Context-Sensitive Deliberation for Scalability in Realistic Social Simulations

Maarten Jensen[1], Loïs Vanhée[1], and Frank Dignum[1]

Umeå University, Umeå, Sweden

Abstract. Simulating for policy making requires modelling multiple aspects of life, realistic social behaviour and the ability to simulate up to millions of agents. However models with realistic social behaviour are not easily scalable due to the complex deliberation that takes into account all information at every time step which is slow. Explicitly taking into account context in the deliberation can increase scalability, through a complexity by need principle. The Dynamic Context-Sensitive Deliberation (DCSD) framework uses minimal information when possible, but gradually draws in more information when necessary. To validate whether DCSD can increase scalability while retaining realism we implement DCSD into an example large scale model, the Agent-based Social Simulation of the Coronavirus Crisis (ASSOCC). We compare the original deliberation from the ASSOCC model with the implemented DCSD. We conclude that DCSD can increase scalability while retaining realism in large scale social simulation models.

Keywords: Context deliberation · Scalability · Realism · ASSOCC

1 Introduction

Simulating for policy making has been argued to require modelling multiple aspects of life, realistic social behaviour and the ability to simulate up to millions of agents. However state of the art models containing multiple aspects of life and realistic social behaviour, in other words a model that achieves high realism, struggles at being scalable. As an answer to this challenge, [6] proposed the Dynamic Context-Sensitive Deliberation (DCSD) that can increase computational scalability while retaining realism. This model uses context to deliberate using minimal information initially while gradually increasing complexity if necessary.

However, to our knowledge the DCSD has so far only been formalised and argued for from a theoretical standpoint, without empirical evidence of the proposed theories. This paper is dedicated to providing this empirical validation of the DCSD. As an approach, we will integrate the DCSD within the Agent-based Social Simulation of the Coronavirus Crisis (ASSOCC) [3] a model that uses a complex deliberation system. This deliberation system draws in all information from all aspects of the model to make realistic decisions. While able to output realistic behaviour for the agents the model is slow, leading to relatively poor scalability over all. The model suffers in terms of scalability, it is not practically possible to expand the model by e.g. additional daily life aspects or additional agent actions without increasing run time to a large degree. The model is practically limited to run with 2000 agents if one results ready in about one hour. Even though this model has been extensively optimised, these inherent computational limits exist which has been demonstrated in [9]. In this work we will show DCSD and the ASSOCC model as background, compare the original deliberation from the ASSOCC model with the implemented DCSD in regards to its computational scalability and behavioural realism. Based on the results, we will draw conclusions on the pros and cons of the DCSD in regards to the scalability and behavioural realism of context-based deliberation models.

2 Background

2.1 Dynamic Context-Sensitive Deliberation

Dynamic Context-Sensitive Deliberation (DCSD) can be potentially used to increase scalability while retaining realism [6]. The framework presented in the paper uses a complexity by need principle. Initially minimal information from the situation an agent is in is considered. Only if this is not enough information to choose an action more information is added, until an action can be chosen. Context in this framework is defined differently from traditional definitions of context within computational sciences. For example Dey [2], defines context as: *'Context is any information that can be used to characterise the situation of an entity'*. However this definition is meant for a system (entity) that interacts with a user. For DCSD we are interested in understanding information within a system, i.e. the social simulation. Edmonds has extensively studied context for social simulations. His work focuses on understanding context to help determine which elements should be taken into account or not in a social simulation [4]. Important work, however in DCSD we define context as the information that is relevant to the decision making of an agent within a social simulation. This information is limited by the implemented aspects in the simulation, which is a finite amount of information.

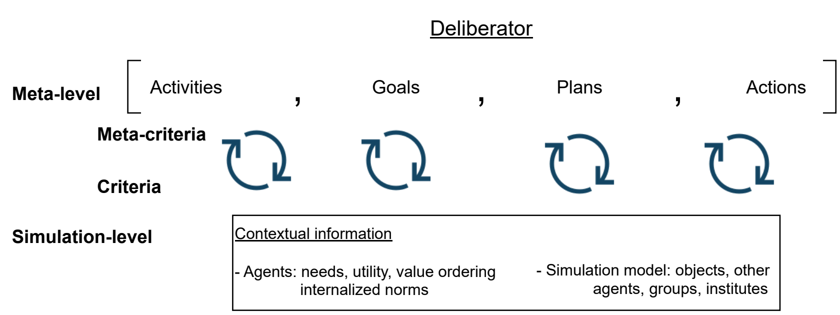


Fig. 1. The Dynamic Context-Sensitive Deliberation cycle adopted from [6].

Figure 1 shows the Dynamic context-sensitive deliberation (DCSD) [6]. It consists of a meta-level tuple that consists of the elements activities, goals, plans and actions. These elements can be adjusted using information from the simulation context. The main idea is that the framework attempts to end with a single action. If there is no action in the tuple the *meta-criteria* will indicate that actions need to be expanded. Then a *criteria* could be: consider typical actions given the context. This may fill up the tuple with a couple of available actions. Then the framework should narrow down actions (*meta-criteria* = narrow down actions) using a different *criteria*, e.g. considering whether an action fulfils the most salient need. It should be noted that the meta-level elements are not set in stone, they are rather a guideline and some simulations may consider only a subset of these.

2.2 The ASSOCC model

The ASSOCC model [3] is a large scale social simulation model of the Covid crisis. The agents behave according to a complex need based system to determine their daily life behaviour. The ASSOCC model represents a city containing a couple of location types that the agents visit to satisfy their needs. The relevant locations are: essential shops, homes, non-essential shops, private leisure places, public leisure places, schools, university faculties and workplaces. Since we do not study the effect of the spread of the virus in this paper, we excluded the hospitals and migration. The locations determine rigidly what action the agents can perform. E.g. at a workplace agents can only work, or go to a different location. Note that some agents work at for example an essential shop, during working hours the action is still *work* for those agents. The following actions are defined. *Actions* = {Rest at home (RH), Leisure at home (LH), Work (W), Study at school (SS), Study at university (SU), Leisure at public leisure (LPU), Leisure at private leisure (LPR), Buy at Essential Shop (BE), Buy at Non-Essential Shop (BNE)}. Social distancing will not be further used in this work as the virus will not be introduced in the experiments, making social distancing irrelevant.

The time is represented through four slices of the day: *morning*, *afternoon*, *evening* and *night*. Each of them have different implications for the agents. For example, in the night the agents sleep, while in the other parts of the day they go to their jobs or other places. The days of the week are explicitly modelled and there is a difference between weekdays (when agents study and work) and weekends. The agents are represented with four different age groups. The *young* representing the age group 0-19, the *students* representing the age group 20-29, the *workers* representing the age group 30-69 and the *retired* representing the age group 70+. The children have limited actions, only rest at home, study at school and have leisure time. The students study at the university.

The needs are represented by the following set $\mathcal{N}$={*food_safety*, *fin_survival*, *sleep*, *health*, *conformity*, *compliance*, *risk_avoid*, *fin_stability*, *belonging*, *autonomy*, *luxury*, *leisure*}. The needs are modelled as a tank that, although dependent on the specific need, usually diminishes over time. Agents need to

Need	RH/LH	SS	SU	W	LPU	LPR	BE	BNE
Risk-Avoidance	+			-	-	-	-	-
Complying to rules		+	+	+				
Financial Stability				+			-	-
Belonging	+	+	+		+	+		+
Leisure	+				++	++		
Luxury								+
Autonomy	-	+	+	+	-	-	-	-
Food Safety							+	
Financial Survival				+			-	-
Health	*Only applies when sick*							
Sleep	+							
Conformity	*The action chosen by the network is the preferred action*							

Fig. 2. The need satisfaction for each action. Based on Appendix C in [3] The needs in red only apply during working hours.

perform specific action to fulfil the needs. A completely satisfied need has a value of 1. A depleted need has a value of 0. The lower the value compared to the other need values, the more *salient* the need is. Certain actions can have a positive or negative effect on the needs. A simplified mapping of actions and their effect on the needs is given in figure 2. The ASSOCC model's deliberation will calculate for every action the expected need satisfaction and will choose the action that has the highest overall expected need satisfaction. It is completely described in [7]. In this paper the *health* is not considered as the agents cannot get sick in our experiments as a virus is not introduced. *risk_avoid* is not considered as social distancing is not relevant either. *sleep* is not considered as this is automatically satisfied in the night by an agent Resting at home. Also *autonomy* is not considered as it is only relevant during working hours, where there is already a typical action available.

Even though the ASSOCC model is a complex model with many submodels, it has been optimised [9]. Not at every time all actions are available, e.g. working hours its only work, school, university. Deliberation is context dependent in the sense that the location determines the action directly. E.g. being at work, only allows the agents to work, or go to a different location. This makes ASSOCC efficient but also less flexible. It is for example not possible to work in the evening, to compensate for doing something else during the afternoon on a working day. It should be noted that during the work on this paper we encountered a small bottleneck in the need calculations of the ASSOCC model. It increased execution time quadratically, however we managed to make this function linear without impacting its function. The execution time of the updated ASSOCC model is therefore quicker than the implementation that is referred to by the book. In the next section we will argue for a conceptual model of DCSD in ASSOCC.

3 Conceptualising DCSD in ASSOCC

The simulation context, as shown in figure 1 can be any type of information in a social simulation. In order for the framework to be able to use this information it has to be structured. The information relevance matrix shown in 3 on the left provides such a structure. It is based on the Contextual Action Framework for Computational Agents (CAFCA) [5]. The CAFCA framework categorises nine distinct deliberation types (see figure 3 in each cell in italic) from computational agents studies. Figure 3 shows the framework containing information relevant to information in the ASSOCC model. It can be seen that different decision contexts require different types of information. Generally the further to the bottom right, the more complexity is added by considering more information.

	Individual	Social	Collective
Habitual	Accessible objects, Accessible people, Actions currently performed Accessible means being accessible to the DA in the current context.	Theory of Mind: G, B, I Actions performed by relevant people Accessible objects, Accessible people, Actions currently performed Relevant people are those who have a similar goal to the DA. There is a minimal theory of mind.	Theory of Group: G, B, I Expected action as team member ToM: G, B, I Actions performed by relevant people The group considered is the group that the DA wants to join. The DA need information to perform actions to belong to the group.
Strategic	Useful objects, useful people, Utility Accessible objects, Accessible people, Actions currently performed The set of objects and people is extended to include also not directly accessible objects for plan making.	ToM: Mental attitudes ToM: G, B, I Actions performed by relevant people, Utility Useful objects, useful people Relevant people are those who can aid or hinder the DA. Mental attitudes referes to the information needed to make an estimation of the actions that other agents will perform.	ToG: Mental attitudes, roles Agents in my group ToM: Mental attitudes, Theory of Group: G, B, I Expected action as team member The mental attitudes and roles are information needed for the DA to make decisions in the group. E.g. status, structure of team, mental models, roles
Normative	Related rules, Related laws, Useful objects, Useful people, Utility Rules and laws that are relevant for the current context	Related social norms People's opinion towards those norms Related rules, Related laws, ToM: Mental attitudes Social norms related to the current context. That may hinder or lead behavior of the DA .	(Moral) values of self, Theory of Mind: values, Theory of Group: values ToG: Mental attitudes, roles Agents in my group Related social norms People's opinion towards those norms Consider values of self, others, group.

	Individual	Social	Collective
Habitual	*Repetition* **Information used** Time: 1. Morning, afternoon, evening, night 2. Workday, weekendday Available locations Age group The typical actions given the time and age group.	*Imitation* Not represented	*Joining-in* Not represented
Strategic	*Rational choice* **Information used** The levels of the needs to select which need is most salient. The typical actions that can satisfy that need.	*Game theory* **Information used** The past actions of people in the social network (family/friends) at a similar time. E.g. what the network did last working day in the evening.	*Team reasoning* Not represented
Normative	*Institutionalized rules* **Information used** The policies that are enables such as quarantine and recommended to work from home.	*Social norms* Not represented	*Moral values* **Information used** The full needs table and all actions and locations that are available during that time. All need based ASSOCC deliberation

Fig. 3. Information relevance (left) by [8] and information relevance ASSOCC (right). **DA:** Deliberating Agent, **G:** Goals, **B:** Beliefs, **I:** Intentions, **ToM:** Theory of Mind, and **ToG:** Theory of group

The most basic information is considered in the *repetition* cell, this can be the time, available locations, and the schedule of the agents, which already gives enough information to determine the typical/habitual actions. If the repetition cell does not provide enough information to make a decision, information needs to be expanded. Information from the need system can be used to select an action. Using the most salient need to determine an action is a form of utility reasoning (which fits in the *rational choice* cell). Sometimes agents want to satisfy the conformity need, this requires information on the actions of other agents. This information fits best in the *game theory* cell as the agent does not just simply imitate but rather uses information from the past to infer the action. Rules in ASSOCC are the policies that are active such as quarantine and recommended to work from home. The bottom right cell, values, contains all information, consequently this is where the original ASSOCC need based deliberation can be placed. Other cells are not used in ASSOCC at the moment, e.g. the agents do not imitate directly what other agents do at their location. Or also do not join groups so *joining-in* and *team-reasoning* are not represented either. *Social norms* are also not explicitly in the model.

3.1 Dynamic Context-Sensitive Deliberation in ASSOCC

Figure 4 shows the deliberation of the original ASSOCC model (left) and our proposed DCSD ASSOCC, from now on called context ASSOCC (right). The ASSOCC model considers the available actions, consequently selects an action based on all the needs. This draws in much information from the context, e.g. the needs, the economic system, the health system, what the social network does, which agents are expected to be at a location, etc. Which is a time consuming process. Then based on the highest expected need satisfaction an action is selected. The world is updated and in the next time step the agents deliberate again. For context ASSOCC, based on the information relevance diagram, we propose a three step DCSD model. 1) Using typical actions based on the ASSOCC schedule (is inspired by the *repetition* cell). 2) Selecting an action using the most salient need, i.e. the need with the lowest value of the relevant needs (is inspired by information from the *rational choice* and sometimes *game theory* cell). 3) If all else fails, using the original ASSOCC deliberation, which considers all information (see the *'moral' values* cell). The *'institutionalised' rules* are out of scope for this paper, as they are not directly relevant to show scalability.

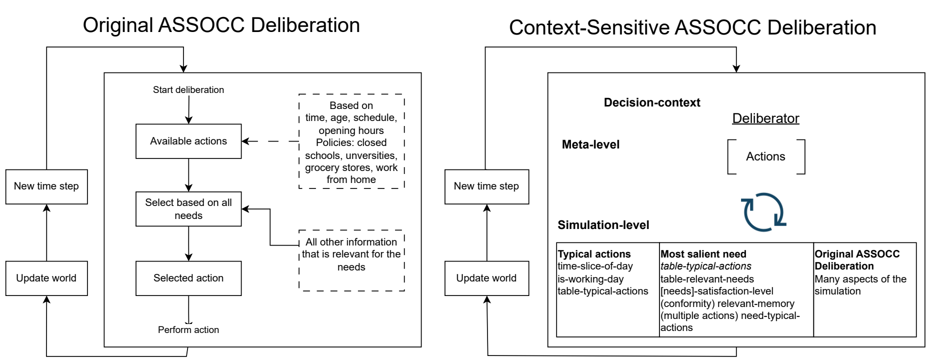


Fig. 4. Original ASSOCC Deliberation and context ASSOCC

Figure 5 illustrates an example of how an agent can use DCSD in ASSOCC. The first step is to expand the available actions. 1) The deliberator does this by considering which typical actions are available given the time (in this case, evening and a working day). Since there are more than one actions, the actions

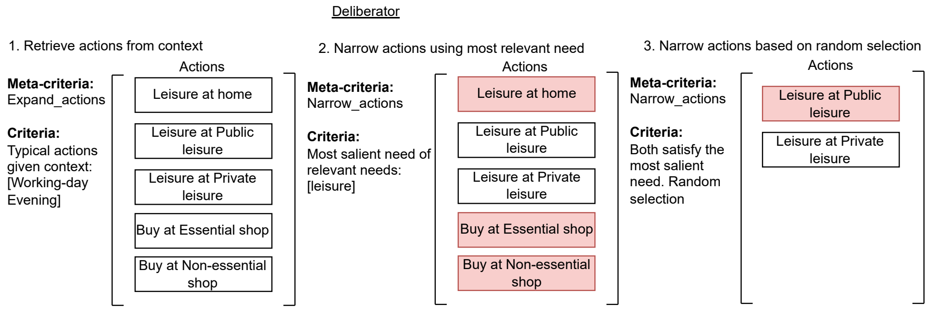


Fig. 5. Example DCSD for ASSOCC, the time is evening.

have to be narrowed down. Contrary to original ASSOCC, not all the needs are considered but just the ones relevant to the typical actions. 2) The most salient of these needs (leisure) is used to filter the actions. There are still more than one action left, but since they both fulfil the most urgent need, one of them can be selected at random.

4 Implementation of Dynamic Context-Sensitive deliberation

In principle the only adjustments made to the ASSOCC model are in the deliberation of the agents. The function *context-select-activity* is added to the model and replaces the function *select-activity* when the *context-sensitive deliberation* parameter is activated. The DCSD model consists of three main deliberation criteria. 1) Typical actions, 2) Most salient need, and 3) All need deliberation (Original ASSOCC). Figure 6 shows the deliberation flow at meta-level. The implementation (implemented in Netlogo 6.1.1) can be found at GitHub[1].

1) Typical actions At first the context is determined with the *get-context* function, it is only the time. The time consists of the *day-type*: a workday or weekend

[1] ASSOCC-Context https://github.com/maartenjensen/ASSOCC-context

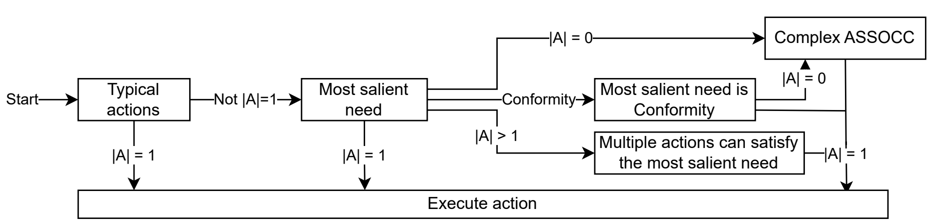


Fig. 6. Flow diagram of the implemented DCSD in ASSOCC

Time		*Typical actions*							
Day-Type	**Day-part**	**RH/LH**	**SS**	**SU**	**W**	**LPU**	**LPR**	**BE**	**BNE**
Workday	Morn/aft	Retired	Young	Student	Worker	Retired	Retired	Retired	Retired
Workday	Evening	All				All	All	All Excl young	All Excl young
Workday	Night	All							
Weekend	Morn/aft/eve	All				All	All	All Excl young	All Excl young
Weekend	Night	All							

Fig. 7. Typical actions based on time of day, type of day and agent age.

and a *day-part*: morning, afternoon, evening, or night. The typical actions are determined based on the time according to table 7. One can see that typically during working days, young only have the Study at school action, students only the Study at university action, and workers only the Work action. Also during the night the agents typically only sleep. In these cases the deliberation will be terminated as there is only one action available. At other times there are more than one action available thus more deliberation needs to be performed. These typical actions are in accordance with the schedule in the ASSOCC model.

2) Most salient need When multiple actions are available a selection between actions has to be made. As an intermediate step before consolidating all the needs, only the most salient need is considered. The needs and actions figure 2 serves as a basis for this however not all needs are considered. The needs that are considered are $belonging, leisure, food\_safety, luxury, fin\_survival, fin\_stability$ and $conformity$. To make the deliberation as efficient as possible, only the needs that are affected by the action set are considered. Table 1 shows the needs that are related to the action set. For example the actions LH, LPU and LPR (which are relevant to Youth) only affect belonging and leisure.

After determining the set of relevant needs, the most salient need of those needs is selected. Lets assume the most salient need is $leisure$. Then the agent will intersect the typical action $\{LH, LPU, LPR\}$ set with the set of actions satisfying leisure $\{LPU, LPR\}$, leading to LPU and LPR, which both satisfy leisure more than LH. This does not lead to a single action, therefore one action of those is chosen at random (see also figure 6). In case conformity is the most salient need the agent considers the action that the network previously did on that time.

Actions	Needs
LH,BE	$\{belonging, leisure, food\_safety, fin\_stab, fin\_sur\}$
LH,BE,LPR	$\{belonging, leisure, food\_safety, fin\_stab, fin\_sur$
LH,BE,LPR,BNE	$\{belonging, leisure, food\_safety, fin\_stab, fin\_sur, luxury\}$
LH,BE,LPR,BNE, LPU	$\{belonging, leisure, food\_safety, fin\_stab, fin\_sur, luxury\}$
LH,LPR	$\{belonging, leisure\}$
LH,LPR,LPU	$\{belonging, leisure\}$

Table 1. The action sets and their relevant needs, includes both positive and negative.

3) All need deliberation (Original ASSOCC) When the previous deliberation criteria did not come to a single action the *all need deliberation* is used. This is the original complex ASSOCC deliberation that takes into account all the needs and available actions, not only the typical actions. This deliberation will calculate for every action the expected need satisfaction and will choose the action that has the highest overall expected need satisfaction.

5 Validation of the framework

To validate that Dynamic Context-Sensitive Deliberation (DCSD) increases scalability we perform a comparison of execution time between original ASSOCC and context ASSOCC. The comparison is performed using Netlogo's behaviour space, investigating an increasing number of agents and an exploration of available actions. We chose to not run models in parallel as this influences the execution time of individual runs. Instead runs are performed serial, only one run at a time. The experiments use the following parameter settings. The *context-sensitive-deliberation* parameter which is set to false (original ASSOCC) and true (context ASSOCC) for the comparison. The households are set to 350, the number of agents for this country setting is 1004. The *action-space* variable indicates the available actions, six means all earlier described actions are available. The tick limit is by default set to 120 ticks which is 30 days which represents a month. The preset-scenario is *Context-ASSOCC* which sets the country, no-infected and migration. The country is set to Great Britain distribution. The *no-infected* is set to *true* so the model runs without infected.

5.1 Increasing amount of agents

In the first experiment the number of agents are adjusted. The settings for the households (households) are the following $\{350, 700, 1400, 2100, 2800, 3500\}$ leading to respectively the following numbers of agents $\{1004, 2008, 4016, 6016, 8024, 10028\}$. Figure 8 shows the results of this experiment. On the left the execution

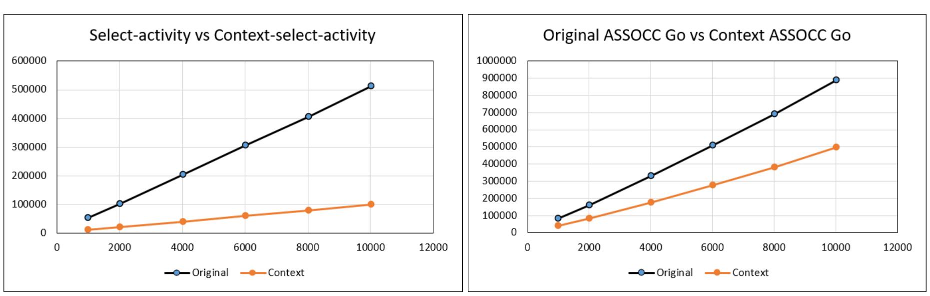
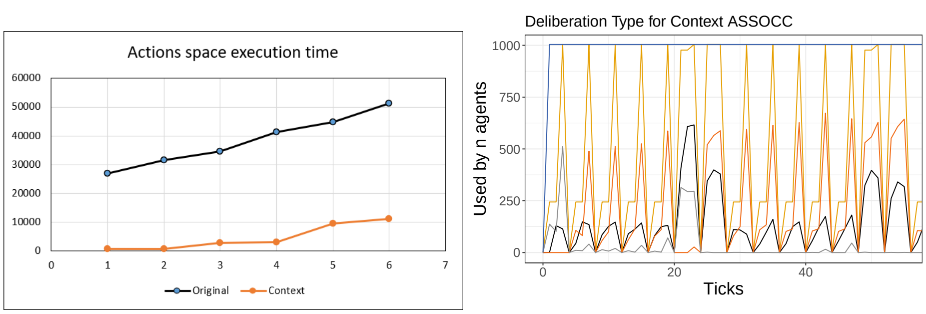


Fig. 8. Original ASSOCC vs Context ASSOCC execution time

time of the deliberation function. It can be seen that DCSD takes five times less time than original ASSOCC deliberation. This is a large improvement which is retained even with larger amount of agents as both graphs are continuing linearly. The right figure 8 shows the execution time of the go function, that includes needs updating, performing the action, etc. Even here we can see that context ASSOCC is almost twice as fast. In terms of execution time 10000 agents in context ASSOCC is similar to 6000 agents in original ASSOCC.

5.2 Experimenting with the number of available actions

In this experiment we adjust the available actions. The actions are added in the following order dependent on the *action-space (AS)*. if $(AS \leq 1)[RH/LH]$, if $(AS \leq 2)[SS, SU, W]$, if $(AS \leq 3)[BE]$, if $(AS \leq 4)[LPR]$, if $(AS \leq 5)[BNE]$, if $(AS \leq 6)[LPU]\}$. Figure 9 on the left shows that original ASSOCC's execution time increases roughly linear with the addition of additional actions. However for context ASSOCC it highly depends on what type of actions are added, some actions that are added do not increase the execution time at all as the time remains constant. Context ASSOCC is extremely efficient with an AS of one or two, since for all agents at all times there is only one typical action available, so the deliberation is only a HashMap lookup (which is very efficient in Netlogo). Deliberation time increases as agents need to sometimes make a selection between home and buy at grocery, first based on the most salient need and otherwise on the original ASSOCC deliberation. Adding another action (BE) does not increase the execution time. Probably since agents now get an option to satisfy the leisure need using LPR. The computational time increases again after adding BNE since an additional need has to be checked which is often not salient. In addition when *all need deliberation* is considered this action has to be checked also, increasing the execution time even further. Adding the last action, LPU, increases the execution time only slightly, now when leisure is the most salient need a selection between LPR and LPU has to be made. These results



Action space

Fig. 9. Figure on the left, execution time of different action-space settings, original ASSOCC vs context ASSOCC. Figure on the right, the different deliberation criteria used by n agents.

Deliberation criteria	Calls	Call %	Time (ms)	Time %	Time per call
Total deliberation	120480	-	10891.0 ms	-	-
Typical actions	120480	100%	299.5 ms	2.75%	0.0025 ms
Most salient need	56704	47.1%	1325.5 ms	12.17%	0.0234 ms
All need deliberation	15500	12.9%	8942.5 ms	82.11%	1.7332 ms

Table 2. The execution time in Context-Sensitive ASSOCC.

show that in context ASSOCC, if one is considerate one can potentially add many more actions without a large increase in execution time.

5.3 How is dynamic context-sensitive deliberation efficient?

Figure 9 at the right shows the deliberation criteria that are used. The graph shows two weeks (56 ticks) from a run with an *action-space* of six and 350 households thus 1004 agents. Inferring from the graph one can see that typical actions are always explored. During evenings the most salient need (in yellow) is always considered since agents always have multiple actions to choose from. The *conformity* need (in orange) is considered quite often in both evenings and weekends. All need deliberation (black) is considered only in about 10% of time during the day, and about 40% during the weekends. This makes sense as agents have more options in the weekend while throughout the week they are more likely to go to work/study.

Table 2 shows a more precise result. This table shows for each function the number of times it is called and the total execution time. The percentage of time does not add up since there is a small amount of time going to the meta-deliberation and some other functions such as updating the numbers of used deliberation criteria. The percentage of the calls is the percentage of calls of a deliberation criteria divided by the percentage of calls of total deliberation. Typical actions are called always that is why they are 100%. In 47.1% of cases the *typical actions* do not provide a solution and *most salient need* criteria is called. In only 12.9% of the time *all need deliberation* is necessary. Note that this is only called 12.9% of the time but still takes the largest chunk of execution time, i.e. 82.11%! One should note that if the amount of calls of *all need deliberation* can be decreased, by for example adding additional deliberation criteria, a large drop in execution time can be expected. Halving for example the use of *all need deliberation* by using another efficient deliberation criteria, would make the total deliberation time potentially almost two times as fast.

6 Discussion & Conclusion

The comparison shows that Dynamic Context-Sensitive Deliberation (DCSD) can increase scalability by, decreasing even for large amount of agents. Realism is retained since the behaviour of the agents is comparable. With both the original ASSOCC and the context ASSOCC the agents go to work, to school, sleep at night, while also visiting leisure places and shops during the evening and weekends. There are variations between the models, however this does not necessarily make the behaviour less realistic. Also the model can be re-calibrated to account for the change in deliberation.

Considering the original ASSOCC model, the agents are still quite rigid in their behaviour. They for example will not shop during the afternoon and compensate this by working in the evening. With DCSD we can potentially add this ability to plan which makes the agents behaviour more flexible and even more realistic. We are planning on exploring this in future work.

It should be noted that in context ASSOCC most of the execution time in the go function now no longer comes from deliberation but rather the other processes. As ASSOCC is already optimised, if one wants to go beyond this, another platform or other techniques should be used [10]. A suggestion is to use for example High Performance Repast [1].

Computational complexity with regards to the number of agents is only linear in original ASSOCC. It can be expected that in models with quadratic computational complexity DCSD can improve the scalability even more. These would be models that for example use more techniques from the social and collective dimensions (from Figure 3) in their decision making. E.g. considering at a location what other agents do to decide their own actions. Which can be relevant if agents for example want to decide whether to social distance based what other agents do.

To conclude, based on the discussed results DCSD can increase scalability in large scale social simulation models without sacrificing on the model's realism.

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