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DAMS: A model to assess domino effects by using agent-based modelling and simulation

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ABSTRACT

Historical data analysis shows that escalation accidents, so-called domino effects, have an important role in disastrous accidents in the chemical and process industries. In this study, an agent-based modelling and simulation approach is proposed to study the propagation of domino effects in the chemical and process industries. Different to the analytical or Monte Carlo simulation approaches, which normally study the domino effect at probabilistic network levels, the agent-based modelling technique explains the domino effects from a bottom-up perspective. In this approach, the installations involved in a domino effect are modelled as agents while the interactions among the installations (e.g., by means of heat radiation) are modelled via the basic rules of the agents. Application of the developed methodology-model to several case studies demonstrates the ability of the methodology-model not only in modeling higher-level domino effects and synergistic effects but also in accounting for temporal dependencies. The model can readily be applied to large-scale complicated cases.

KEYWORDS

Domino effect, Agent-based modelling, Major accident hazard, Computational experiments

1 INTRODUCTION

Domino effects have been responsible for some catastrophic accidents which occurred in the chemical and petrochemical industries.⁽¹⁻⁵⁾ Although there are multiple definitions of domino effects in the chemical and process industries,^(1, 6, 7) this type of accidents features a generic schematization with the following elements: 1) there is a “primary event”, initiating the domino effect; 2) there is an escalation vector (e.g., fire impingement, heat radiation, explosion overpressure, etc.), facilitating the propagation of the domino effect; 3) one or more secondary accident events, involving one or more target equipment.^(8, 9) In the second element, the influence of synergistic effects should be considered to account for the occurrence of multiple accident scenarios. Through synergistic effect, the escalation vectors of concurrent events are superimposed to identify the possibility of causing damage to other target equipment.

Domino effect occurred several times in the chemical and process industry, featuring high destructive potential.⁽¹⁰⁾ Kourniotis et al.⁽¹¹⁾ examined 207 major chemical accidents and found that 114 of them involved a domino effect. The existence of domino effects make assets in process plants dependent on each other, resultant in a systemic risk.⁽¹²⁾ The potential severity of such accident scenarios led to important efforts for the prevention of domino effects,^(3, 13, 14) and also made relevant technical standards and legislation take into account measures to assess, control, and prevent domino effects.

Cozzani et al.^(7, 8) developed a methodology for risk assessment based on the adoption of vulnerability models, which relied on simplified modeling and characterization of the escalation vectors. Khan and Abbasi^(15, 16) synthesized the quantitative methodologies used in domino effects estimation, and developed a software named “DOMIFFFECT” to support the domino effect estimation in complicate situations. Reniers and Dullaert⁽¹⁷⁾ developed a software named

“DomPrevPlanning” to support decision making on safety barriers to prevent/mitigate domino effects in complex chemical installations, which succeed in considering multiple domino scenarios. Abdolhamidzadeh et al.^(9, 18) developed an algorithm named “FREEDOM” based on Monte Carlo Simulation to assess domino effects. Khakzad et al.⁽¹⁹⁻²¹⁾ developed a methodology based on Bayesian network both to probabilistically simulate the propagation of domino effects and to identify the most likely sequence of events in a potential domino effect. In their methodology, both the possibility of higher-order domino effects and the influence of synergistic effects were taken into account.

Nevertheless, despite the relevant progress made in the framework of domino effect understanding and modeling, the time dimension and evolution of domino effects, which is critical for emergency preparedness and response,⁽²²⁾ is not systematically accounted for. Khakzad et al.⁽²³⁾ developed a dynamic Bayesian network (DBN) methodology to capture both spatial and temporal propagation of domino effects. However, in application of large-scale cases, the DBN model needs a combinatorial-increasing number of conditional probabilities. Furthermore, the DBN model uses a discrete time scheduling method, which has been proofed to be not efficient. To this end, the extension of DBN models feature a high level of complexity and demand relevant computational resources for the extension to realistic industrial cases, featuring the simultaneous analysis of dozens of units.

In the present work, an agent-based modelling and simulation model – DAMS – is proposed to support domino effect analysis in the chemical and process industries. The aim of this study is to provide a quick yet effective tool for the chemical and process industries to support the emergency response and mitigation strategies. The methodology-model is applied to i) a demonstration case study for verification purposes; ii) as well as to a real industrial setting for illustrating the

implementation of the model; and iii) an intentionally constructed large scale ~~case~~-study to investigate computational issues. Furthermore, a discussion on computation resources and potential applications is also addressed.

2 AGENT-BASED MODELLING AND SIMULATION

Agent-based Modelling and Simulation (ABMS) is a bottom-up approach to study complex systems.⁽²⁴⁾ Given a system, instead of modelling the patterns, structures, and the system behaviors, the ABMS approach focuses on the basic units (namely, the “agents”) of the system, including their attributes and interactions.⁽²⁴⁾ By performing computational experiments on the agent models, the response and behavior of the global system may be derived.⁽²⁵⁾ Several examples of ABMS applications in different disciplines and contexts are available in the literature.

Epstein and Axtell⁽²⁶⁾ proposed an agent-based social simulation model, named Sugarscape, in which multiple agents move, interact, and behave in order to get sources (i.e. sugar). In Epstein and Axtell’s seminal book,⁽²⁶⁾ by defining simple but different rules for the agents, some complex social phenomena such as groups, war, trading, etc. emerged in the Sugarscape model. Since the Sugarscape, ABMS has been widely used in social science as well as complex system studies and prediction of pandemics,⁽²⁷⁾ economic crisis management,⁽²⁸⁾ and manufacturing.⁽²⁹⁾ In recent years, ABMS has also been used in the risk analysis domain; some examples among others are the analysis of hurricane evacuation procedures,⁽³⁰⁾ flood incident management,⁽³¹⁾ and defensive resources allocation for spatially distributed networks.⁽³²⁾ However, the potential application in the framework of industrial safety, and especially in relation to domino effect assessment, is innovative and is discussed in this study.

In ABMS, an agent model normally consists of several static attributes and several simple rules. The rules and the interactions of agents should not be complex, since simple individual behaviors and interactions can already generate complex system behaviors.

In the case of the application to domino effect assessment, the accident propagation and evolution may be considered as a behavior of the system, resulting from the interactions (heat radiation propagation and/or overpressure following accidents) of items (target equipment, such as tanks, pipelines, etc.) in the industrial areas. For this purpose, the behavior and interactions of the items should be reproduced with simple rules, which is normally not the case for domino targets. In fact, several studies pointed out the complicating physical phenomena associated with equipment exposed to fire,^(33, 34) overpressure,^(35, 36) and missile projection.^(37, 38) Specific advanced model tools such as Finite Elements Modeling⁽³⁹⁾ or computational fluid dynamics⁽⁴⁰⁾ may be required for a comprehensive detailed assessment. Nevertheless, previous research^(33, 41) was dedicated to the development of simplified approaches aimed at reproducing the behavior of target equipment exposed to a given escalation vector. Such simple rules and models may be adopted in order to trace the behavior and interaction of single items. Even though the behavior of target equipment during domino effects can be simplified, the domino effect itself is still quite complicated due to several reasons: (i) the probabilistically propagation; (ii) the synergistic effects; (iii) the dynamic evolution. Therefore, ABMS features a suitable approach to support the analysis of complex domino effects.

3 MODEL DESCRIPTION

3.1 Overview

Among others, the AnyLogic software group, which is one of the most successful groups in developing simulation platforms in the world, defines ABMS as: “from the viewpoint of practical applications agent based modelling can be defined as an essentially decentralized, individual-centric (as opposed to system level) approach to model design. When designing an agent based model the modeller identifies the active entities, the agents (which can be people, companies, projects, assets, vehicles, cities, animals, ships, products, etc.), defines their behaviour (main drivers, reactions, memory, states, ...), puts them in a certain environment, establishes connections, and runs the simulation.”⁽⁴²⁾ Storage tanks are the most frequently involved items in domino effects in the chemical and process industries.^(4, 43) Some global information such as weather, geography etc. also act as an important role in domino effects. To this end, active entities in the **D**omino effect assessment by **A**gent-based **M**odelling and **S**imulation (DAMS) model are the tanks and the environment, as shown in Figure 1. In the following sections, Figure 2 illustrates the static model of the tank agents; Figure 4 depicts the tank agent’s behaviour model; The environment model is given in Figure 5; Connections (or interactions) among agents and between the agent and the environment model, are given in Figure 4 and Figure 6 respectively; Finally, the DAMS model is implemented on 3 case studies, and Monte Carlo Simulation is employed to get the statistic results.

Figure 1. Framework of the ABMS model for supporting Domino Effect assessment.

In the following, the presented framework is explained in more details. For illustrative purposes, the analysis is devoted to domino effects triggered by fire, but the approach can be extended to consider domino effects triggered by overpressure.

3.2 Tank agent model

3.2.1 Static model

Storage tanks (tank agents) are the main agent type involved in the domino effect chain. Because modelling is an abstract form of reality, it cannot capture all the properties of the concerned object; thus, only the properties which are relevant to the modelling and simulation goal should be taken into consideration. Therefore, only the domino effect related attributes of a tank are considered in the tank agent models (and the same for other models in this study). All these attributes should be initialised at the beginning of the simulation, given the concerned process plant. The static model

of the tank agent is shown in Figure 2, modelled in the software Generic Modelling Environment (GME).⁽⁴⁴⁾

GME is a configurable toolkit for creating domain-specific modelling and program synthesis environments. It provides interfaces for secondary developers, enabling the users to define their own domain specific model libraries. In this study, all the static models are graphically shown in the GME while the implemented simulations are coded in C++. GME provides interfaces for the model developer to link their models coded in some programming languages (e.g., C++) and the graphic icons in the GME.

Figure 2. Static model of Tank Agent.

As shown in Figure 2, the Tank Agent model consists of several attributes:

- Index: unique identity of the tank;
- Position: coordinates of the tank;
- Material: nature of the chemical substance stored in the tank, such as Benzene, Gasoline, etc.;

- PressureType: indicating whether the tank is an “Atmospheric” or “Pressurized” tank;
- Q_{tot} : the accumulated heat radiation that the tank received from other tanks, more explanation of this attribute is given in the following paragraph;
- State: the state of the tank, as summarized in Table 1;
- Shape: shape information of the tank, consisting of:
 - ShapeType: indicating if the tanks is “Vertical Cylinder”, or “Horizontal Cylinder”, or “Spherical”;
 - Diameter: diameter of the tank;
 - Height: the height (length) of “Vertical (Horizontal) Cylinder” tank; this attribute does not apply to “Spherical” tank;
 - FullPercentage: indicating how full (%) the tank is.

In case at least one tank within the area of interest (AOI)¹ is in failure mode, leading to a primary fire scenario such as a pool fire, one or more neighbouring tanks receive heat radiation. Heat radiation exposure may cause a structural damage on each tank. This in turn can result in secondary fires; as a result, possible synergistic effects between the primary and secondary fires should be taken into account. In fact, the resultant heat radiation received by a given target may be increased by the superimposition of the heat radiation of simultaneous fire. This is particularly relevant when a target tank does not receive enough heat radiation to reach failure conditions but, after the secondary failure of other equipment, the resultant heat radiation on the target is increased due to synergistic effects, increasing the possibility of failure.

¹Area of Interests (AOI), defined by the U.S. military, is the area of concern to the commander. Hereby we use it to describe the areas affected by the domino effects.

3.2.2 Dynamic model

The tank agent has four possible states during the evolution of a domino effect scenario, as summarized in Table 1.

Table 1. Definition of the variables which characterize the tank agent dynamic behaviour.

State	Description
Normal	The tank operates in normal conditions: initial state
Heat-up	The tank is not physically damaged, but due to heat radiation received from external fire the wall and the contains are heating up with consequent pressurization and incipient failure due to structural weakening
Leaking	The tank is physically damaged, thus hazardous materials are released. It is supposed that storage units are provided with a catch basin, which ensures the full containment of the released liquids
Fire	The tank is already on fire in the catch basin.

In a domino effect, the tank agent can probabilistically transfer from one state to another state, as we will show later in this section. To this end, the formal modelling formalism named “probabilistic statechart” is employed to describe the tank agent’s dynamic model.

A probabilistic statechart⁽⁴⁵⁾ is commonly adopted in order to show the probabilistic transition among the different states. A sample p-statechart showing the inner model of a door is depicted in Figure 3.

Figure 3. An Illustrative p-statechart model showing door opening.

The arrows between states (modules) represent the possible transitions from the initial state to the end state. The content in the square bracket assigned to the transition represents the condition of the transition; the content in the braces represents the actions while the transition happens. For

example, only when the condition of “Force” (i.e. someone is opening the door) and “ $p < 0.5$ ” (i.e., he is on the right direction) are satisfied, the transitions “1” and “2” will happen, and if they happen, the door will Compute the opening Angle by “CA”. Note that the door is only characterised by a “Closed” or “Open” state; the “P” module is just a judging point.

The states shown in Table 1 are implemented in the probabilistic statechart, adopted for the modelling and simulation of domino effects, as illustrated in Figure 4. Table 2 describes in detail all the conditions and actions in the model.

Figure 4. Tank Agent – the dynamic model statechart (“Broadcast” indicates that the ‘on Fire’ tank will transmit heat radiation to all other tanks within the AOI).

Table 2. Description of agent behaviours and parameters depicted in Figure 4.

Name	Definition	Details
Q_M	Heat radiation propagation message	The sender of this message is the tank in “FIRE” state (transitions 2 and 9); the receivers of this message are all the other tanks which are not in “FIRE” state (transitions 4, 10, and 12).
UPDATE	Update Q_{tot}	Updating Q_{tot} by adding the received heat radiation.
Q_c	Q_{tot} changes	-
tff	Time to failure	The time to failure is the time lapse between the start of the fire and the failure of a target vessel. It is computed through the simplified correlations reported in Table 3 and APPENDIX A.
P_f	Damage probability	This probability is evaluated according to the procedure summarized in Table 3.
IniEvt	Initial events	Internal process failure, due to corrosion, accidental pressurization, operator mistakes, etc. ⁽⁴⁶⁾
P_i	Probability of immediate ignition	P_{i1} : to be selected when there is no tank on fire within AOI. P_{i2} : to be selected when at least one tank is on fire within AOI.
Q_{th1}, Q_{th2}	Threshold of heat radiation	Q_{th1} : when the tank is already in a HEAT-UP state, the threshold of judging whether to use the Vulnerability Model. Q_{th2} : when the tank is LEAKING, the threshold of judging whether to use ETA2. In this study, we set both Q_{th1} and Q_{th2} equal to a constant small number, as $Q_{th1} = 1kw/m^2$ and $Q_{th2} = 1kw/m^2$.

As shown in Figure 4, the tank agent is able to react either to an initial event or due to the heat radiation received from an external fire. In the first case, an accidental leak with consequent release of hazardous material is supposed to occur only due to internal causes, such as corrosion, erosion, and accidental pressurization.⁽⁴⁶⁾ If the tank is damaged, a secondary scenario may occur, which, in turn, may affect surrounding units in the AOI.

The **four states** in Figure 4 represent the tank possible states shown in Table 1. At a given time, the tank can only be in one of the states listed in Table 1. This implies that the states are mutually exclusive. Figure 4 also shows that there are two main modules (namely ProbM and ETA), which are used as judging points, so the tank never remains in these modules.

The **ProbM module** represents the vulnerability model, based on which the tank agent model can evaluate the probability of being damaged. The vulnerability models for heat radiation exposure based on Probit models developed by Landucci et al.⁽³³⁾ are adopted. Table 3 summarizes the vulnerability models, based on a simplified correlation for the estimation of time to failure, e.g., the time lapse before the eventual failure of a target tank since the start of an external fire. More details on the failure model of tanks are discussed in APPENDIX A.

Table 3. Summary of vulnerability models (heat radiation effects) adopted for the assessment of vessel damage probability due to fire.

Type of Tank	ttf correlations	Probit model
Atmospheric	$\ln(ttf) = -1.13 \cdot \ln(Q) - 2.67 \times 10^{-5} \cdot V + 9.9$ (1)	$Y = 9.25 - 1.85 \cdot \ln\left(\frac{ttf}{60.0}\right)$ (3)
Pressurized	$\ln(ttf) = -0.95 \cdot \ln(Q) + 8.85 \cdot V^{0.032}$ (2)	

In Equations (1) to (3), ttf represents the time to failure (in seconds); Q denotes the total heat radiation received by the tank (in kW/m^2); V denotes the volume of the tank (in m^3); Y denotes the Probit value. In previous research,⁽⁴⁷⁾ a “threshold criteria” has been proposed, where if the received heat radiation was less than a threshold heat radiation, it could not make a credible damage and thus would be ignored. However, in this study, we do not perform a threshold criteria check, assuming that even if a target tank receives less heat radiation intensities, it still might be involved in the domino effect, especially due to the influence of synergistic effects in large scale cases.

The **ETA module** represents the post-release event tree (see APPENDIX B) to determine the occurrence probability of accidental scenarios (explosion, fire, dispersion, etc.).^(1, 46) For illustrative purposes, we only considered pool fire as the possible accident scenario, assuming a null

probability of delayed ignition (see APPENDIX B). Hence, explosions or flash fires are excluded from the analysis.

When the tank is in the “Normal” state (Figure 4):

- 1) it can react to an initial event (transition 1), such as flammable liquid leakage;
- 2) it can react to the heat radiation from other tanks (transition 4) and update the total heat radiation Q_{tot} it receives. After updating the Q_{tot} , the agent will compute the time to failure (ttf);
- 3) it can compute the probability of being damaged P_f , based on the vulnerability model, when the time reaches the ttf(transition 5).

When the tank is in the “HEAT-UP” state(Figure 4):

- 1) it can react to the heat radiation from other tanks, and update the total heat radiation Q_{tot} it receives (transition 10)
- 2) it can compute the ttf, if the updated Q_{tot} is greater than the threshold Q_{th1} (transition 11).

Note that the threshold check here is different from the above-mentioned threshold criteria;⁽⁴⁷⁾ in the present study, when this threshold check is being executed, it means that the tank is already heated up. As shown in Table 2, Q_{th1} (and also Q_{th2}) is set to be a small value.

When the tank is in the “Leaking” state (Figure 4):

- 1) it can react to the heat radiation from other tanks if Q is greater than the threshold Q_{th2} (transition 12).

At the **ETA1 module**, if there is an ignition, a secondary fire will occur and the tank agent broadcasts heat radiation to all other tanks (transition 2). If there is no ignition, the tank will keep

leaking out its content (transition 3). Only the primary tank agent will move to ETA1, thus we can set the ignition probability based on standard literature data, as $p_{i1} = 0.1$.⁽⁴⁶⁾

At the **ProbM module**, the tank will compute the probability of being damaged (P_f) due to fire exposure. In case the tank does not fail, at probability $(1 - P_f)$, it will transfer to “HEAT-UP” state (transition 6, in Figure 4), which means the tank is not physically damaged, but its temperature and pressure are increasing due to the fire. In other words, a deterioration of the tank occurs without compromising its integrity; thus, with no release of hazardous materials. On the other hand, if the tank fails (with a probability P_f), it will transfer to ETA2 (transition 7, in Figure 4). This means that the tank is physically damaged and an event tree model is applied in order to trace the evolution of post-release scenario. It is worth mentioning that the domino targets move to ETA2 only as a consequence of fire exposure. Thus, due to the presence of heat radiation, the ignition probability for ETA2 was set higher than ETA1, for illustrative purpose, $p_{i2} = 0.6$.

At the **ETA2 module**, in case of ignition, a secondary fire scenario occurs (“FIRE” state) and the agent will broadcast heat radiation to all other tanks (transition 9, in Figure 4). If there is no ignition, the tank starts to/continues the release of hazardous material (transition 8).

3.3 Environment model

In the present work, the environment model has two functions. One function of the model, which considers the analysis of domino effect evolution, contains the information of the AOI, such as the geographic properties, the weather information etc. Another function is, on the side of the simulation run, that the environment model acts as an observer, monitoring and storing information about the states of each tank agent.

Figure 5 shows the static model of the environment model, modelled in GME, while the dynamic interaction of the environment model is presented in Figure6.

Figure 5. Static model of the Environment model.

As shown in Figure 5, the static model of the environment model consists of the global information of all the tanks, as well as some geographic information, weather information. The meanings of all the attributes can easily be understood according to their names, except the “HeatRadiationMatrix”. HeatRadiationMatrix is a two-dimensional matrix, whose entry HRM_{ij} represents the heat radiation from tank i to tank j if tank i would be on fire.

Figure 6. Schematization of the dynamic interactions among agents and environmental model.

Since the environment model manages all the global information, the tank agents need to Get the required Information (the GrI line in Figure6) from it. For instance, when computing the heat radiation to other tanks, the tank on fire needs to know how many tanks are there in the AOI, and how many of them have already failed. When the tank agent changes state, it needs to Report the State change (the ReS line in Figure 6) to the environment model.

4 DESCRIPTION OF CASE STUDIES

In this section, three case studies are used to demonstrate the application of DAMS model. Case study #1 is a simplified demonstration case study, aiming at interpreting the correctness of the DAMS model; case study #2 is a real scale case study composed of 34 chemical tanks, used to show the advantages of the DAMS model, compared to previous models;⁽²³⁾ case study #3 is an intentional constructed case study, aiming at illustrating the extensibility of the model to large scale cases possibly containing hundreds of tanks in industrial practice.

4.1 Case study #1: verification of the methodologymodel

In order to test the validity of the methodologymodel, a demonstration case study is firstly considered. The simplified example was defined in order to obtain the analytical solution of the problem, thus providing external validation data for the current methodologymodel.

4.1.1 Description of the tank farm

The tank farm considered for the analysis of the simplified case study is represented in Figure 7(a) (modified version of the case used in Khakzad et al.⁽²⁰⁾) and consists of three atmospheric storage tanks storing flammable liquids; the features of the tanks are summarized in Table 4. The same

type of failure due to internal process causes was assumed to affect every tank, causing the release of the entire liquid content in the catch basin in ten minutes.⁽⁴⁸⁾

Figure 7. Layout of the case studies considered in Section 4.

Table 4. Features of the tanks considered for the analysis of case study#1 and consequence assessment of the primary scenarios.

ID	Coord. (x;y in m)	Subst.	Diameter (m)	Height (m)	Volume (m ³)	Initial event frequency (y ⁻¹)	Radiation on each target (kW/m ²)		
							T1	T2	T3
T1	0.0; 59.8	Hexane	20	10	3142	1×10^{-4}	-	23. 8	15.7
T2	50.0; 59.8	Benzene	14	8	1232	1×10^{-4}	25.5	-	26.4
T3	45.3; 0.0	Benzene	14	8	1232	1×10^{-4}	9.54	12. 5	-

The ALOHA software for consequence analysis⁽⁴⁹⁾ allowed estimating the heat radiation caused by the pool fire following the ignition of the flammable material. The following meteorological conditions were considered for the analysis of the case study: stability class D, wind at 5 m/s blowing from North, ambient temperature of 25°C and 50% relative humidity. The results of the consequence assessment are also reported in Table 4. It is worth noting that the outputs of the

ALOHA software (i.e., the heat radiation matrix) are used as the inputs of the DAMS model. By setting critical (extreme) conditions for the ALOHA software, the output heat radiation results would also be high, thus and hence the domino risk assessed by the DAMS model are would be the worst-case results as well.

For illustrative purpose, T1 is assumed to be tagged with an initial event.

4.1.2 Analytic results of case study #1

Figure 8 shows the analytic results of the demonstration case, based on the Dynamic Event Tree Analysis,⁽⁵⁰⁾ considering not only the probabilistic dimension, but also the time dimension.

Figure 8. Dynamic Event Tree Analysis: analytic result of the simplified case study.

At $t = 0$, there is a probability of p_{i1} that T1 would be ignited. If T1 is ignited, then T2 and T3 would be heated. By employing Equation (1) and data shown in Table 4, we have $ttf_2^1 = 536$, and $ttf_3^1 = 858$. At time $t = ttf_2^1$, T2 would be heated up, thus by employing the vulnerability model (i.e. Equation (3)), T2 would be physically damaged at probability $pf_2^1 = 0.5779$; furthermore, T2 would be ignited at that time by probability p_{i2} . If T2 is also on fire, T3

would receive heat radiation from both T1 and T2. By employing Equation (A.6) in APPENDIX A, we have $t_r^2 = 631$. At time $t = t_r^2$, T3 would be physically damaged and ignited, at probabilities pf_3^{1+2} and p_{i2} , respectively. Note that while computing pf_3^{1+2} by using Equation (1) and (3), the total heat radiation received (i.e. 15.7 kW/m^2 and 26.4 kW/m^2 from T1 and T2 respectively) by T3 should be used as input, obtaining $pf_3^{1+2} = 0.9175$, as further explained in APPENDIX A.

The above paragraph explains the scenario 13, other scenarios can be explained in an analogous way. Table 5 summarizes all the 13 scenarios shown in Figure 8. Events in the description column are shown as (tank index, state, time), and they are listed according to the time of occurrence.

Table 5. Analytical solution of case study #1.

Scenario	Description (L: Leaking; H: Heat-up; F: Fire)	Probability
Sce1	(1,L,0)	$1 - p_{i1}$
Sce 2	(1,F,0)→(2,H,ttf ₂ ¹)→(3,H,ttf ₃ ¹)	$p_{i1} \cdot (1 - pf_2^1) \cdot (1 - pf_3^1)$
Sce 3	(1,F,0)→(2,H,ttf ₂ ¹)→(3,L,ttf ₃ ¹)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot (1 - p_{i2})$
Sce 4	(1,F,0)→(2,H,ttf ₂ ¹)→(3,F,ttf ₃ ¹)→ (2,H,ttf ₃ ¹)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot p_{i2} \cdot (1 - pf_2^{1+3})$
Sce 5	(1,F,0)→(2,H,ttf ₂ ¹)→(3,F,ttf ₃ ¹)→ (2,L,ttf ₃ ¹)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot p_{i2} \cdot pf_2^{1+3} \cdot (1 - p_{i2})$
Sce 6	(1,F,0)→(2,H,ttf ₂ ¹)→(3,F,ttf ₃ ¹)→ (2,F,ttf ₃ ¹)	$p_{i1} \cdot (1 - pf_2^1) \cdot pf_3^1 \cdot p_{i2} \cdot pf_2^{1+3} \cdot p_{i2}$
Sce 7	(1,F,0)→(2,L,ttf ₂ ¹)→(3,H,ttf ₃ ¹)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot (1 - pf_3^1)$
Sce 8	(1,F,0)→(2,L,ttf ₂ ¹)→(3,L,ttf ₃ ¹)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot pf_3^1 \cdot (1 - p_{i2})$
Sce 9	(1,F,0)→(2,L,ttf ₂ ¹)→(3,F,ttf ₃ ¹)→ (2,L,ttf ₃ ¹)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot pf_3^1 \cdot p_{i2} \cdot (1 - p_{i2})$
Sce 10	(1,F,0)→(2,L,ttf ₂ ¹)→(3,F,ttf ₃ ¹)→ (2,F,ttf ₃ ¹)	$p_{i1} \cdot pf_2^1 \cdot (1 - p_{i2}) \cdot pf_3^1 \cdot p_{i2} \cdot p_{i2}$
Sce 11	(1,F,0)→(2,F,ttf ₂ ¹)→(3,H,t _r ²)	$p_{i1} \cdot pf_2^1 \cdot p_{i2} \cdot (1 - pf_3^{1+2})$
Sce 12	(1,F,0)→(2,F,ttf ₂ ¹)→(3,L,t _r ²)	$p_{i1} \cdot pf_2^1 \cdot p_{i2} \cdot pf_3^{1+2} \cdot (1 - p_{i2})$
Sce 13	(1,F,0)→(2,F,ttf ₂ ¹)→(3,F,t _r ²)	$p_{i1} \cdot pf_2^1 \cdot p_{i2} \cdot pf_3^{1+2} \cdot p_{i2}$

4.2 Case study #2: application of the methodologymodel

In this section, we apply the DAMS model to a realistic chemical area containing 34 tanks, as shown in Figure 7(b). Further information of this case study is given in APPENDIX D.

Analytical methods such as dynamic event trees and Bayesian networks could be quite complex if they are implemented on this case study. However, the DAMS model proposed in this study can easily be implemented on this case study. Section 5.2 gives some computational results of this case study.

4.3 Case Study #3: computational complexity of the methodologymodel

Although one advantage of DAMS model is that the number of replications will not be influenced by the number of tanks (see proofs in APPENDIX C), the computational time of each replication will increase when the number of tanks increases. In this section, we will show the computational time of cases with different numbers of tanks in case study # 3.

When the number of tanks increases, it becomes difficult to collect and input all the required data to the model. A typical tank farm is represented in Figure 7(c) in order to generate typical inputs for the computational time testing. As shown in Figure 7(c), the tank farm consists of $n = (2k + 1)^2$ tanks, and each tank is located on one grid in a $(2k + 1) \times (2k + 1)$ square.

The tank agents' index and position are given in the Figure. We assume that all the tanks are atmospheric vertical cylindrical tanks ($d = 14\text{m}$, $h = 8\text{m}$) storing benzene. The same environment information used in the simplified case were adopted in the present assessment. The consequence assessment of the pool fire resulting from the failure of each tank were assessed using ALOHA.

We set the middle tank (the red one) as the primary unit W and run $N = 10^6$ replications for increasing the values of k .

5 RESULTS

5.1 Analysis of case study #1

Based on the information given in Section 4.1, the tank agents and the environment model were initialized.

When tagged with an initial event, tank T1 has $(1 - p_{i1})$ probability of being in “LEAKING” state. In this case, the simulation would stop since the tank no longer contributes to the domino effect. Thus, such a case is excluded from the simulation. In other words, in the simulation, tank T1 is set on a “FIRE” state, and each simulation result is multiplied with the respective probability of immediate ignition (p_{i1}).

Figure 9 shows the comparison of the results obtained via the application of the DAMS model against the analytical results described in Table 5. As shown in the figure, a good agreement is obtained, with a maximum relative error of 1.66% and a maximum absolute error of 5.2284×10^{-5} in case of running 10^6 replications. Therefore, the present approach is considered reliable and can be extended to the analysis of more complex cases.

Figure 9. Results of case study #1. Parity plot comparing analytic and simulation results.

5.2 Analysis of case study #2

Based on the information given in Section 4.2, we can initialize the tank agents and the environment model. T17 (indicated in red colour, in Figure 7(b)) is set to be the primary unit that is on “FIRE” (as explained above). To make sure that the probabilistic results are reliable on the thousandth, 10^6 replications were used, see APPENDIX C for further explanation.

Figure 10 shows the mean time $\mu (\pm\sigma)$ of catching fire of each of the tanks. For example, T1 is on fire in 500,668 replications among the 10^6 replications, and it might be on fire at different times in each of the replications.

Figure 10. Time distribution of catching fire of each tank.

As shown in Figure 10, since T17 is set as the primary unit, and is assumed on “Fire” initially, its time of being on fire is 0 sec. Generally, the nearer a tank to tank T17, the quicker it would be affected by a domino effect, resulting the roughly “V” shape of the time bars. However, due to the

different materials stored in the tanks and different environmental conditions (e.g. the wind direction), the time of being affected is not strictly propotional to the distance from T17.

Figure 11 shows the probabilities of being on “Fire” of each tank, with respect to different response times. The white bars (in (a)) show the probabilities of each tank of being fire, under the condition that there is no emergency response at all (and also without heat radiation threshold check); the light grey bars (Figure 11(a)) show the probabilities of each tank being on fire up until 20 minutes (this knowledge is important as the emergency response teams are usually able to intervine and mitigate the fires within 20 minutes); the medium grey bars (Figure 11 (b)) show the results up until 10 minutes, while the dark grey bars (Figure 11 (c)) show the results up until 5 minutes.

Figure 11. Conditional Probabilities of catching fire of each tank, w.r.t. different emergency response times. (a):in case of no response at all (the white bar) and an emergency response time of 20 minutes (the grey bar); (b):in case of an emergency response time of 10 minutes; (c) in case of an emergency response time of 5 minutes.

Figure 11 shows that, when there is no emergency response (the white bars), the tanks from index 10 to 30 have similar conditional probabilities of being on fire ranging from 0.9 to 1.0. That is, if we only consider the probabilistic dimension of domino effect, these 20 tanks have similar risks. However, by considering the emergency response time (i.e., the grey bars in Figures 11(b) and (c)), it can be noted that tanks 9 to 11 and 13 to 19 have higher domino risks than the others.

It can be concluded that, if a leakage happens at T17, all the other tanks in this area will have a risk of being on fire at a probability ranging from around 0.05 to 0.1 (recall that with an initial event, T17 will be on “Fire” with $p_{i1} = 0.1$). However, if the emergency response team starts the intervention within 5 minutes after the first fire, the risk of the whole plant will decrease significantly.

5.3 Analysis of case study #3

The results of the computational times are summarized in Figure 12. The computational times in case of $n \geq 169$ are estimated based on 10^4 replications, and are drawn as mean time $\pm \sigma$.

Figure 12. Results of computational time analysis.

As shown in Figure 12, the computational time increases exponentially with the number of tanks. In order to implement the model to a realistic case as given in Reniers et al.⁽¹²⁾ (i.e., $n = 225$), the estimated time would be around 52.32 hours.

Nevertheless, the DAMS model can still be applied to large scale cases because:

- 1) The computational time shown in Figure 12 is based on a personal computer with a limited computational and storage capacity. Since the different replications are independent, if we employ distributed/parallel computing techniques, the computational time will reduce linearly to the computational capacity. For example, in case of $n = 225$, if we employ a work station with 50 cores (not very high requirement), then the computational time will be around 4.18 hours.
- 2) According to the Law of Moore, the computational capacity of computers will double every 24 months.⁽⁵¹⁾ The last 50 years show the correctness of Moore's Law, however, the number of tanks in the chemical and process industries will not increase so quickly.
- 3) The proposed model can be used to explore possible scenarios, without knowing the probabilities, which otherwise would be very difficult if done by a human. In this case, it is not necessary to run the model so many times (see APPENDIX C). For example, if we just run the model 5000 times (thus the computational time will be 1/200 of the time given in Figure 12), then a 99.3% reliability can be reached that any notable scenario (i.e., those with a probability higher than 0.001) will be recorded.

6 DISCUSSION

The three case studies implemented in Sections 4 and 5 demonstrated that DAMS model is reliable in terms of the correctness of probabilistic, the advantages of capturing the time dimension, and the extensibility to large scale cases. Figure 8 and 9 demonstrates that DAMS correctly gets the

probabilistic assessment of domino effects, taking into consideration of higher level domino effects (see, e.g., Sce 6, 10, and 13) and synergistic effects (see, e.g., Sce 10). Figure 11 illustrates how the time dimension of domino effect could change the risks, which however, is one of the main achievements of the developed model. Figure 12 shows the capability of the model of calculating domino risks of plants containing hundreds of tanks, whereas the current existing models are only able to deal with dozens of tanks.

Compared to the case studies, the realistic situation in industrial practice is more complicated, mainly due to three reasons: (i) the variety of domino agents (e.g. tanks, pipeline, mobile vehicles, etc.); (ii) the variety of accident scenarios (e.g., jet fire, VCE, etc.); (iii) the number of domino agents.

To deal with the variety of domino effects, we proposed the tank agent model, which with different static attributes can describe most kinds of tanks in a typical chemical and process industry (for instance, different shape attributes can describe different geometries, and then in the dynamic model, different types of tanks will use different parameters in the Vulnerability Model). For pipelines and mobile vehicles as well as some other kinds of domino agents, we need to develop agent-specific models. However, these models can be built in a similar way to the tank agent model. To deal with the variety of accident scenarios, we only considered heat radiation escalation to represent pool fires jet fires, etc. In order to take other escalation vectors such as overpressure escalation and fragments into consideration, more chemical-related domain knowledge is needed, and thus stronger cooperation between simulation experts and chemical engineering experts.

To address the number of domino agents, we propose the “tank agent model”, which is the basic unit in a domino effect; thus, regardless of the number of tanks, each physical tank is represented as a tank agent. In fact, the model proposed in this study has two important properties: (i) the tank

agent's static and dynamic model will not be influenced by the number of tanks; (ii) the necessary replications of computational experiments will not be influenced by the number of tanks (see APPENDIX C).

To address the first and second reason, new models are needed though they can be developed analogously. The model proposed in this study can be used in case of an increasing number of domino agents (i.e., the third reason).

7 CONCLUSIONS

In the present work, an agent-based modelling and simulation approach is proposed to estimate the potential domino risks in chemical plants. Tanks are modelled as agents who receive heat radiation from the tanks already on fire, run state transformation based on the received heat radiation, and if get on fire broadcast heat radiation to other tanks. The environment is modelled as an observer to manage global information. The proposed approach is able to capture not only the probabilistic dimension of domino effect, but also the time dimension which describes the timing when the domino effect may happen. Higher-level domino effect, as well as synergistic effects are also considered. The correctness, the advantages, and the extensibility of the model are illustrated by the computational experiments carried out on several case studies.

This work is a first attempt to employ an agent-based modelling and simulation (ABMS) approach to do domino risk assessment in chemical plants. By successfully modelling the dynamic procedure of domino effects, the outcome of this research can be used to support optimal and dynamic allocation of emergency resources. Furthermore, by tagging initial events on multiple targets, the model can support domino effect assessment triggered by a number of simultaneously failed tanks, a situation which may occur in case of a terrorist attack.

APPENDIX A

The dynamic evolution of tanks exposed to fire is a complex problem, which would need a dedicated assessment through physical models, especially contemplating the possible synergistic effects due to increment of heat load during fire exposure. Some simplifying assumption were needed to instruct model and simulations.

Assuming a tank receives Q_i at time $t_i (i = 1, 2, 3, \dots, T)$, the following text discusses how to compute the time t_r that the tank would employs the vulnerability model to judge whether being damaged or not.

If $T = 1$, which means the tank only receives one time the heat radiation, then the formula A.1 and A.2 can be employed to compute the ttf ,⁽³³⁾ for atmospheric and pressurized equipment respectively. In these cases, we have $t_r = t_1 + ttf_1$.

$$\ln(ttf) = -1.13 \cdot \ln(Q) - 2.67 \cdot 10^{-5}V + 9.9 \quad (\text{A.1})$$

$$\ln(ttf) = -0.95 \cdot \ln(Q) + 8.845V^{0.032} \quad (\text{A.2})$$

If $T > 1$, which means the tank receives heat radiation from more than one sources. Note that A.1 and A.2 can be re-written as:

$$ttf = Q^{-1.13} \cdot e^{-2.67 \cdot 10^{-5} \cdot V + 9.9} \quad (\text{A.3})$$

$$ttf = Q^{-0.95} \cdot e^{8.845 \cdot V^{0.032}} \quad (\text{A.4})$$

Furthermore, we define $k = 1.13$ and $g(v) = e^{-2.67 \cdot 10^{-5} \cdot V + 9.9}$, then A.3 can be re-written as:

$$ttf^{\frac{1}{k}} \cdot Q = g(v)^{\frac{1}{k}} \quad (\text{A.5})$$

A.4 can be re-written in the same format, by using different $k, g(v)$.

A.5 is a linear equation for the heat radiation Q , thus it can be used to compute the t_r . According to the physical meaning of ttf , A.6 and A.7 computes the t_r when the tank receives multiple times heat radiation.

$$\sum_{i=1}^N (t_r - t_i)^{\frac{1}{k}} \cdot Q_i = g(v)^{\frac{1}{k}} \quad (\text{A.6})$$

In condition of that:

$$t_r^{N-1} > t_N \quad (\text{A.7})$$

In A.6 and A.7, the t_r^{N-1} denotes the root of A.6 when $N - 1$ times heat radiation received.

The explanation of A.6 and A.7:

Recalling the A.5, given a target tank, the right part of A.5 is a constant number, while the left part can be re-written as $(t_r - t)^{\frac{1}{k}} \cdot Q$, showing the relationship of the time needed to heat up the tank and the heat radiation received. Furthermore, A.5 is a linear equation of Q , so that the addition law can be used, reaching the A.6. Formula A.7 further explains only when the tank is not heat up yet, then it is necessary to use A.6.

Figure A.1 gives the procedure of how to use A.6 and A.7.

Figure A.1 Procedure of Computing t_r .

Observation A.1 In condition of A.7, formula A.6 has and only has one root between time interval (t_N, t_r^{N-1}) .

Proof: Define $f(t_r) = \sum_{i=1}^N (t_r - t_i)^{\frac{1}{k}} \cdot Q_i - g(v)^{\frac{1}{k}}$. Firstly, $f(t_r)$ is an elementary function, and $f(t_r)' > 0$ when $t_r \geq t_N$; Secondly, $f(t_r) = \sum_{i=1}^N (t_N - t_i)^{\frac{1}{k}} \cdot Q_i - g(v)^{\frac{1}{k}} = \sum_{i=1}^{N-1} (t_N - t_i)^{\frac{1}{k}} \cdot Q_i - g(v)^{\frac{1}{k}}$, considering that $f(t_r)' > 0$ and $t_N < t_r^{N-1}$, we have $f(t_r) < \sum_{i=1}^{N-1} (t_r^{N-1} - t_i)^{\frac{1}{k}} \cdot Q_i - g(v)^{\frac{1}{k}} = 0$; Thirdly, $f(t_r^{N-1}) = \sum_{i=1}^N (t_r^{N-1} - t_i)^{\frac{1}{k}} \cdot Q_i - g(v)^{\frac{1}{k}} = (t_r^{N-1} - t_N)^{\frac{1}{k}} \cdot Q_N > 0$.
Combining the above 3 condition, we know that there exist and only exist one $\bar{t}_r \in (t_N, t_r^{N-1})$ s.t. $f(\bar{t}_r) = 0$. $\square$

Based on the Observation A.1, Figure A.2 gives an approximately algorithm to solve A.6.

Figure A.2 A Binary Search Algorithm for Solving A.6.

However, when using the Vulnerability Model to compute the probabilities of being damaged, formula A.1 and A.2 should be used: using $Q = \sum_N Q_i$ as input, getting the ttf , and use the ttf as the input for Equation (3) (in section 3.2.2).

APPENDIX B

Figure B.1 reports the quantified event trees considered for the analysis.⁽⁴⁶⁾ Table B.I shows the exact parameters used for the ETA1 and ETA2 modules.

Figure B.1. Event Tree Analysis of Quantification in case of Flammable Liquid Releasing.

Table B.I. Parameters in Figure B.1

	p_A	p_B	p_C
ETA1	0.1	0	0
ETA2	0.6	0	0

Since ETA1 will only be used by the primary unit, which means at that time, there is no tank on fire yet, thus the immediate ignition probability p_A is set to be a smaller number, i.e. 0.1. The ETA2 will only be used by the domino units, which means there is one or more tanks on fire already, thus the immediate ignition probability p_A for ETA2 is set to be a greater number, i.e. 0.6. Both for

ETA1 and ETA2, p_B is set to be 0, which means in this study, only the heat radiation escalation is considered, while the overpressure, fragment etc. are not considered. Since p_B is set to be 0, it does not matter what value the p_c is, specifically, we set $p_c = 0$.

APPENDIX C

In this appendix, we will discuss how many replications are necessary for the computational experiment.

Table C.I Notations in this appendix

Notation	Definition
N	experiment times
p	the probability of the concerned event
v_N	the number of times that the concerned event happens, within the N times repeat experiments
$\tilde{p}$	$\tilde{p} = v_N/N$, the observed probability of the concerned event

Since every replications are independent, thus the N times experiments are Bernoulli process.

According to the properties of Bernoulli process,⁽⁵²⁾ we have

$$E(v_N) = Np \quad (C.1)$$

And

$$V[v_N] = Np(1 - p). \quad (C.2)$$

(C.2) is equal to

$$V\left[\frac{v_N}{N}\right] = \frac{p(1-p)}{N}. \quad (C.3)$$

Furthermore, according to the central limit theorem (CLT) and law of large numbers⁽⁵²⁾ we have

$$Z = \frac{(v_N/N) - p}{\sqrt{V[\frac{v_N}{N}]}} \sim N(0,1). \quad (C.4)$$

Thus we have

$$P \left\{ \left| \frac{(v_N/N) - p}{\sqrt{V[\frac{v_N}{N}]}} \right| \leq Z_{1-\alpha/2} \right\} = 1 - \alpha. \quad (C.5)$$

Normally we set $\alpha = 0.05$ (i.e. 95% confidence interval), we have $Z_{0.975} = 1.96$. Considering to (C.3), (C.5) can be rewritten as:

$$P \left\{ \left| \frac{(\tilde{p} - p)\sqrt{N}}{\sqrt{p(1-p)}} \right| \leq 1.96 \right\} = 0.95 \quad (C.6)$$

Furthermore (C.6) can be rewritten as:

$$P \left\{ |\tilde{p} - p| \leq \frac{1.96\sqrt{p(1-p)}}{\sqrt{N}} \right\} = 0.95 \quad (C.7)$$

$|\tilde{p} - p|$ represents the error of the observed probability and the real probability.

In this study, we are doing experiments under the condition that the primary unit is already on fire (as explained in section 5.1), thus the events whose occurrence probabilities are lower than 10^{-3}

can be ignored. So it is acceptable if $|\tilde{p} - p| \leq 0.001$. Thus we need $\frac{1.96\sqrt{p(1-p)}}{\sqrt{N}} \leq 0.001$, getting:

$$N \geq 3.8416 \cdot p(1-p) \cdot 10^6 = N_{min} \quad (C.8)$$

It is obvious that $N = 10^6$ satisfies the formula (C.8).

This means if we do $N = 10^6$ experiments, then all the conditional probabilistic results are 95% reliable on the thousandths, and the accuracy will not be influenced by the scale of the question (i.e. the number of tanks in this study).

APPENDIX D

The layout of the tank farm considered for case study #2 is reported in Figure 7(b). The vessels are atmospheric tanks containing flammable liquids. The features of the tanks, the stored substances and the considered inventories are summarized in Table D.1. The meteorological conditions assumed for case study are $T = 15^{\circ}\text{C}$, relative humidity = 25%, limited wind speed, leading to negligible flame tilting effects. The consequence assessment of the pool fires following the ignition of the total inventory of tank T17 after a major leakage are analysed applying the software ALOHA. The heat radiation received by each of the other vessels is reported in Table D.2 at the correspondent ID.

Table D.1 Main features of the vessels considered in case study 2.

ID	Diameter (m)	Height (m)	Capacity (m ³)	Filling level (%)	Substance	Density (kg/m ³)	Inventory (ton)
T1	24	12.6	5710	0.5	Crude oil	950	2712
T2	30	10.8	7630	0.7	Crude oil	950	5074
T3	30	10.8	7630	0.7	Crude oil	950	5074
T4	24	12.6	5710	0.49	Crude oil	950	2658
T5	15	12.6	2225	0.44	Gasoline	750	734
T6	27	9	5182	0.26	Crude oil	950	1280
T7	21	12.6	4350	0.8	Gasoline	750	2610
T8	15	12.6	2225	0.27	Gasoline	750	451
T9	24	12.6	5710	0.58	Gasoline	750	2484
T10	18	7.2	1843	0.39	Gasoline	750	539
T11	18	7.2	1843	0.59	Gasoline	750	815
T12	12	7.2	806	0.23	Gasoline	750	139
T13	7.5	9	397	0.76	Benzene	876	265
T14	7.5	9	397	0.14	Benzene	876	49
T15	15	12.6	2225	0.62	Toluene	867	1196
T16	27	9	5129	0.46	Methanol	792	1869
T17	21	12.6	4350	0.74	Ethanol	789	2540
T18	21	12.6	4350	0.36	Ethanol	789	1236
T19	15	12.6	2225	0.32	Methanol	792	564
T20	21	12.6	4350	0.42	Solvent	650	1188
T21	13.5	9	1282	0.28	Solvent	650	233
T22	12	7.2	806	0.44	Solvent	650	231

T23	15	18	3179	0.46	Solvent	650	951
T24	18	7.2	1843	0.72	Ethanol	789	1047
T25	21	12.6	4350	0.34	Ethanol	789	1167
T26	15	14.4	2543	0.45	Benzene	876	1003
T27	24	12.6	5710	0.77	Benzene	876	3852
T28	18	7.2	1843	0.8	Gasoline	750	1106
T29	18	7.2	1843	0.43	Toluene	867	687
T30	18	7.2	1843	0.63	Methanol	792	919
T31	12	7.2	806	0.23	Solvent	650	121
T32	15	9	1590	0.42	Solvent	650	434
T33	15	9	1590	0.54	Solvent	650	558
T34	21	12.6	4350	0.68	Gasoline	750	2219

Table D.2 Results of the consequence assessment of the pool fires associated to each tank. Radiation received by each target is reported in kW/m². Values lower than 10 kW/m² are excluded (Na).

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	
T1	-	23.7	Na	10.9	Na	Na	Na	Na	Na	Na	15.4	15.2	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T2	30.1	-	55.6	43.3	24.8	12.2	Na	12.9	Na	11.4	13.8	17.9	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T3	12.3	55.6	-	32.2	44.2	11.4	Na	17.5	Na	Na	Na	10.3	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T4	11.1	33.5	25.5	-	35.4	29.5	13.8	24.9	Na	17.0	14.0	23.4	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T5	Na	13.2	21.2	34.2	-	22.4	23.6	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	12.8	Na	Na	Na	Na	Na	Na	
T6	Na	Na	Na	26.1	14.1	-	35.6	27.0	Na	25.2	11.5	17.3	Na	10.3	10.3	14.1	16.3	Na	Na	Na	Na	Na	Na	31.3	16.8	27.0	17.8	18.9	Na	Na	Na	Na	Na	Na	
T7	Na	10.2	12.3	23.8	25.2	57.1	-	63.2	Na	15.7	Na	12.5	Na	Na	Na	12.2	16.0	Na	Na	Na	Na	12.7	11.0	36.5	30.8	52.8	57.1	91.7	20.4	26.5	12.0	17.1	12.0	Na	
T8	Na	13.2	21.2	34.2	70.0	22.4	23.6	-	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	12.8	Na	Na	Na	Na	Na	Na	
T9	Na	Na	Na	Na	Na	Na	Na	Na	-	21.4	22.9	14.7	37.6	36.5	51.1	36.5	18.3	31.7	18.7	16.4	Na	11.3	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T10	Na	Na	Na	13.3	Na	24.7	Na	Na	Na	-	43.5	51.0	28.3	36.2	29.7	25.9	13.8	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T11	10.6	Na	Na	Na	Na	Na	Na	Na	Na	40.2	-	58.8	42.5	31.2	18.3	11.4	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T12	Na	Na	Na	10.6	Na	Na	Na	Na	Na	33.4	42.5	-	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T13	Na	Na	Na	Na	Na	11.4	Na	Na	25.5	55.2	58.7	26.5	-	99.0	91.8	36.8	14.1	14.6	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T14	Na	Na	Na	Na	Na	11.4	Na	Na	25.5	55.2	58.7	26.5	99.0	-	91.8	36.8	14.1	14.6	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T15	Na	Na	Na	Na	Na	10.1	Na	Na	10.8	22.9	10.1	Na	15.9	23.9	-	73.8	73.8	26.3	13.8	Na	Na	10.5	Na	10.1	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T16	Na	Na	Na	Na	Na	10.1	Na	Na	10.8	22.9	10.1	Na	15.9	23.9	73.8	-	73.8	26.3	13.8	Na	Na	10.5	Na	10.1	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T17	Na	Na	Na	Na	Na	10.1	Na	Na	10.8	22.9	10.1	Na	15.9	23.9	73.8	73.8	-	26.3	13.8	Na	Na	10.5	Na	10.1	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T18	Na	Na	Na	Na	Na	Na	Na	Na	15.5	Na	Na	Na	Na	12.0	24.6	44.0	29.8	-	46.2	29.1	17.2	19.9	11.1	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T19	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	18.9	-	26.0	15.0	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T20	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	20.6	23.0	54.5	78.2	-	42.3	28.9	22.2	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	
T21	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	10.9	19.7	15.0	24.8	25.8	-	57.8	77.1	12.8	17.2	Na	Na	Na	16.6	Na	12.4	Na	Na	Na	
T22	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	21.9	56.2	23.8	39.6	24.9	65.0	-	60.2	23.8	26.0	12.0	Na	Na	16.0	Na	Na	Na	Na	Na	
T23	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	10.9	19.7	15.0	24.8	25.8	77.1	57.8	-	12.8	17.2	Na	Na	Na	16.6	Na	12.4	Na	Na	Na	
T24	Na	Na	Na	Na	Na	16.1	24.8	30.3	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	-	36.5	36.5	36.5	36.5	26.7	31.2	10.8	17.3	Na	Na	
T25	Na	Na	Na	Na	Na	16.1	24.8	30.3	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	36.5	-	36.5	36.5	36.5	26.7	31.2	10.8	17.3	Na	Na	Na
T26	Na	Na	Na	12.1	10.3	33.2	49.3	59.7	Na	13.3	Na	Na	Na	Na	Na	15.2	23.3	11.9	12.8	10.5	16.2	22.2	22.2	74.3	74.3	-	74.3	74.3	53.0	61.5	25.6	35.3	23.3	16.8	
T27	Na	Na	Na	12.1	10.3	33.2	49.3	59.7	Na	13.3	Na	Na	Na	Na	Na	15.2	23.3	11.9	12.8	10.5	16.2	22.2	22.2	74.3	74.3	74.3	-	74.3	53.0	61.5	25.6	35.3	23.3	16.8	
T28	Na	Na	Na	10.8	Na	33.2	49.7	60.6	Na	12.0	Na	Na	Na	Na	Na	14.1	22.7	10.6	11.5	Na	15.1	21.6	21.6	75.5	75.5	75.5	75.5	-	53.5	62.4	25.1	35.3	22.7	15.8	
T29	Na	Na	Na	Na	Na	12.5	15.5	Na	Na	Na	Na	Na	Na	Na	Na	12.4	15.8	10.5	12.9	12.5	21.1	21.1	31.0	22.6	39.6	25.0	35.7	20.7	-	79.8	79.8	79.8	79.8	79.8	
T30	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	Na	11.4	Na	15.5	Na	13.7	Na	29.5	-	29.5	29.5	29.5	29.5	
T31	Na	Na	Na	Na	Na	12.8	16.0	Na	Na	Na	Na	Na	Na	Na	Na	12.6	16.4	10.6	13.3	12.8	22.3	22.3	33.1	23.9	42.3	26.5	38.2	21.7	85.2	85.2	-	85.2	85.2	85.2	
T32	Na	Na	Na	Na	Na	12.8	16.0	Na	Na	Na	Na	Na	Na	Na	Na	12.6	16.4	10.6	13.3	12.8	22.3	22.3	33.1	23.9	42.3	26.5	38.2	21.7	85.2	85.2	85.2	-	85.2	85.2	
T33	Na	Na	Na	Na	Na	12.8	16.0	Na	Na	Na	Na	Na	Na	Na	Na	12.6	16.4	10.6	13.3	12.8	22.3	22.3	33.1	23.9	42.3	26.5	38.2	21.7	85.2	85.2	85.2	85.2	-	85.2	
T34	Na	Na	Na	Na	Na	10.5	13.4	Na	Na	Na	Na	Na	Na	Na	Na	10.3	13.7	Na	10.9	10.5	19.2	19.2	29.3	20.8	37.8	23.2	34.0	18.7	75.6	75.6	75.6	75.6	75.6	-	

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