation attributes that are modelled in the negotiations are assumed to be the most relevant in the context of aircraft maintenance materiel procurement.
- **Negotiation Protocol**
  The extended contract net protocol that is proposed in this research is assumed to resemble the way negotiations take place in real aircraft maintenance material procurement negotiations.
- **Package-deal Procedure**
  The package-deal procedure is assumed to represent bidding procedures that take place in the real negotiations.
- **Parameter Values**
  The parameter values are assumed to represent manager and supplier characteristics.
- **Performance Indicators**
  The performance indicators and KPIs considered in this research are assumed to be adequate for assessing the performance of the system.
- **Stock Levels**
  With competition, stock levels may only decrease. Re-stock and backordering are assumed to be unavailable in this research.
- **Supplier Characteristics**
  The characteristics of suppliers are based on personal experiences and experiences shared by KLM E&M. Changing the supplier characteristics may lead to different outcomes of negotiations.
- **Supplier Presence**
  The five supplier are assumed to be present and accessible by the hangar manager for the material that is required.
- **Supplier Types**
  The identification of the five suppliers is based on personal experience and experiences shared by KLM E&M. Specific situations may arise in which one of more of the suppliers characteristics does not meet the characteristics used in the model.
- **Urgency**
  The method of representation of urgency of a material request is assumed to resemble a real life situation.
- **Volume Discount**
  In this research it is assumed that volume discounts are not applied when ordering larger amounts of material.

Introduction

The following chapters in this document are considered as addition to the Thesis Paper regarding *Multi-agent Automated Negotiation Approach to Aircraft Maintenance: Non-routine Materiel Procurement*. In the following chapters, aspects of the research are highlighted, elaborated, or introduced because they are not (fully) discussed in the paper.

This document consists of nine chapters.

The first chapter elaborates on the case study that formed the basis of the methodology and model, which was briefly introduced in the paper (1). Chapter 2 elaborates on the extensions to the case that were used for modelling reasons. The methodology that is proposed is discussed in the paper, but an elaboration and motivation of certain aspects are described in Chapter 3. The manager's reservation values concerning negotiation attributes are presented in the paper, but the supplier parameter values are presented in Chapter 4. The agent specification based on LEADSTO relations is presented in Chapter 5. Chapter 6 elaborates on the `matlab` structure that was used to implement the model. The model's performance indicators and system requirements are elaborated on in Chapter 7. Chapter 8 presents results concerning the model's efficiency and verification results. Chapter 9 elaborates on opportunities for future research. [1]

[1] *Cover Image:* Grokhovskaya, V. (2018, September 24). 5 MRO Supply Chain Challenges Aviation Companies Need To Prepare For. Retrieved November 9, 2018, from `https://supplychainbeyond.com/5-mro-supply-chain-challenges-in-aviation/`

1
KLM Case Description

In cooperation with KLM Royal Dutch Airlines' Engineering and Maintenance (E&M) department a representation of a real life situations has been created to serve as a case for modelling purposes. A team of anthropologist has spend several months inside of KLM's E&M hangar environments to research their ability to deal with changes in technology. The team has spend time working with people from different departments within various hangar organizations. The case that forms the context of the model is not a specific case that has occurred, but it is composed from several similar events and is described below.

Mechanic H. is part of the cabin team and is assigned to perform a cabin inspection. As part of the cabin inspection, H. marks seats that have been damaged. From memory, H. is aware that a modification is performed on chair covers to improve fire resistance. H. marks the damaged chair covers and also takes the ones with smaller rips. After finishing inspecting all chair covers and marking the damaged ones on a cabin map, H. proceeds towards the desktop computer located in the hangar.

At the desktop, H. uses Maintenix, i.e. a support tool that contains information on tasks, tools and materials among others, in an attempt to order new chair covers to replace the damaged ones. After consulting the manual in Maintenix, H. obtains the correct material codes associated with the chair covers. When H. tries to order the material, Maintenix informs H. that the material is blocked. The meaning of this message is not clear. Either it can mean that the code of the material is outdated or that the material is new and a connection between Maintenix and SAP concerning the material has not been made yet. SAP is another software support tool that displays availability of material inside and just outside the hangar.

In a new attempt to order the material, H. enters the codes directly into SAP to assess the availability. Again, the system displays that the materials are blocked. It appears that the chair covers are not in stock anymore due to the modification that is carried out. After a thorough search, H. finds that there are still some chair covers in stock at the material center Schiphol, i.e. a centralized location that serves as spare part pool for MROs). If H. wants to obtain the covers quickly, i.e. before the end of the shift, someone should take one of the vans and pick the covers up themselves. This must be checked first, because maybe material center needs the materials themselves. First, permission has to be granted to pick up or let it be delivered to the hangar. A runner is responsible for delivering goods from material center to the hangar. Their schedule is not transparent and therefore H. is not entirely sure when the materials will arrive if they are brought to the hangar.

H. moves to the office in the hangar to locate the cabin team lead and Duty Manager Base (DMB) in order to discuss other options of retrieving the seat covers. The DMB serves as support staff in the hangar and relies on extensive personal knowledge and network. Together, H., the cabin team lead and DMB narrow down options to retrieve material. The material is not available in other hangars as they do not service the same type of aircraft there. There are indeed some chair covers with the correct material code at the material center. The DMB and cabin team lead now really come into action. They need to contact the material center and figure out if, how and when the materials can be obtained by the hangar where the inspection was carried out. The removed chair covers are not disposed yet, so if the materials cannot be obtained, they could place back the best ones and use older copies to replace the really damaged ones. The replacement is then postponed.

The DMB performs a phone call with material center. After negotiation with the DMB, the material center agrees to deliver the covers the same afternoon. It becomes apparent that only if the right combination of understanding of the information systems, KLM system understanding and authority understanding could solve the problem. Much information and knowledge on what to do is based on personal experience. A possible solution has been reached and it is now out of their hands until the materials arrive.

Other problems occur as the situation proceeds, but these are not relevant for this research and are not used in the model or case extension. The following chapter elaborates on the specific problem from the case that is modelled.

2
Case Extension

The case that was formulated by the team of anthropologists has shown many opportunities to apply ABM techniques. The choice was made to focus on the negotiations that are performed in order to retrieve the required materials. This choice was made based on personal preference, but also because multi-agent negotiation is a rapidly growing field of research [2].

In order to produce a contribution to the ABM as well as the aircraft maintenance field of research, the negotiation that take place in the case are extended. The DMB is represented as the hangar manager, who is responsible for the retrieval of the required materials. Basically, the hangar manager can be seen as a buyer and the material center can be seen as supplier. The purpose of negotiations from the manager perspective is to retrieve the required number of materials as soon as possible for minimum costs.

Besides the material center, four other possible material suppliers have been identified based on personal experiences and talks with the anthropologists. Please note that the characteristics and types of suppliers are based on personal experiences and experiences from KLM E&M. The model assumes that the five suppliers described below are present in the hangar's environment and representatives of the suppliers are modelled as agents:

1. **Inventory Hangar X (IHX):** represents the inventory of the hangar where the non-routine emerges, i.e. hangar manager is manager of the hangar that contains inventory X. Hangar X Inventory characteristics are a relatively small inventory of components, usually cooperative in finding a solution for problems appearing in the same hangar and charges relatively low prices and short delivery times.

2. **Inventory Hangar Y (IHY):** represents the inventory of a neighbouring hangar. This inventory is assumed to have a greater stock level than Hangar X, but smaller than other suppliers. Unit prices are higher and delivery times are longer than from Hangar X.

3. **Central Inventory (CI):** represents the material center that serves as spare part pool for MROs. The central inventory contains a large inventory with moderate prices of material, but higher delivery times. Also, this supplier usually provides materials to other buyers, thus competition for materials between buyers is likely to be present.

4. **Third Party Supplier (TPS):** representative of a company that produces materials for aircraft, e.g. aftermarket parts, which are very present in the aircraft maintenance market. This supplier is associated with higher prices and longer delivery times than the suppliers discussed above. The service provided by third party suppliers is usually lower than from official OEM suppliers, e.g. shorter guarantees.

5. **Official Supplier (OS):** represents the OEM of the maintenance material. Provides spare components or expendables at high prices, high delivery times and high service.

3
Elaboration on Methodology

As mentioned in the Thesis Paper, automated negotiations are specified by three elements: the negotiation set, protocol and strategies. These building blocks are described and their interpretation to this research is explained consecutively in this chapter. Starting with an more elaborate explanation of the negotiation set in Section 3.1. Section 3.2 describes how the negotiations proceed. The negotiation strategies used by the manager and supplier agents are explained in Section 3.3. Lastly, the model incorporates four adaptive features in order to represent human behaviour. These features are elaborated on in the paper already, thus omitted here.

3.1. Negotiation Set

The negotiation set comprises a specification of all possible deals the agents are allowed to make. For this research, two scenarios are drawn up to simulate procurement of two types of aircraft materials (3.1.1). Two aspects of real-life aircraft maintenance material requests are also taken into account in the methodology presented to simulate the negotiations: urgency (3.1.2) and competition (3.1.3).

3.1.1. Scenarios

Aircraft Components

The first scenario (SC1) is representative of the procurement of aircraft components, either rotables or repairables. These parts are relatively high valued parts. Usually orders for these parts are placed carefully to minimize inventory stock levels, i.e. minimize costs. To simulate the procurement of these parts, the negotiation attributes comprise of unit price (UP), delivery time (DT) and delivery service (DS). Delivery service is a binary value, meaning either material pick-up, i.e. 0, or material delivery, i.e. 1. The other two attributes can take any value in the domain of natural numbers $\mathbb{N}$. If an agreement has been reached with a supplier, the manager may choose what quantity of material to procure from the supplier for the agreed unit values. The space of possible outcomes is extensive and bounded by the manager's reservation utility and values and the supplier's stock levels and reservation values.

This scenario of aircraft components is selected for modelling because it allows the manager to precisely order the number of materials that is desired. The order quantity is bounded by the number of materials the specific supplier has in stock at that time, but imagine the following case. The manager requires 100 units of material and order 50 of them at one supplier because it is the total stock level of that supplier. Another supplier has 100 units in stock but the manager needs only 50 to retrieve the required number of materials. This is now possible because the manager may order 50 of the 100 materials at the costs of the unit attributes.

Aircraft Expendables

The second scenario (SC2) is representative of the procurement of aircraft expendables, i.e. consumables. The unit price of these parts is relatively low compared to aircraft components. Usually it is more expensive to repair an expendable than to replace it. Procurement of expendables is usually done periodically and in greater volumes than components. To simulate the non-routine procurement of these aircraft parts, a fourth attribute is introduced alongside the three attributes from the aircraft components scenario: the material quantity (MQ). The value of the material quantity negotiation attribute can take any value in the set of natural numbers. Again, the space of possible outcomes is extensive and bounded by the manager's reservation utility and values and the supplier's stock levels and reservation values.

This second scenario has been selected for modelling to assess the differences in results compared to SC1. Whereas the manager in SC1 can choose the amount of materials it wants to procure from a certain supplier, in SC2 this is comprised by the agreed negotiation attributes. Also, this scenario is representative for the case study as the chair covers are also aircraft expendables. However, aircraft expendables are usually associated with lower unit prices and are subject to discounts when purchasing larger volumes, but these aspects are omitted here for comparison reasons.

The methodology that is used in this research and presented in the paper can be adopted to simulate other types of aircraft materials, e.g. equipment. Also, elements usually associated with specific materials, e.g. volume discounts, could be incorporated to assess simulation capabilities and represent real aircraft maintenance material procurement.

3.1.2. URGENCY

As described in the paper, researches attempt to optimize maintenance schedule in attempts to minimize costs. Disruptions of the maintenance schedule will negatively influence the schedule and thus increase cost levels. One can imagine that when such a disruption occurs, efforts are made to solve it as quickly as possible. To resemble this type of situations, the element of urgency of a request for materials is incorporated in the model. Three levels of urgency are introduced to resemble three types of situations:

- **High urgency** $ur = 1$**:** situations in which not replacing the faulty material directly will lead to an Aircraft on Ground (AOG) situation, e.g. safety critical material or line maintenance operations.
- **Medium urgency** $ur = 2$**:** situations with reduced urgency, where materials will be required relatively soon as the aircraft spends time in the hanger for longer, e.g. C-check.
- **Low urgency** $ur = 3$**:** situations associated with periodically ordering, no rush to retrieve materials, but they should be retrieved at that time, delivery time is not the main priority in this situation.

The urgency level is communicated from the manager to the suppliers in order to stress the time pressure that is involved in the situation. In the model, the offer strategy of the suppliers is subject to this level of urgency, assuming that the suppliers are willing to cooperate in urgent situations. This method of incorporating urgency levels in the model is assumed to represent three different real-life situations. The methodology and model allows for further extensions on this topic by designing more complex ways of representing urgency of material requests. It should be noted that the level of urgency does not affect the size of the negotiation outcome space.

3.1.3. COMPETITION

Competition is included in the model to assess if elements of competition could be included in the model and how competition would affect the negotiation outcome. Also, as competition is an element that is present in operational maintenance, it would be realistic to incorporate some method of competition.

Competition is included in the model by decreasing the supplier stock levels every simulated 30 minutes. The level of competition (CO) determines how quickly the stock levels decrease. Whereas the initial stock levels of suppliers differ, the rate of decrease does not. In the model the decrease rate of stock levels has been varied from 0 to 5 and 10 percent. The behaviour of the stock level in case of CO=5 is presented in the paper. This method is chosen because of its relatively simple way of implementation and still a simulated way of representing competition. Also, the purpose of research is not to explore the most realistic or sophisticated way to include competition in the model.

3.2. NEGOTIATION PROTOCOL

The negotiation protocol applied in the research is an extension of the classic CNP [4] to allow for automated multi-attribute package-deal negotiations. In a package-deal procedure a proposal from a contractor comprises of a bid for all issues. The manager may accept or reject the proposal based on the proposed package of attribute values. Other methods of multi-attribute bidding are discussed briefly in the paper. The package-deal procedure is considered as the one that best resembles the real-life negotiations. The protocol that is applied in this research is adopted from [5], which uses a multi-attribute bargaining protocol for buyer-seller negotiations. A figure of the protocol is presented in the paper and is not repeated here, but a more elaborate explanation is presented below. The protocol consists of four main stages:

1. Pre-negotiation Phase
2. Bidding Phase
3. Proposal Evaluation Phase
4. Order Awarding Phase

In the *Pre-negotiation Phase* the manager requests all five suppliers to share their stock level of the material that is required. The request includes the urgency of the request from the manager. The request from the manager can result in three different replies from any supplier. Firstly, the supplier may reply to the manager that the request is not understood for any particular reason. The probability associated with this action is related to the performance of the supplier $P_s(t)$: $p_1^1 = 1.0 - P_s(t)$. If the manager receives this reply from the supplier, it creates a belief with probability p_m^2 that the supplier is not willing to cooperate, then the supplier will be excluded from further negotiation. With probability $p_m^1 = P_s(t)$, the manager will send a new request for quantity to the specific supplier.

A supplier may also respond to the request by refusing the request to share its stock level. The motivation may be that the supplier is not interested to supply the materials or not willing to share information about its stock. The probability that this reply is chosen by the supplier equals $p_1^2 == 1.0 - P_s(t)$. If this reply is received by the manager, the supplier is automatically excluded from the negotiation.

The third possible reply is performed with a probability of $p_1^3 = 2P_s(t) - 1.0$ and results in the supplier informing the manager with the stock level that is available for purchase. The reply is followed by a call for proposal by the manager, requesting the supplier to propose a deal.

The *Bidding Phase* follows from the call for proposal from the manager. In the extended CNP the bidding is performed by the suppliers only. A bid may be accepted or rejected by the manager, but cannot be adjusted. Furthermore, a rejected bid cannot be accepted at a later point in time. Because a package-deal procedure is used, a proposal from any supplier comprises of a value of each of the attributes. After receiving the manager's call for proposal the supplier can either refuse to propose a bid. The motivation may be that another buyer is also interested in the same material, or the supplier's lack of interest in selling the material. The probability associated with this reply equals $p_2^1 = 1.0 - P_s(t)$.

Otherwise, the supplier proposes a deal to the manager. The probability of this response equals $p_2^2 = P_s(t)$. The bidding strategy is elaborated on in section 3.3.2.

In the *Proposal Evaluation Phase* the manager evaluates the proposal made by the suppliers. The manager can respond in three different ways. The proposal is rejected if at least one of the proposed values for any attributes exceeds the minimum or maximum reservation values of the manager regarding each of the attributes. The proposal is also rejected if the utility gained by the manager regarding the proposal does not exceed its reservation utility. If the supplier has proposed in the final negotiation round that is allowed, then the proposal is rejected and the supplier is excluded from further negotiation.

If the proposal should be rejected because of above mentioned criteria but the supplier has not yet reached the final bidding round, then the proposal is rejected but the supplier is requested to propose again as part of the next round. This message from the manager places the supplier back to the *Bidding Phase*.

If the proposal meets the managers acceptance values and reservation utility and the maximum allowed bidding rounds is not exceeded, then the proposal is accepted by the manager. The specific acceptance strategy is varied and elaborated on below (3.3.1).

The *Order Awarding Phase* is dependent on the scenario and manager acceptance strategy. Therefore, the rules associated with this phase are discussed below (3.3.1). However, in each scenario and acceptance strategy, the supplier has the opportunity to cancel the agreement, i.e. de-commit. After the supplier has been informed that the proposal is accepted, the supplier will cancel the deal with a probability of $p_3^1 = 1.0 - P_s(t)$. With probability $p_3^2 = P_s(t)$, the agreement is read-back to the manager and the order is placed. If all orders are placed by the manager, then negotiation ends.

3.3. NEGOTIATION STRATEGIES

This section elaborates on the manager acceptance strategies that are used in the model (3.3.1). A brief elaboration and motivation for the supplier strategy is given in Section 3.3.2.

3.3.1. MANAGER ACCEPTANCE STRATEGY

Three different manager acceptance strategies, or manager types, are created in order to assess their effect on negotiation results. The manager types attempt to represent three different ways a hangar manager can accept and reject proposals. The manager types and the ways they accept proposals is discussed below.

The first manager type is the *greedy* manager. This manager type represent a human being who is looking to close a deal as quickly as possible, taking time pressure into account. This manager accepts any proposal that is regarded as acceptable following the requirements discussed in section 3.2. For scenario 1, this means that a supplier is immediately informed when a proposal is accepted. If it is read back by the supplier, the manager will directly place an order at the supplier, regardless the state of negotiation with the other suppliers. For scenario 2, where the order placement is associated with the acceptance of an order, the proposal is accepted directly and the supplier is informed accordingly.

Another type of manager is a *patient* manager. This manager represents a human being who is willing to take time in finding a beneficial deal by evaluating multiple deals, regardless of the time pressure. For scenario 1, the patient manager waits until an acceptable proposal has been made by every supplier, as long as they are not out of negotiation, before accepting one of them. The manager informs the supplier that has made the best proposal, i.e. highest utility, that the proposal is accepted. The other suppliers are informed that their proposal is rejected and are send to the next round, if the maximum number of rounds is not exceeded. This process continues until the manager has accepted a deal from all suppliers who are still in negotiation. The manager postpones order placement until this state has been reached. Then, in ascending order, the manager places an order for the total stock level of the supplier that results in the highest utility. When the required number of materials has been ordered, the agreements with the remaining suppliers are cancelled.

For scenario 2, when all suppliers have proposed an acceptable deal, the manager selects the proposal that results in the highest utility. The supplier associated with this proposal is not informed, the other suppliers are informed that their proposal is rejected and are entering the next round. This process is repeated until all suppliers have been selected as most beneficial in respective rounds. Then, in ascending order, the suppliers that provide the highest utility to the manager receive an acceptance of their proposal. When the required amount of quantity has been ordered as part of the deals, the agreements with other suppliers are cancelled.

The third manager type is the *balanced* manager which uses a combined strategy from greedy and patient manager types. As the greedy manager, the balanced manager accepts any acceptable proposal and does not compare proposals between suppliers. A more patient strategy is used to determine which suppliers receive an order. The balanced manager postpones order placement until all suppliers have proposed an acceptable deal.

These three manager types are modelled to represent three ways of manager behaviour. Other manager behaviour could also be simulated by designing other proposal acceptance strategies in order to simulate particular cases. The model and methodology allows for almost any acceptance strategy. The three chosen for this research are believed to represent main acceptance strategies.

3.3.2. SUPPLIER BIDDING HEURISTICS

As mentioned, proposals are made by the suppliers in the negotiation protocol. For the proposal, a heuristic approach is used because the research does not attempt to maximize the outcome, but rather explores its applicability. Different methods of heuristics are known and have been researched [2]. For this research, the classic time and resource-dependent strategies have been adopted to make them more applicable for this situation. For example, because the maximum allowed number of bidding rounds equals ten for all suppliers, they would require to increase their offer more quickly then with more classic approaches. The behaviour of the offer strategy is discussed in the paper. It should be noted that other offer strategies could also be applied to simulate other supplier bidding strategies, for instance to model other cases. The methodology allows for implementation of any supplier bidding strategy.

4
Supplier Negotiation Parameter Values

In the paper, the manager's negotiation values and reservation utility are presented thus these are omitted here. However, the supplier negotiation values are not discussed in the paper and therefore are included below (Table 4.1).

Supplier	Attribute	min_s^i	$I_s^i(0)$	max_s^i	w_s^i (SC1)	w_s^i (SC2)
1. IHX	UP	0	20	25	0.1	0.1
	DT	30	120	120	0.8	0.4
	DS	0	0	1	0.1	0.1
	MQ	0	25	$Q_1(t)$	n/a	0.4
2. IHY	UP	25	85	100	0.3	0.2
	DT	60	180	180	0.4	0.3
	DS	0	0	1	0.3	0.1
	MQ	0	30	$Q_2(t)$	n/a	0.4
3. CI	UP	100	200	250	0.5	0.3
	DT	200	450	480	0.4	0.3
	DS	0	0	1	0.3	0.1
	MQ	50	50	$Q_3(t)$	n/a	0.3
4. TPS	UP	100	300	400	0.8	0.5
	DT	200	600	720	0.1	0.1
	DS	0	0	1	0.1	0.1
	MQ	100	100	$Q_4(t)$	n/a	0.3
5. OS	UP	150	450	500	0.8	0.5
	DT	200	660	720	0.1	0.1
	DS	0	0	1	0.1	0.1
	MQ	150	150	$Q_5(t)$	n/a	0.3

Table 4.1: Reservation values, initial offers and weights for suppliers regarding negotiation attributes

Attribute	Unit	Range
UP	[€]	$\mathbb{N}$
DT	[min]	$\mathbb{N}$
DS	[-]	$\mathbb{N}$
MQ	[-]	binary

Table 4.2: Negotiation attributes unit and range

Supplier	$Q_s(0)$	$P_s(t)$
Inventory Hangar X	50	0.95
Inventory Hangar Y	100	0.95
Central Inventory	150	0.95
Third Party Supplier	200	0.95
Official Supplier	200	0.95

Table 4.3: Supplier initial material stock level $Q_s(0)$ and supplier performance $P_s(t)$

It should be noted that, just as with the reservation values and weights used by the manager, the values of the supplier are all based on estimations and assumptions. The reason for these assumptions is that no real data was available that could be used to represent real reservation values. The assumed values are estimated to represent the type of supplier (Chapter 2). Table 4.2 shows the unit of the negotiation attributes that are used.

The first supplier, IHX, is assumed to be cooperative with the manager from the same hangar. Also, because the inventory of hangar X is relatively close, the unit price is assumed to be between €0 and €25 and delivery time between 30 and 120 minutes. The initial offer of DT is put at 120 minutes because from the IHX perspective, then no rush is needed to have the materials ready in time. This inventory is assumed to be close to the place where the materials are needed, but still the supplier would prefer pick-up of the materials in favour of delivery to that place, these values are assumed to apply to all suppliers. Considering MQ, supplier 1 is assumed to offer 25 units of materials initially. The weights are assumed with the following motivation, for an inventory that is cooperative with the manager, the delivery time is the most important because this gives the supplier time to get the materials ready. UP and DS have been given a lower priority. For SC2 the weights of DT and MQ are equal to 0.4 because it is assumed that these two are of equal importance to the supplier.

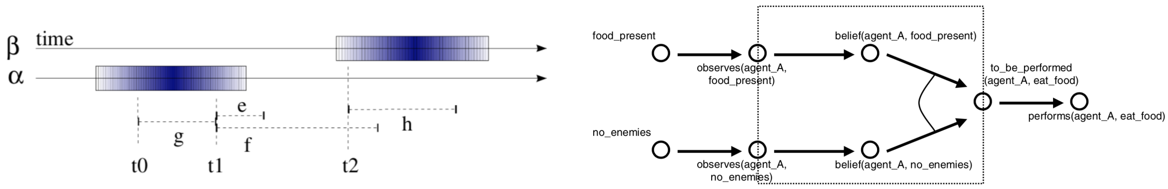
Supplier 2, IHY, is assumed to be less cooperative than supplier 1. The neighbouring hangar can be helpful in solving material issues in other hangars, but the materials can also be required to perform maintenance work in hangar Y. Therefore, the reservation values for the negotiation issues are slightly less favourable to the hangar manager. This is a trend when considering the other suppliers, the suppliers' reservation values become less favourable to the manager. The assumptions that are mentioned concerning suppliers 1 and 2 also apply to the other ones. Considering the weights of the negotiation attributes, the prioritization on the unit price becomes higher as the scale of supplier increases, with less attention for delivery time and service. Table 4.3 recalls the initial stock levels of materials of all suppliers. As mentioned in the paper, the manager is required to retrieve at least 200 units of material in this research. Again, it is assumed that all values discussed in this chapter represent real suppliers in the aircraft maintenance material industry.

5
LEADSTO Agent Specification

In this chapter the formal specification is presented using LEADSTO graphical specification. First, this method of specification is introduced in Section 5.1. Then the agents are specified using the presented notation in Section 5.2.

5.1. LEADSTO: Introduction and Notation

For specification of the dynamics of the negotiation, LEADSTO methodology has been used [1]. Dynamics of a system are considered as the evolution of states of the system over time. The LEADSTO language is able to present direct dependencies between to successive states using the following notation: $\alpha \rightarrow_{e,f,g,h} \beta$ (Figure 5.1a,[1]), meaning [1]: "*If state property α holds for a certain time interval with duration g, then after some delay (between e and f) state property β will hold for a certain time interval of length h*"



(a) LEADSTO notation [1]

(b) Example of LEADSTO graphical representation [1]

Figure 5.1: LEADSTO notation and graphical representation [1]

LEADSTO state transitions can be specified formally in a graphic representation, as depicted in Figure 5.1b [1]. State properties are presented as circles and LEADSTO relationships by arrows. Arcs connecting two arrows indicate conjunctions between state properties. In the graphical specification created for this research, a single arc denotes an *and* relationship, and a double arc represents an *or* relationship. Agents are depicted as rectangular dotted boxes. State properties, i.e. circles, depicted inside the box represent internal state properties. Circles located on the left border represent input state properties, mostly observation states in this case. On the right, the circles correspond to output state properties. Circles depicted outside the box are environmental states and can be observed by other agents. In the specification that follows, the timing factors are presented along with the arrows to give a more detailed specification.

5.2. LEADSTO Specification

This section shows three graphical LEADSTO specifications of:

- Specification of the manager agent in SC1 (Section 5.2.1)
- Specification of the manager agent in SC2 (Section 5.2.2)
- Specification of the supplier agents (Section 5.2.3)

5.2.1. Manager Specification (SC1)

In the figure below (Figure 5.2), the graphical LEADSTO specification of the manager is shown in SC1. The red arrows only apply when the greedy acceptance strategy is active and the blue arrows represent patient acceptance strategy. Because the balanced acceptance strategy uses a combination of both strategies, this is mentioned alongside the arrows. All black coloured arrows are applicable to all acceptance strategies. The following abbreviations are used in the figures considering the manager agent: Global State (GS), Manager Observation State (MOS), Manager Belief State (MBS) and Manager Action State (MAS).

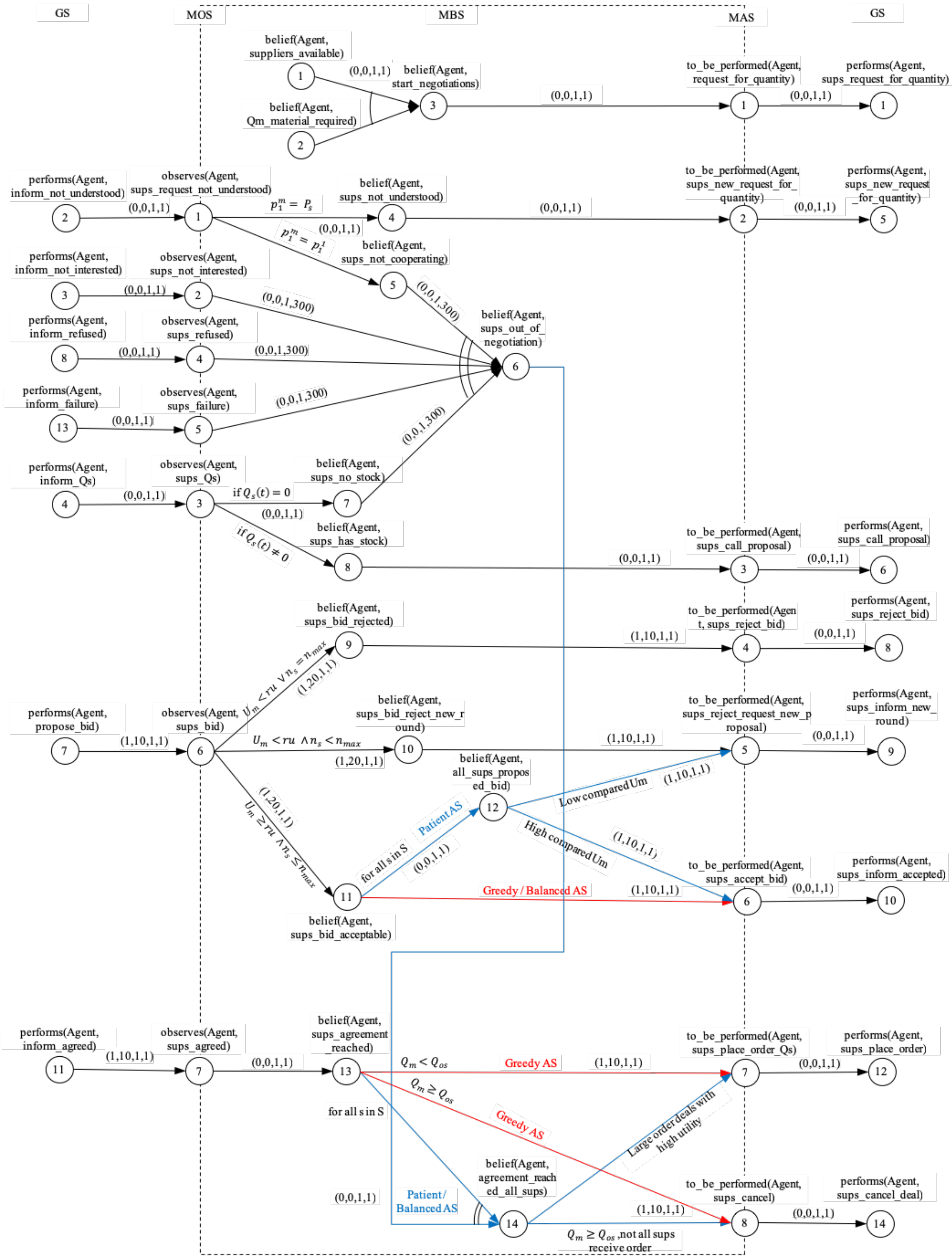


Figure 5.2: Graphical LEADSTO specification of manager for SC1

5.2.2. MANAGER SPECIFICATION (SC2)

Figure 5.3 shows the graphic LEADSTO specification for the manager when simulating SC2. Because acceptance of an agreement is corresponding to the order placement, this requires a different agent lay-out. The coloured arrows and abbreviations are similar to Figure 5.2.

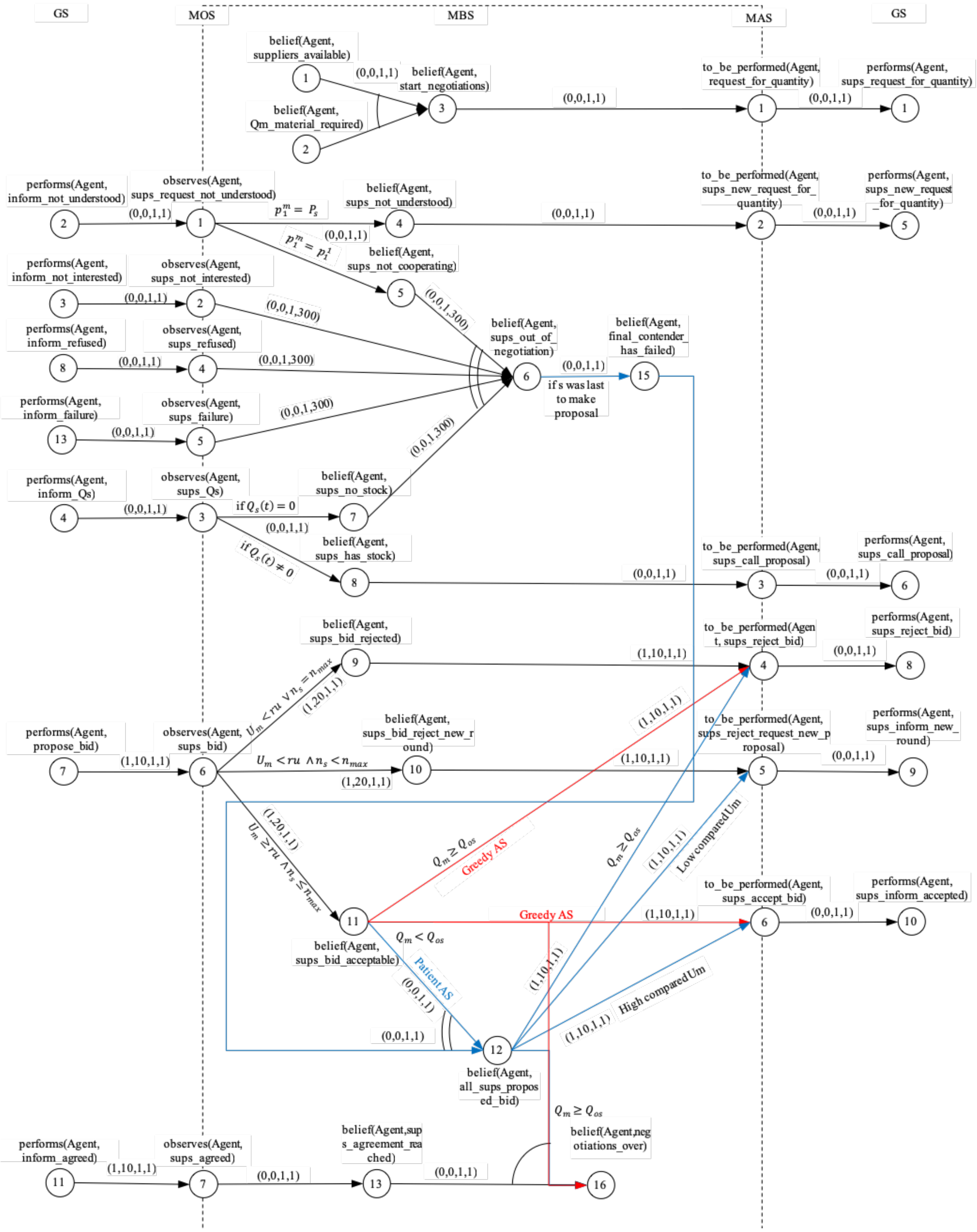


Figure 5.3: Graphical LEADSTO specification of manager for SC2

5.2.3. SUPPLIER SPECIFICATION

Regardless of the simulated scenario and manager acceptance strategy, the same supplier agent applies. The specification is presented in Figure 5.4. The figure uses the following abbreviations: Supplier s Observation State (SsOS), Supplier s Belief State (SsBS) and Supplier s Action State (SsAS).

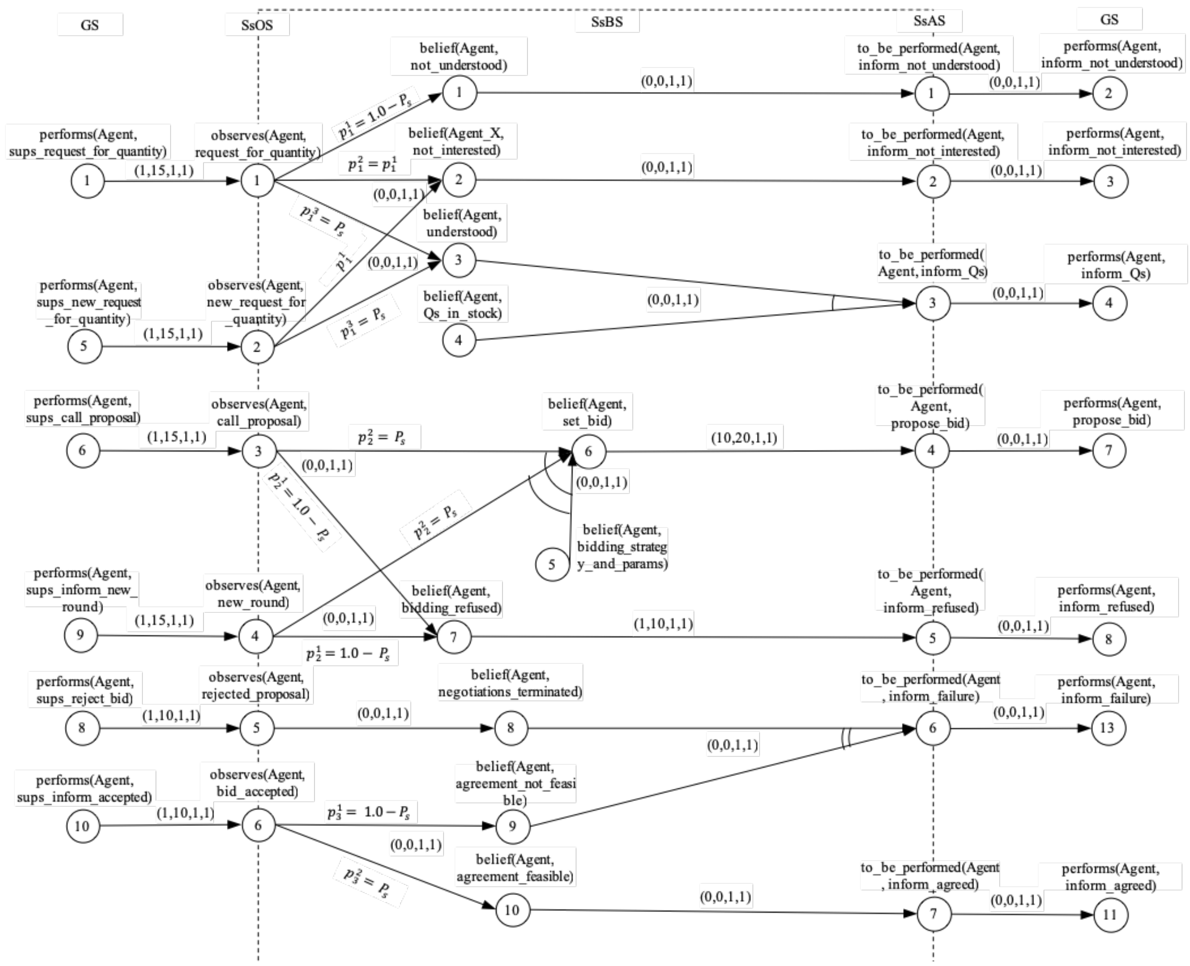


Figure 5.4: Graphical LEADSTO specification of suppliers

6
DESCRIPTION OF `matlab` FILES

Whereas software is available to relatively simple implement a LEADSTO specification [1], the software is only supported by Windows operating systems and does not allow for implementation of complex negotiation functions. This is the main reason why `matlab` was chosen for the implementation of the model. Luckily, VU University in Amsterdam, the Netherlands has developed an extension for `matlab` to make it relatively easy to implement LEADSTO specifications [3]. This extension is called *l2-matlab* and is freely available for download. An extensive manual is available on how to use the extension, it simply requires to have *l2-matlab* functions in the same directory as the model. In Figure 6.1, a overview of the model structure in `matlab` is presented. Below, a short description of each element from the Figure above is given.

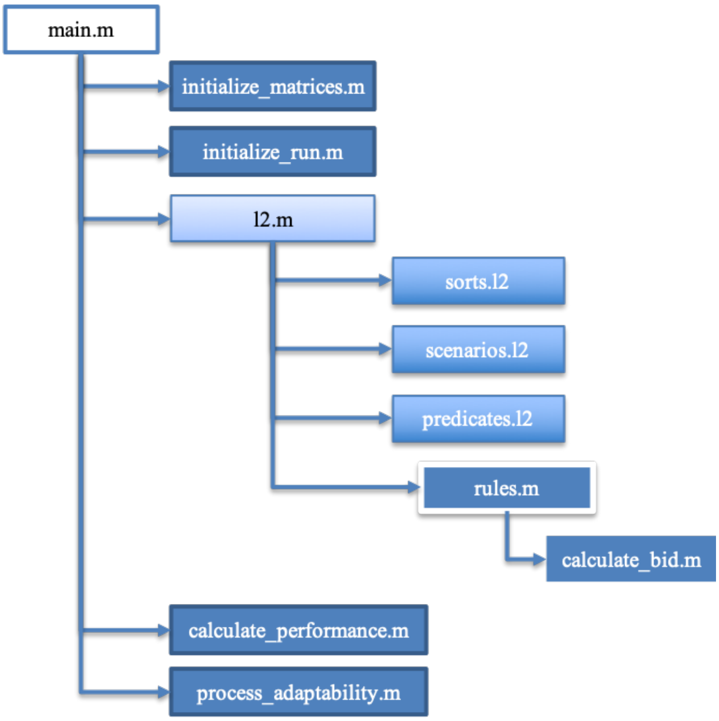


Figure 6.1: Overview of `matlab` structure

`main.m` the main file in which the simulation is initiated by specifying the scenario, acceptance strategy, urgency and competition level that is simulated. This scripts calls the initialize functions and l2 model functions to run the simulation and afterwards calls calculation functions and adaptability for the next run.

- **`initialize_matrices.m`** function that is used to initialize the simulation by defining matrices containing e.g. reservation values for negotiation attributes. This function is called at the start of simulations, not with every new run.
- **`initialize_run.m`** function that is executed at the start of each run, with purpose of clearing or resetting matrices containing information from the previous run.
- **`l2.m`** script that executes the *l2-matlab* extension. Mainly four files from this extension are altered and mentioned here, for more information on the extension, please refer to the manual [3].

- **`sorts.l2`** l2 file that define instances that are used in the model. In this model `sorts.l2` defines the agents, observation states, belief states and action states.
- **`scenarios.l2`** l2 file that defines the initial state of the model in order to start execution. In this model, `scenarios.l2` defines a few belief states that initize the simulation.
- **`predicates.l2`** this l2 file defines the relation between the sorts, in other words, defines the ontology.
  - **`rules.m`** this function is called by the l2 extension and describes the dynamics from the LEADSTO specification. The rules are implemented as `matlab` functions and called once every time-step.
    - **`calculate_bid.m`** this function calculates the proposal that is made by a supplier and is called in the rules function when a supplier has belief: `belief(Agent,set_bid)`.

`calculate_performance.m` this function is executed once the run has been completed, and calculates values for the performance indicators and assesses verification measures.

`process_adaptability.m` this function processes the adaptive features of the model based on the results, and renews values to be used in the next run.

7
Performance Indicators and System Requirements

The following sections describe included performance indicators (7.1) and system requirements (7.2) in the current `matlab` implementation.

7.1. Performance Indicators

Below, a description of the performance indicators is given that are implemented in the `matlab` model. When running the model, the performance indicators are automatically exported to an `Excel` worksheet that also saves information concerning the simulated scenario, acceptance strategy, urgency level and competition.

Average delivery service: determines the average value of delivery service that is computed by multiplying the delivery service agreed by one supplier with the order quantity at this supplier and then dividing it by the total quantity that is ordered.

Average delivery time: measure to determine the average delivery time that is agreed between the manager and suppliers. Basically, it is the mean of the agreed delivery times and is calculated similarly the average delivery service.

Average unit price of material (AUP): measure that is used as KPI and is explained in the paper.

Computational costs (c_{comp}): measure of efficiency of the model that is calculated as the number of times the utility of any agents is calculated.

Number of messages send between manager and suppliers (c_{tot}): measure that keeps track of the number of messages that are send from the manager to suppliers and vice versa. The value of this measure is increased each time a transition is made from the output state of any agent to the global state.

Number of rounds required to finish negotiations (n_{tot}): measure to indicate how many proposal rounds have elapsed before the negotiations are finished. Please note that only the rounds that have elapsed for the suppliers that have received an order are considered in this measure.

Overall utility of manager (U_m): measure explained in the paper, that gives the utility gained by the measure considering the outcome of negotiations.

Time elapsed before final materials are delivered (TFD): measure that is used as KPI and is explained in the paper.

Time elapsed before final order placement (t_{finalo}): measure to indicate how much simulated time has elapsed before the last order is placed.

Time elapsed before first materials are delivered (t_{firstd}): measure similar to TFD that keeps track of the soonest moment in time that materials are delivered.

Time elapsed before first order placement (t_{firsto}): measure similar to t_{finalo}, that keeps track of the time elapsed before the first order is placed by the manager.

Time elapsed in simulation to complete run (t_{sim}): measure that gives an indication of effiency of the implementation, at the start of each run, a timer is initiated and at the end of the run the timer is terminated.

Total costs of material: measure that indicates the total costs of the procured material.

Total quantity of material retrieved (TQR): measure that is used as KPI and is explained in the paper.

Utilitarian Social Welfare (USW): measure that is used as KPI and is explained in the paper.

7.2. SYSTEM REQUIREMENTS

Five system requirements were defined to verify whether if the implemented model would represent the model specification and on the other hand be representative of the real life negotiations. These are explained below. Results concerning these verification measures are presented in the following chapter.

- **Quantity Check (QC):** this system requirement is used as KPI in the paper. It is used as a requirement for the retrieved number of materials. If the required amount of materials are retrieved by the manager, i.e. 200, then QC equals 1, otherwise 0.
- **Timely First Order (TFO):** the time elapsed from the start of negotiation till first order placement (t_{firsto}) must be less or equal to two hours of simulated time. It is assumed that in the real negotiations, a first order will be placed within two hours. This requirement assesses if this is achieved. TFO equals 1 if it is achieved, 0 otherwise.
- **Timely Delivery (TD):** similar requirement as TFO, only the delivery time is considered. TD considers the time that has elapsed from the start of negotiation till the point in time where all materials are delivered. In order to resemble real negotiations, this measure equals 1 if all materials are delivered within five hours of simulated time, 0 otherwise.
- **Supplier Out (SO):** requirement that states that no order must be placed at a supplier that is out of negotiations. SO equals 1 if an order is placed at a supplier that is no longer participating in the current negotiation, 0 otherwise.
- **Exceeded Rounds (ER):** requirement that states that no supplier may exceed the maximum allowed number of proposal rounds, i.e. 10. If a supplier has exceeded this maximum, ER equals 1, 0 otherwise.

8
Model Efficiency and Verification

The sections below present results from the performed simulations in terms of model efficiency (8.1) and verification based on the system requirements discussed in the previous chapter (8.2).

8.1. Efficiency Results

Table 8.1 below shows results of four performance indicators that relate to the model efficiency, i.e. c_{tot}, t_{sim}, c_{comp} and n_{tot} for all performed simulations. For each of the simulations the minimum, maximum and mean value of the performance indicators is given.

The values in the table below give insight in the efficiency of the model and shows some interesting results related to particular strategies. No statistical evaluation of these results are performed so no statistical significant relations can be established. However, one can observe for instance the differences in elapsed time t_{sim} between the patient strategy in 1-2-2-0 and balanced strategy in 1-3-2-0.

Simulation	c_{tot} [-]			t_{sim} [sec]			c_{comp} [-]			n_{tot} [-]		
SC-AS-UR-CO	min	mean	max	min	mean	max	min	mean	max	min	mean	max
1-1-2-0	19	44.2	88	14.00	45.12	221.55	12	66.3	192	2	11.1	32
1-2-2-0	18	49.8	86	19.20	69.46	135.30	18	95.5	198	3	15.9	33
1-3-2-0	16	44.8	86	10.09	50.49	109.13	18	79.3	192	3	13.2	32
2-1-2-0	18	40.1	64	13.84	34.30	93.95	16	86.1	176	2	10.8	22
2-2-2-0	18	44.0	78	15.31	58.52	121.89	24	120.9	256	3	15.1	32
2-3-2-0	16	38.1	72	12.03	43.43	98.12	24	100.2	224	3	12.5	28
1-1-1-0	22	41.2	88	13.86	34.92	98.25	18	57.1	192	3	9.5	32
1-2-3-0	18	45.5	84	10.16	62.42	126.89	12	81.8	198	2	13.6	33
1-3-3-0	16	44.9	84	9.06	54.10	110.47	18	80.0	192	3	13.3	32
2-1-1-0	15	35.2	52	8.31	29.23	80.09	16	64.5	120	2	8.1	15
2-2-3-0	20	50.9	94	20.53	68.11	156.19	24	147.2	312	3	18.4	39
2-3-3-0	14	44.5	82	10.96	45.67	94.76	16	124.9	280	2	15.6	35
1-1-1-5	24	41.0	75	14.93	34.37	80.04	18	55.4	150	3	9.2	25
1-1-1-10	22	39.8	72	16.59	34.87	99.64	18	52.3	150	3	8.7	25
2-1-1-5	15	34.9	56	9.88	28.54	50.89	16	64.2	136	2	8.0	17
2-1-1-10	16	43.6	98	12.56	44.18	111.29	16	99.3	312	2	12.4	39

Table 8.1: Model efficiency results

8.2. Verification Results

Table 8.2 below shows the results for the simulations concerning the system requirements. One may observe that in the 2-2-2-0 simulations the totals add up to 96 instead of 100, this is the result of 4 runs in this simulation in which no agreement was reached between the manager and any supplier. For the other requirements, it is interesting to see the differences between the urgency levels 1, 2 and 3. Especially for the TFO, in which the requirement has been achieved a lot more for 1-1-1-0, 1-1-1-5 and 1-1-1-10 simulations than for 1-2-3-0 or 1-3-3-0 simulations. In all simulations the SO and ER requirements have been verified.

Simulation	QC		TFO		TD		SO		ER	
SC-AS-UR-CO	#0	#1	#0	#1	#0	#1	#0	#1	#0	#1
1-1-2-0	8	92	0	100	76	24	100	0	100	0
1-2-2-0	19	81	98	2	98	2	100	0	100	0
1-3-2-0	10	90	87	13	89	11	100	0	100	0
2-1-2-0	17	83	42	58	83	17	100	0	100	0
2-2-2-0	6	90	93	3	96	0	96	0	96	0
2-3-2-0	3	97	94	6	98	2	100	0	100	0
1-1-1-0	1	99	0	100	89	11	100	0	100	0
1-2-3-0	14	86	86	14	91	9	100	0	100	0
1-3-3-0	8	92	84	16	84	16	100	0	100	0
2-1-1-0	4	96	3	97	80	20	100	0	100	0
2-2-3-0	25	75	99	1	98	2	100	0	100	0
2-3-3-0	15	85	87	13	95	5	100	0	100	0
1-1-1-5	0	100	0	100	87	13	100	0	100	0
1-1-1-10	4	96	0	100	76	24	100	0	100	0
2-1-1-5	3	97	1	99	74	26	100	0	100	0
2-1-1-10	40	60	4	96	69	31	100	0	100	0

Table 8.2: Model verification results

9
Opportunities for Future Work

This chapter elaborates on possible future work in terms of model extensions (9.1) and case studies (9.2).

9.1. Model Extensions

The list below presents possible model extensions. The extensions allow for further or specific studies regarding aircraft maintenance procurement negotiations.

- **Adopting Other Protocols**
  Possible extensions are present in terms of application of different negotiation protocols. Other protocols that allow many-to-one negotiations, e.g. auctions, would be interesting to apply to assess their applicability and results compared to the extended CNP that was applied in this research.

- **Attribute Bidding**
  The package-deal procedure used for proposing deals to the manager in this research was applied because it resembled the case study as closely as possible. However, other ways of multi-attribute bidding exist, e.g. simultaneous or consecutive bidding over attributes. It would be interesting to assess the model's results when one or both of these other methods would be applied.

- **Complete Information**
  In this research information was considered incomplete, meaning that reservation values and utilities were private and suppliers were unable to observe other suppliers or proposals. A great number of extensions is possible here, e.g. proposals could be openly observable by suppliers, number of suppliers could be openly observable, manager reservation values could be observable, among many others. The extension would most probably also require an adaptation of negotiation strategies to deal with the information obtained by agents.

- **Complex Adaptability**
  In this research, four adaptive elements were used to resemble individual behaviour of agents. However, the method of adapting parameters was equal for all agents. Extensions are possible in introducing diversity in adaptability for specific agent types. This would also increase realism because it is likely that different supplier types would apply various adaptive strategies.

- **Complex Competition**
  In this research, competition is simulated by decreasing supplier stock levels over time. The same decrease rate was applied to all suppliers. In real-life the stock level decrease does not have to be equal to all suppliers. Besides, more complex ways of representing competition would be possible, e.g. supplier preference or multiple buyers.

- **Complex Urgency**
  Urgency of a request was used in this model to adapt supplier bidding behaviour over time. More complex ways of representing urgency could be applied, e.g. changing supplier preference for specific buyers or changing probabilities for agent decisions. The model allows for introduction of other ways to represent urgency.

- **More and/or Other Suppliers**
  Changing the characteristics of the supplier would be an interesting extension because it would be possible to model specific types of suppliers that are common in the aircraft maintenance industry. Adding suppliers or introducing multiple suppliers with the same characteristics would be possible to assess its effect on the system.

- **Multiple Buyers**
  Introducing multiple buyers would be an extension related to competition, as it would be possible to simulate multiple buyers negotiating with the same suppliers over the available materials. Extending supplier bidding strategies would be interesting in attempts to maximize revenue.

- **Supplier Preference**
  When introducing multiple buyers, it would be interesting to not only use supplier performance to express trust from managers in suppliers, but also introduce supplier preference of managers over other buyers. Further extensions would be possible when considering complete or incomplete information for managers concerning multiple buyers and supplier preferences.

- **Supplier-Supplier Communication**
  In the current model, suppliers are not allowed or capable to communicate with other suppliers. However, in real-life negotiations this would be possible. Extending the model to allow this would also allow for further extensions, e.g. coalition formation of suppliers.

9.2. CASE STUDIES

The list below discussed future work opportunities within the proposed methodology in terms of possible case studies.

- **Agent Options for Decisions**
  In the current model, supplier response decisions are determined by probability. It would be interesting to use other decision rules, which could relate to specific negotiation circumstances or supplier characteristics.

- **Material Restock**
  Introducing material restock would be an interesting study in the context of competition, taking the current implemented method of competition into account. Including backordering would also show potential for a case study.

- **Remove Adaptability**
  The current simulations all consider adaptive elements. It would be interesting to perform simulations without the adaptive elements to simulate less adaptive agent behaviour.

- **Non-linear Reservation Utility Adaptability**
  In the current model, the reservation utility is related linearly to the number of suppliers that are in negotiation. It would be interesting to assess other relationships, e.g. non-linear.

- **Optimize Negotiation Outcome**
  In current research, strategies are applied to explore the model's applicability to aircraft maintenance material procurement. A specific study would be required to find optimal circumstances or strategies to achieve optimal results.

- **Sensitivity Analysis on Reservation Values**
  Sensitivity analysis has been performed on negotiation parameters such as ω, but no parameter variation has been applied to supplier or manager reservation values. It would be interesting to assess their sensitivity and effects on results.

- **Validation Scenario**
  The current model and parameters are based on a case study, but not on a real data set. Model validation is required to assess its realism and capability to simulate real-life negotiations.

Bibliography

[1] Tibor Bosse, Catholijn M Jonker, Lourens Van Der Meij, and Jan Treur. Leadsto: a language and environment for analysis of dynamics by simulation. In *German Conference on Multiagent System Technologies*, pages 165–178. Springer, 2007.

[2] Shaheen Fatima, Sarit Kraus, and Michael Wooldridge. *Principles of automated negotiation*. Cambridge University Press, 2014.

[3] J de Man. Measuring and modeling negative emotions for virtual training. 2016.

[4] Reid G Smith. The contract net protocol: High-level communication and control in a distributed problem solver. *IEEE Transactions on computers*, (12):1104–1113, 1980.

[5] TN Wong and Fang Fang. A multi-agent protocol for multilateral negotiations in supply chain management. *International Journal of Production Research*, 48(1):271–299, 2010.