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Simulation Modeling of Epidemic Risk in Supermarkets: Investigating the Impact of Social Distancing and Checkout Zone Design

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Abstract. We build an agent-based model for evaluating the spatial and functional design of supermarket checkout zones and the effectiveness of safety regulations related to distancing that have been introduced after the COVID-19 outbreak. The model is implemented in the NetLogo simulation platform and calibrated to actual point of sale data from one of major European retail chains. It enables realistic modeling of the checkout operations as well as of the airborne diffusion of SARS-CoV-2 particles. We find that opening checkouts in a specific order can reduce epidemic risk, but only under low and moderate traffic conditions. Hence, redesigning supermarket layouts to increase distances between the queues can reduce risk only if the number of open checkouts is sufficient to serve customers during peak hours.

Keywords: Agent-based model · Indoor infection spreading · Checkout zone architecture · Decision support · COVID-19 · NetLogo

1 Introduction

The COVID-19 pandemic is unprecedented in contemporary history. In response to this worldwide threat, governments implemented public health measures which include isolation/quarantine and social distancing [3]. This has had an adverse effect on the retail sector. On one hand, it has been badly affected by the closure of services. On the other, grocery stores have been struggling with rising demand as consumers tried to stock up for long periods of isolation [8]. To address concerns, most brick-and-mortar stores have set or have been required to set restrictions on operating activities (closing of shopping malls, limiting the number of customers) as well as improved customer safety (installing protective shields and disinfectant dispensers, ensuring distancing). While all these actions lead to incurring costs and negatively impact functionality, their actual value as anti COVID-19 measures is generally unknown.

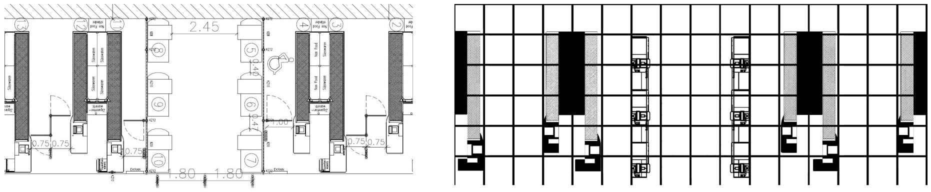


Fig. 1. Blueprint of an actual supermarket checkout zone with six self-service checkouts in the middle and service checkouts to the left and right (*left*), and its representation using NetLogo's square patches of size 1m × 1m (*right*).

It is exactly the aim of this study to examine the effectiveness of safety regulations related to distancing that have been introduced in (grocery) supermarkets. These include encouraging customers to keep distance in the queue and closing some checkouts to reduce the congestion in the checkout zone. Although catching the virus from surfaces is plausible, SARS-CoV-2 is predominantly airborne [5]. It is transmitted through the air by people talking, coughing and breathing out small particles called aerosols. To address this problem, we utilize a data-driven agent-based model (ABM) for simulating aligning in queues and movement of customers in the checkout zone introduced in [1] and expand it – by borrowing ideas from [10] – to enable realistic modeling of exhaling, dispersion and absorption of aerosols.

Our model is implemented in the open-source NetLogo simulation platform [11]. Given that ABMs allow designers to evaluate projects to avoid functionally wrong and ineffective solutions [4], our model is not limited to testing the effectiveness of distancing measures for existing checkout zone layouts in supermarkets, but can be also utilized for redesigning them to achieve a desirable customer flow while reducing the risk of infection. This can be achieved by changing the layout, running simulations and measuring if the resulting customer flow has increased and/or the infection risk decreased.

2 Modeling Infection Transmission

The starting point is a recently proposed ABM for simulating customer dynamics in the checkout zone of a (grocery) supermarket [1]. Although customers can be infected at any time, the exposition to potentially hazardous aerosols is the highest at checkout, because of a much higher concentration of people than in other parts of the store. In order to provide a realistic test ground, we calibrate the ABM to actual POS data [2] and consider the checkout zone layout of an existing supermarket. For simplicity and to speed up simulations, the latter is mapped to a square grid with patches of size 1m × 1m, see Fig. 1. Finer spatial granularity can be readily implemented.

Without loss of generality, we assume that agents pick the line with the lowest number of customers in front of them; a scenario labeled #1 in [1]. Again, this can be easily changed to any of the line picking scenarios considered in the cited

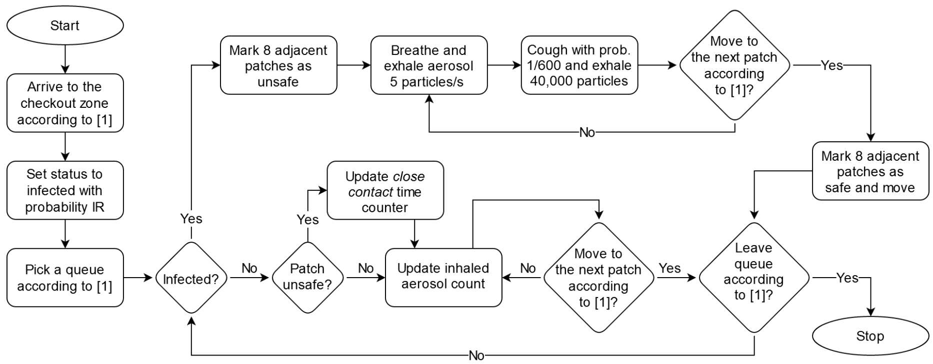


Fig. 2. Flowchart of the simulation steps from the perspective of an agent.

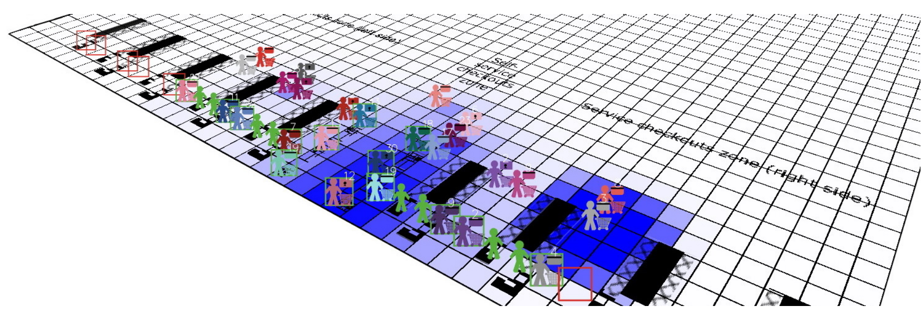
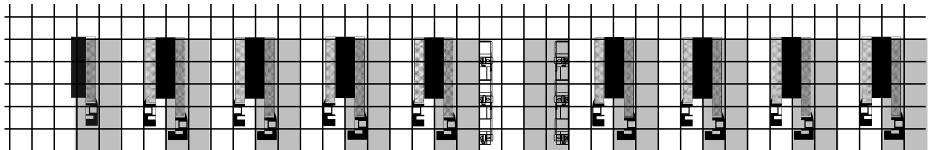


Fig. 3. Visualization of the intensity of aerosol particles at the control height of 1m. The scale ranges from 0 (white) to 300 particles (dark blue). Two hazardous areas are visible – in the center in the self-service area and in the lower right corner next to one of the service checkouts. Human figures at the checkouts represent cashiers, figures with baskets – customers, and green/red hollow squares – open/closed checkouts.

paper. Moreover, we assume that queues are straight lines and formed along service checkouts or in the axis of the self-service checkout zone.

To evaluate epidemic risk, we expand this ABM to account for the physics of aerosol and droplet dispersion relevant to the hypothesized airborne transmission of SARS-CoV-2. We assume that a hazardous 'close contact' takes place when a susceptible agent is in the immediate proximity of an infected one, i.e., when it occupies one of the 8 squares adjacent to the location of an infected agent. Following [10], we let infected individuals release aerosol at a constant rate of 5 particles/s and occasionally cough (on average 6 times/h, each time releasing 40,000 particles). Given that our simulation clock has a granularity of one second, the probability of coughing in each time interval is $6/3600 = 1/600$.

The aerosol is released at the location of the infected individual into a volume of 1m^3 at the control height of 1m. After that, it is immediately diluted via removal and diffusion processes. The removal, e.g., by ventilation or adherence to surfaces, is modeled by a sink term $-c/\tau$ with a timescale of $\tau = 100\text{s}$, where



#0 #1	17	15	13	11	9	7	5	3	1			2	4	6	8	10	12	14	16
#2 #3		7		5		3		1					2		4		6		8
#4 #5	9	7	11	5	13	3	15	1	16			17	2	14	4	12	6	10	8

Fig. 4. Opening sequence of the service checkouts in the six considered scenarios. For instance, in scenarios #0 and #1 the checkout to the left of the self-service zone is opened first (1), followed by the checkout to the right (2), then the second checkout to the left (3), etc. Note, that self-service checkouts in the middle are always open.

c is the amount of aerosol particles. The diffusion is modeled using NetLogo's function 'diffuse' [11], which transfers 5% of aerosol particles within the patch to its eight adjacent patches, see Fig. 3. Finally, susceptible agents accumulate aerosol proportional to their rate of inhalation, on average 0.33dm^3/s.

3 Simulation Setup

We consider a supermarket of a large European chain located in southern Poland. The store is equipped with 17 service and 6 self-service checkouts, see Fig. 4, with separate queues to each service and one to the all self-service checkouts. According to standard work rules, all self-service checkouts are constantly open during working hours. The service checkouts are opened dependent on traffic and the availability of cashiers [1]. In the analysed store, as per standard work rules, they were opened in a particular order – starting from the checkout to the left of the self-service zone, followed by the checkout to the right, then the second checkout to the left, etc., see the row labeled '#0 #1' in Fig. 4. Obviously, such rules lead to a congested center of the zone, even under relatively low traffic.

To evaluate the impact of the checkout zone design (here: through the sequence of opening checkouts) and adherence to distancing rules on the risk of infection we consider six scenarios. In the base **scenario #0** standard work rules are in place, all checkouts are available to be opened and safety distances between customers within queues are not respected. **Scenario #1** is a variant of #0 with increased COVID-19 restrictions – markings on the floor make customers keep safety distance within the queues. In **scenarios #2** and **#3**, 50% of service checkouts are permanently closed – every other checkout, including the closest to the self-service checkout zone. In **scenarios #4** and **#5**, the opening sequence first follows the 'every other' rule of #2 and #3, then opens the remaining checkouts starting from the most distant from the center, see Fig. 4. In scenarios #2 and #4 safety distances between customers within queues are not respected, while in #3 and #5 they are.

Table 1. Percentage of customers with violation of safety distances for all opening hours and peak hours only (i.e., Saturdays 12pm–4pm), and three infection rates (IR). By definition there are no violations in scenario #3, hence the missing row.

IR	2.5%	5%	7.5%	2.5%	5%	7.5%
Scenario	*All hours*			*Peak hours*		
#0	3.68%	6.76%	9.55%	4.20%	8.18%	11.46%
#1	3.02%	5.67%	7.97%	3.47%	6.45%	9.53%
#2	1.02%	1.92%	2.82%	4.92%	9.40%	13.59%
#4	0.93%	1.75%	2.58%	2.92%	5.57%	8.14%
#5	0.34%	0.72%	1.00%	1.93%	3.78%	5.56%

4 Results

The simulations are conducted for a period of 14 days based on historical POS data regarding customer traffic, basket sizes and cashier availability [2]. Because the number of infected individuals in a population changes dynamically, we consider three levels of the infection rate (IR): 2.5%, 5% and 7.5%. Based on variance stability analysis for the underlying ABM [1, Sec. IV], we perform 10 simulation runs for each scenario and IR level, and average the results.

In Table 1 we report the percentage of customers that violated the safety distance (for any length of time). Note, that by definition, there are no violations in scenario #3, as both horizontal (every second checkout closed) and vertical (markings on the floor) distances between customers exceed one patch or 1.5–2m measuring from the centers of the occupied patches. This scenario, however, would be difficult to implement in practice due to the significant increase in queue lengths (ca. 1.5 times) and service times (ca. 2 times), and unfeasible during peak hours (i.e., Saturdays 12pm–4pm; ca. 7 times longer queues and ca. 15 times longer service times). Out of the remaining ones, scenario #5 yields the lowest values across all infection rates. The percentages are ca. 10 times lower than for the base scenario when all opening hours are considered and over 2 times lower during peak hours. The second best scenario is #4. Scenario #2 trails closely behind, but only for all hours. For peak hours #2 is the worst, even worse than #0. Quite surprising is the advantage of scenario #4 over #1 – both for all and peak hours only – which indicates that avoiding contacts between customers in different queues is more beneficial than contacts within a queue. Of course, only if it is not at the expense of capacity, as in #2.

In the left panels of Fig. 5 we plot the reliability function $R(t)$ of the 'close contact' time t, where $R(t) = 1 - F(t)$ and $F(t)$ is the (empirical) cumulative distribution function. Clearly, scenario #2 is suboptimal as it yields by far the highest probabilities of very long close contact times, potentially leading to infection. Recall, that by definition, scenario #3 does not allow for 'close contact', hence the vertical reliability function. The drawback is that the much longer queues (see above) lead to larger numbers of inhaled aerosols – scenarios #2 and #3 are much higher than the remaining ones in the right panels of Fig. 5.

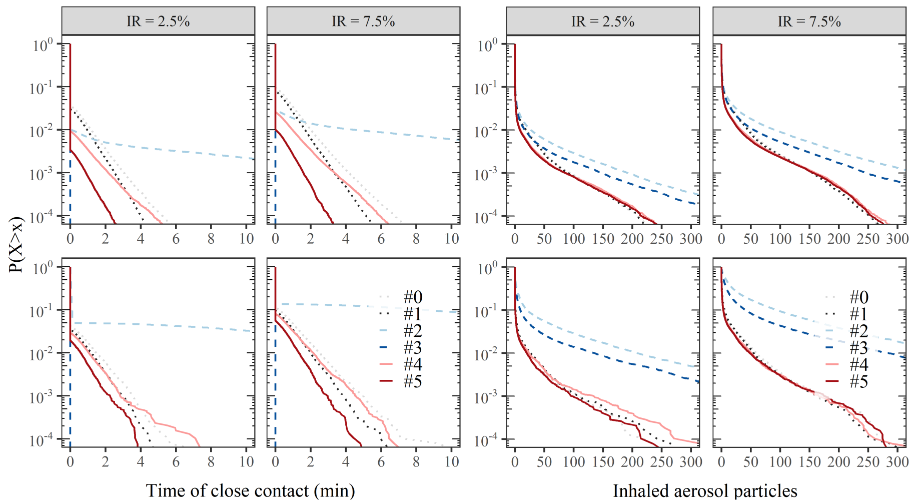


Fig. 5. Reliability function (logarithmic scale) of the 'close contact' time (*left*) and the number of potentially hazardous aerosol particles inhaled by customers (*right*) for all opening hours (*top*) and peak hours only (i.e., Saturdays 12pm–4pm; *bottom*) for infection rates IR = 2.5% and 7.5%, and all six scenarios (#0, ..., #5).

Although scenario #5 yields the shortest times of 'close contact', its advantage over the remaining scenarios is not that visible in terms of the number of inhaled particles. For small amounts of absorption (up to ca. 75 particles) and for all opening hours (two upper right panels), strategies that limit close contact between customers in different queues (#4, #5) perform better than the other. However, during peak hours (two lower right panels) the differences nearly disappear as these strategies allow to open adjacent checkouts in case of increased traffic. Interestingly, the numbers of inhaled aerosols are not much higher for peak hours compared to the values obtained for the entire period. This may indicate that – under the considered conditions – the risk of hypothesized aerosol transmission does not increase much with customer traffic.

5 Conclusions

Using an agent-based model able to mimic customer dynamics in the checkout zone [1], expanded to enable realistic modeling of exhaling, dispersion and absorption of potentially hazardous aerosols [10], we evaluate the spatial and functional design of supermarket checkout zones and the effectiveness of safety regulations related to distancing that have been introduced after the COVID-19 outbreak. We find that opening checkouts in a specific order can reduce epidemic risk, but only under low and moderate traffic conditions. During peak hours the differences nearly disappear as strategies #4 and #5 allow to open adjacent checkouts in case of increased traffic. Moreover, scenarios where only every second checkout can be opened turn out to be suboptimal. They increase the social distance and provide a buffer of 1.5–2m, however, at the cost of significantly increasing the time spent queuing. As a result, the numbers of inhaled aerosol particles are larger than for the other scenarios. Hence, redesigning supermarket layouts to increase distances between the queues can reduce epidemic risk only if the number of open checkouts is sufficient to serve customers during peak hours.

Our model is implemented in the open-source NetLogo simulation platform [11] and can be easily adapted to various situations; the source codes are available from GitHub [1]. In particular, it can be utilized for optimizing supermarket layout, similarly as in [9] for logistic warehouses, or increasing the social-spatial comfort of the customers [7]. We are also aware of the limitations of our study. Our model does not take into account aerodynamic disturbances which may increase the range of airborne droplets [6] nor utilize a realistic collision-free velocity model for pedestrian dynamics [12]. Nevertheless, we believe that it may be used as a decision support tool for architects (re)designing supermarkets and for managers making staffing decisions and planning checkout operations.

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